Smart and Sustainable Architecture and Urban Resilience

SSAUR 2026

International Conference on Smart and Sustainable Architecture and Urban Resilience 2026 (SSAUR 2026) - College of Architecture and Design, Prince Mohammad Bin Fahd University AL-Khobar - Saudi Arabia, 29-30 April 2026

Edited by
Jamal Nayfeh
Chuloh Jung
Nadine Fayad

MRF

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Editors

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Preface

The *International Conference on Smart Systems, Architecture, and Urban Resilience (SSAUR 2026)* represents an evolving intellectual platform situated at the intersection of architectural innovation, urban systems, and emerging technological frameworks. Within the context of accelerating environmental, social, and infrastructural transformations, the conference can be interpreted as a response to the increasing need for integrative and adaptive approaches to the built environment.

SSAUR 2026 convened scholars, practitioners, and policymakers whose work collectively examines the mechanisms through which smart systems and resilient urban strategies can be conceptualized, implemented, and critically evaluated. The contributions presented in this volume reflect a diverse yet convergent set of inquiries, ranging from computational design methodologies and smart infrastructure systems to sustainability-driven urban strategies and human-centered spatial frameworks. Rather than operating within isolated disciplinary boundaries, many of these studies adopt hybridized perspectives that synthesize architecture, engineering, data science, and environmental analysis.

The selected papers included in this publication underwent a structured peer-review process designed to ensure academic rigor, methodological clarity, and conceptual relevance. This process not only reinforces the credibility of the presented research but also situates the volume within a broader scholarly discourse that prioritizes innovation alongside critical reflection. The resulting collection can therefore be understood as both a documentation of current advancements and a framework for future investigation.

A recurring dimension across the contributions is the repositioning of “smartness” beyond purely technological optimization toward a more nuanced integration with social, environmental, and spatial considerations. While digital systems and artificial intelligence offer new operational capabilities, several studies indicate that resilience emerges more effectively when these tools are embedded within adaptive urban ecosystems and responsive architectural strategies. This shift suggests an expanded understanding of resilience as a multi-scalar and interdisciplinary process rather than a singular technical outcome.

The organization of this volume reflects thematic clusters that align with key research trajectories addressed during the conference. These include, but are not limited to, smart urban infrastructure, sustainable architectural systems, digital design and simulation, resilient urban planning, and emerging materials and technologies. Each thematic grouping highlights specific dimensions of inquiry while collectively contributing to a broader analytical framework concerned with the future of cities and built environments.

The realization of SSAUR 2026 and this subsequent publication is the result of collaborative efforts across multiple levels. The contributions of authors, reviewers, session chairs, and organizing committee members have been instrumental in shaping both the intellectual depth and organizational coherence of the conference. Their engagement reflects a shared commitment to advancing knowledge within the field and fostering meaningful academic exchange.

This volume is intended to serve not only as a record of the conference proceedings but also as a reference point for ongoing research and professional practice. The studies presented herein may inform future investigations, support evidence-based design approaches, and contribute to the development of more resilient and adaptive urban systems. In this sense, the publication extends beyond documentation, functioning as part of a continuous dialogue on the evolving role of architecture and urbanism in addressing complex global challenges.

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Track Summaries*

The SSAUR 2026 conference, as outlined in the conference material, reflects a competitive and curated academic platform, with 138 submissions resulting in 67 accepted papers and an overall acceptance rate of approximately 48%. This distribution indicates a selective review process that prioritizes methodological rigor and thematic relevance. The accepted contributions are organized into five tracks, each representing a critical dimension of contemporary discourse in architecture, urbanism, and the built environment. While the tracks are differentiated by focus, they collectively suggest a convergence toward integrative approaches that address technological innovation, environmental challenges, and socio-cultural transformation within urban contexts.

Track 1: Smart & Sustainable Design

This track includes 15 accepted papers that collectively examine sustainability as a multi-scalar design framework, extending from material selection and building components to integrated performance systems. A significant portion of the contributions focuses on environmental performance at the building scale, particularly within hot-arid and hot-humid contexts. For instance, empirical studies on hygrothermal conditions in residential environments demonstrate how microclimatic imbalances, such as elevated relative humidity in enclosed spaces, can generate latent risks for material degradation and occupant health. Complementary research on indoor air quality further indicates that contemporary airtight construction practices, while improving energy efficiency, may exacerbate pollutant accumulation and ventilation deficiencies. These findings collectively suggest that sustainable design must move beyond energy metrics to incorporate indoor environmental quality as a critical performance dimension, particularly in rapidly urbanizing regions.

At the envelope and system level, several papers explore advanced strategies for thermal regulation and energy reduction. Experimental analyses of solar control window films and shading systems demonstrate their capacity to significantly reduce solar heat gain while maintaining visual comfort, indicating their relevance for retrofit applications in high-radiation climates. In parallel, investigations into adaptive materials, such as bio-based phase change materials, propose a transition toward dynamic building skins capable of storing and releasing thermal energy, thereby reducing temperature fluctuations and energy demand. Renewable energy integration is further addressed through studies on building-integrated photovoltaics, which highlight the dual role of façade systems in both energy generation and environmental control . These contributions collectively indicate a shift toward performance-oriented envelopes that function as active environmental mediators rather than passive barriers.

At a broader systems level, the track also engages with lifecycle performance, material sustainability, and integrated design frameworks. Research on sustainable construction materials emphasizes the role of lifecycle assessment in reducing embodied energy and environmental impact, while advocating for regionally adapted material strategies. Similarly, studies on sustainable housing prototypes demonstrate how the integration of green materials, renewable energy systems, and smart technologies can achieve both environmental and economic efficiency without compromising structural performance. Additional contributions extend sustainability into water management and ecological systems, such as the implementation of artificial wetlands for greywater reuse in dense urban buildings. Finally, research on vernacular

architecture, including the performance of rawashin in historic Jeddah, suggests that traditional passive strategies remain relevant for contemporary design, particularly in enhancing thermal comfort and reducing energy demand. Collectively, the track positions smart and sustainable design as an integrative process that synthesizes environmental performance, technological innovation, and contextual knowledge into a coherent architectural framework.

Track 2: Urban Planning, Governance & Smart City Transformation

This track brings together a diverse body of research that repositions urban planning as a socio-technical and governance-driven process, where spatial design, digital infrastructures, and policy frameworks operate as interdependent systems. A central theme across the contributions is the transition from technology-led smart city narratives toward human-centered and context-responsive urbanism. For instance, research on urban media in Al Khobar demonstrates how digital infrastructures—such as interactive façades and real-time communication platforms—extend beyond information delivery to enable participatory engagement and cultural expression within public space. This shift from passive information systems to interactive urban interfaces suggests that smart city transformation can be interpreted as a reconfiguration of public space into a responsive socio-digital environment, where governance mechanisms increasingly incorporate citizen interaction and feedback loops.

Parallel to digital integration, several studies examine the role of governance frameworks and policy transfer in addressing environmental and urban resilience challenges. Comparative analyses of urban heat island mitigation strategies highlight the importance of adapting international policy models—such as those developed in Japan—into locally responsive planning tools suited to Saudi Arabia's climatic and urban condition. Similarly, research on cool roof technologies situates building-scale interventions within a broader urban governance agenda, demonstrating how regulatory frameworks and large-scale implementation strategies can significantly reduce urban heat stress and energy demand. These studies collectively indicate that effective smart city transformation is contingent not only on technological innovation but also on the institutional capacity to translate environmental strategies into actionable planning policies and performance-based evaluation systems.

At the urban design and public realm scale, multiple contributions emphasize the importance of human-centered planning in enhancing urban livability, inclusivity, and identity. Empirical research on urban edges in Al Khobar reveals that spatial qualities such as continuity, permeability, and public realm activation directly influence city imageability and wayfinding, suggesting that human-scale interventions remain critical even within technologically advanced urban contexts. Complementary studies on public space and walkability further demonstrate that environmental comfort, accessibility, and socio-cultural factors shape everyday urban experiences, particularly in hot-arid regions where climatic constraints limit pedestrian activity . In parallel, emerging frameworks such as climate-adaptive park recommendation systems and user-centered green space design tools indicate a shift toward data-informed and participatory planning approaches, where user preferences and environmental performance metrics are integrated into decision-making processes. This convergence of spatial design, environmental data, and user feedback suggests a redefinition of planning practice as an adaptive and evidence-based process.

The track also extends into broader governance and socio-economic dimensions of smart city development. Research on smart city applications for vulnerable groups highlights the necessity of inclusive planning frameworks that address disparities in access to digital and urban services, positioning equity as a fundamental component of smart governance. At the same time, studies on smart campus transformation and smart creative city ranking systems propose evaluative and benchmarking tools that integrate performance indicators across domains such as mobility, environment, digital infrastructure, and cultural economies. These frameworks indicate a growing emphasis on measurement, accountability, and strategic alignment within urban governance processes. Finally, contributions addressing adaptive reuse, retail transformation, and urban river regeneration illustrate how spatial interventions can operate as catalysts for socio-cultural continuity and economic resilience, reinforcing the role of planning as a mediator between heritage, innovation, and urban transformation.

Collectively, Track 2 reframes urban planning and smart city development as a multidimensional process that integrates governance, technology, environmental adaptation, and human experience. Rather than treating smart cities as purely technological constructs, the contributions suggest that their success depends on the alignment between policy frameworks, spatial design strategies, and the lived realities of urban users, thereby advancing a more holistic and context-sensitive model of urban transformation.

Track 3: AI, IoT & Digital Innovations in the Built Environment

This track consolidates emerging research that examines the integration of artificial intelligence (AI), Internet of Things (IoT), and advanced digital platforms as transformative mechanisms within the built environment. Across the contributions, digital innovation is not framed merely as a tool for efficiency, but rather as a systemic layer that reconfigures design processes, environmental performance, and user interaction. A central dimension is the increasing role of AI-driven analytics and predictive modelling in supporting sustainable and data-informed decision-making. For instance, a systematic synthesis of machine and deep learning applications demonstrates that AI is predominantly deployed in energy prediction, optimization, and environmental performance evaluation, while also extending into indoor environmental quality and cost forecasting. This distribution suggests that AI functions as both a diagnostic and generative mechanism within building systems, enabling designers and planners to reposition sustainability as a measurable and continuously optimized process.

Within the environmental and infrastructural domain, several studies highlight the capacity of AI and data-driven systems to address complex urban challenges through predictive and integrative frameworks. Research on air quality modelling illustrates how optimized machine learning algorithms—such as Grey Wolf Optimization integrated with support vector regression—can achieve high predictive accuracy ($R^2 \approx 0.94$), enabling real-time environmental monitoring and policy support. Similarly, AI-enabled platforms for road safety demonstrate the transformation of unstructured data streams into actionable urban intelligence, where computer vision and natural language processing convert dashcam footage into structured datasets for transportation planning. These approaches indicate a broader shift toward urban informatics, where heterogeneous data sources are synthesized into decision-support systems, thereby enhancing governance capacity and infrastructural resilience.

At the scale of design innovation, the integration of generative AI and immersive digital environments is redefining conceptual and participatory processes. Studies on AI-assisted architectural visualization reveal both the potential and limitations of image-generation platforms in producing culturally sensitive design outputs, particularly in contexts such as Islamic architectural heritage where accuracy and symbolic meaning are critical. In parallel, research on AI-enhanced urban furniture design demonstrates how combined sensory and generative AI workflows can translate cultural motifs and environmental constraints into sustainable design alternatives, subsequently evaluated through expert-based frameworks. These contributions suggest that AI operates not only as a computational engine but also as a mediating interface between cultural knowledge, environmental constraints, and design generation, thereby expanding the scope of early-stage design exploration.

Beyond generative design, the track emphasizes the emergence of integrated digital ecosystems that connect sensing, simulation, and user participation. The development of immersive urban digital twins illustrates this convergence, where IoT-based environmental sensing is combined with virtual reality interfaces to enable real-time co-design and evaluation of heat-resilient public spaces. This closed-loop framework, linking data acquisition, simulation, participatory interaction, and performance assessment, reframes planning as an iterative and evidence-based process. Similarly, smart home research highlights the integration of IoT-enabled healthcare systems within residential environments, where continuous monitoring and adaptive services support aging populations through spatially embedded technologies . These examples collectively indicate that digital innovation is increasingly embedded within everyday spatial experiences, blurring the boundary between built form and responsive technological systems.
The governance and socio-technical implications of these innovations are further examined through strategic and conceptual frameworks. Research on smart city transformation emphasizes the necessity of integrating Fourth Industrial Revolution technologies, such as AI, IoT, and data governance, within adaptive policy structures and public–private partnerships to enhance urban competitiveness and resilience. Complementary approaches, such as digital identity-based environmental stewardship systems, demonstrate how smart platforms can foster community engagement by linking individual actions to urban ecological performance. At the same time, critical perspectives on architectural education question the implications of generative AI on cognitive and creative processes, suggesting that the displacement of embodied design practices may alter the foundational mechanisms of architectural thinking.

Collectively, Track 3 positions AI, IoT, and digital innovations as multi-layered infrastructures that operate across design, environmental performance, governance, and human experience. The contributions indicate that the future of the built environment lies not in isolated technological applications, but in the synthesis of data-driven intelligence, participatory systems, and culturally responsive design processes, thereby advancing a more adaptive and integrative model of urban and architectural innovation.

Track 4: Climate, Environment & Resilient Urban Systems

This track, comprising 10 accepted papers, examines the environmental and climatic dimensions of the built environment through multi-scalar approaches that range from material innovation to urban systems and policy frameworks. The contributions collectively position climate responsiveness not as a singular technical objective but as an integrated process that connects building performance, spatial configuration, and governance mechanisms. A dominant theme is

the critical role of energy efficiency in mitigating environmental impact, particularly within rapidly urbanizing and climate-sensitive regions. Comparative analyses of global regulatory systems demonstrate that performance-based codes, energy certification mechanisms, and incentive-driven policies form the backbone of effective low-carbon transitions. These findings suggest that regulatory frameworks operate as mediating instruments between technological innovation and large-scale environmental outcomes, especially in contexts such as Saudi Arabia where the building sector accounts for a substantial proportion of national energy consumption.
At the building scale, several studies investigate the environmental performance of architectural elements and material systems as key determinants of energy demand and thermal comfort. Simulation-based research on fenestration strategies illustrates how design variables such as window-to-wall ratio and orientation significantly influence cooling loads, with high glazing ratios in hot-arid climates leading to substantial increases in energy consumption. Complementary research on adaptive façade systems extends this logic by exploring dynamic envelope technologies capable of responding to environmental fluctuations through material transformation and kinetic mechanisms. These studies indicate that building envelopes are increasingly conceptualized as active environmental interfaces rather than passive barriers, thereby enabling real-time modulation of thermal and daylight performance. In parallel, investigations into sustainable acoustic materials demonstrate how bio-based and recycled systems can simultaneously address environmental impact and functional performance, particularly when integrated with emerging energy-harvesting technologies. Together, these contributions reposition material and envelope design as critical levers for achieving both energy efficiency and environmental adaptability.

At the urban and neighborhood scale, the track highlights the importance of spatial configuration and morphological strategies in mediating climatic conditions and resilience outcomes. Research on temporary worker housing demonstrates that cluster morphology significantly affects outdoor thermal stress, with compact configurations reducing solar exposure and improving microclimatic conditions in hot-arid environments. This emphasis on geometry-driven climate performance is further reinforced by broader reviews of sustainable neighborhood design, which reveal a persistent imbalance in the literature toward physical planning aspects such as connectivity and density, while social inclusivity and resilience remain underexplored . These findings suggest that while spatial design remains a primary mechanism for climate adaptation, its integration with social and institutional dimensions is still evolving. At a more systemic level, the concept of regenerative urban design reframes cities as “living systems,” where ecological restoration, nature-based solutions, and adaptive processes collectively enhance resilience and long-term environmental performance. This perspective extends beyond mitigation, proposing a shift toward regenerative practices that actively restore ecological balance within urban environments.

The track also engages with institutional and infrastructural dimensions of environmental sustainability, particularly through the lens of large-scale systems such as university campuses and construction processes. Studies on green campus transformation indicate that while sustainability initiatives are increasingly adopted, they often remain fragmented without cohesive governance structures, performance metrics, and stakeholder integration. Similarly, research on circular construction workflows demonstrates the importance of early-stage decision-making in reducing embodied carbon, where integrated digital frameworks linking BIM, material passports, and immersive visualization can enhance the evaluation of low-carbon material alternatives. These contributions suggest that environmental performance is not solely a

design outcome but also a function of institutional coordination, data integration, and lifecycle-oriented planning processes.

Collectively, Track 4 positions climate and environmental resilience as a multi-dimensional framework that operates across scales, from material innovation and building systems to urban morphology and governance structures. The papers indicate that effective climate-responsive design emerges through the synthesis of performance-based technologies, spatial strategies, and institutional mechanisms, thereby advancing a more integrated and adaptive model of resilient urban systems.

Track 5: Sustainability, Economy & Cultural Identity in Design

This track, comprising 8 accepted papers, examines sustainability through the intertwined lenses of cultural identity, economic processes, and design practice. The contributions collectively suggest that sustainability cannot be reduced to environmental performance metrics alone, but must be understood as a socio-cultural and economic construct embedded within local contexts. A central theme emerging across the papers is the role of culture as an active design parameter rather than a passive heritage reference. Comparative analyses of vernacular architecture demonstrate how socio-cultural factors, such as religious practices, privacy norms, family structure, and social dynamics, directly shape spatial organization and architectural form, producing regionally distinct yet environmentally responsive housing typologies. This perspective reframes vernacular architecture not only as a historical artifact but as a knowledge system through which cultural values are translated into spatial and environmental performance.
Building on this, several contributions critically evaluate the relationship between contemporary design practices and cultural continuity under conditions of globalization. Research on context-responsive versus culturally detached architecture highlights the emergence of "placeless" environments resulting from the adoption of universal design languages that neglect local climate, social practices, and symbolic meaning. In contrast, studies grounded in regional case analyses suggest culturally embedded design strategies—such as courtyard typologies, spatial layering, and material specificity—enhance not only environmental responsiveness but also social vitality and long-term usability. Complementary investigations into architectural archives from the Arab world further demonstrate that historically grounded design approaches integrate climatic adaptation with cultural expression, positioning façade systems and spatial sequences as both environmental regulators and carriers of collective memory. These findings collectively indicate that cultural identity functions as a mediating mechanism that aligns environmental performance with social meaning, thereby extending the scope of sustainability beyond technical optimization.

At the urban and institutional scale, the track explores how cultural identity interacts with governance frameworks, economic development, and spatial transformation processes. Studies on urban regeneration in Bahrain reveal a persistent gap between heritage-based design principles and contemporary regulatory practices, where development agendas often prioritize infrastructural growth over cultural continuity. Similarly, research on heritage conservation in Saudi Arabia emphasizes the importance of integrating advanced digital documentation methods with culturally grounded interpretation, cautioning against superficial representations that reduce heritage to aesthetic replication rather than socio-historical understanding. These contributions suggest that sustainable design requires alignment between cultural values,

regulatory systems, and development strategies, positioning governance as a critical interface in preserving identity within rapidly transforming urban environments.

The socio-economic dimension of sustainability is further examined through frameworks that link cultural identity with long-term economic resilience and adaptability. Studies on sustainable architecture indicate that culturally embedded design strategies—such as the use of local materials, community-oriented spatial organization, and vernacular construction techniques—can enhance economic durability by supporting local industries and extending building lifecycles. In parallel, research on campus design from a user-centered perspective demonstrates that integrating cultural narratives into built environments fosters a sense of belonging and engagement, which in turn supports the social sustainability of institutional spaces. These findings highlight the reciprocal relationship between cultural identity and economic sustainability, where culturally responsive environments contribute to both social cohesion and long-term viability.

Finally, the track includes critical theoretical perspectives that question dominant sustainability paradigms, particularly those grounded in technocratic and anthropocentric frameworks. Such contributions argue that prevailing models often operate as extensions of modernity's instrumental logic, focusing on optimization and efficiency rather than reconfiguring the underlying relationships between humans, nature, and technology. By proposing alternative ethical and philosophical frameworks—such as post-anthropocentric and stewardship-based approaches—these studies expand the conceptual boundaries of sustainability, suggesting the need for a fundamental rethinking of design values and priorities.

Collectively, Track 5 positions sustainability as a multidimensional construct that emerges through the interaction of cultural identity, economic systems, and design practices. The papers indicate that culturally grounded design not only enhances environmental performance but also reinforces social cohesion and economic resilience, thereby advancing a more holistic and context-sensitive understanding of sustainable architecture and urbanism.

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Microclimatic Risk Assessment of Built-In Closets in Saudi Housing: A Hygrothermal Evaluation for Mold Prevention

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Keywords: Condensation Control, Built-In Closets, Hygrothermal Performance, Relative Humidity, Residential Architecture in Saudi Arabia

Abstract. This study investigates the hygrothermal conditions of built-in closets in Saudi residential apartments, focusing on condensation and mold risk in hot-humid environments. Field measurements were conducted in Al Khobar during winter to evaluate temperature, relative humidity, and absolute humidity under varying door configurations and moisture-control strategies. Results showed that while surface temperatures remained above dew point levels, relative humidity frequently exceeded 80%, particularly in closets with ventilated gallery doors, posing significant mold risks. In contrast, sealed closets equipped with desiccants or dehumidifiers substantially reduced absolute humidity, demonstrating improved environmental stability. These findings highlight critical gaps in Saudi building codes, which currently lack provisions for moisture control in semi-enclosed storage areas. As the Kingdom progresses toward airtight and energy-efficient housing under Vision 2030, the study emphasizes the need for integrated design strategies and regulatory updates to manage microclimatic conditions and ensure occupant health and material durability in high-humidity zones.

1. Introduction

In recent years, condensation-related defects have emerged as a critical concern in Saudi Arabia's residential construction sector, reportedly accounting for approximately 16% of building defect dispute cases, particularly within rapidly urbanizing regions such as Riyadh, Jeddah, and Dammam [1]. Among these, many are associated with concealed mold growth in built-in closets and wardrobe spaces, often caused by condensation on the rear surfaces of walls and ceilings adjacent to the building envelope [2]. These areas typically suffer from insufficient air circulation and insulation, creating thermal bridges that create localized dew point conditions [3]. This phenomenon contributes to material degradation, such as swelling, warping, and staining of wooden interiors [4]. It poses health risks due to the proliferation of microbial contaminants, including Aspergillus and Penicillium species, which have been documented in similar climates [5].

Unlike temperate countries where winter conditions are the primary driver of indoor condensation, the unique environmental profile of Saudi Arabia, with extended periods of high temperatures and elevated absolute humidity, presents distinct challenges [6]. During the summer months, especially from May to September, outdoor relative humidity in coastal cities such as Dammam can exceed 80%, increasing the potential for moisture infiltration through vapor diffusion, even in air-conditioned interiors [7]. Furthermore, the increasing adoption of tightly

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sealed building envelopes to enhance energy efficiency under Vision 2030 initiatives has unintentionally exacerbated internal moisture accumulation, particularly in enclosed and unventilated compartments [8].

Despite the rising incidence of such defects, empirical research focusing specifically on the microclimatic conditions within built-in storage areas remains scarce in Saudi Arabia and globally [9]. Prior studies have concentrated on moisture issues in kitchens and bathrooms, neglecting semi-enclosed zones such as wardrobes, which often exhibit markedly different thermal and humid conditions. Recognizing this gap, the present study aims to monitor built-in closet environments in newly developed apartment complexes across the Eastern Province, utilizing sensors to capture real-time data on internal temperature, absolute humidity, and relative humidity [10]. The research also evaluates the role of architectural detailing, insulation methods, and HVAC system performance in mitigating or exacerbating condensation.

In parallel, the study reviews existing domestic and international regulatory frameworks—including the Saudi Building Code SBC 501, ASHRAE 160, and ISO 13788—to assess current moisture control and thermal performance standards [11]. The goal is to establish a foundational data set to inform future regulatory reforms and practical design interventions. Ultimately, this research proposes evidence-based solutions to reduce condensation risks in built-in spaces, contributing to healthier indoor environments, reduced maintenance costs, and enhanced long-term resilience of residential buildings in arid and semi-humid climates.

2. Literature Review

2.1 Condensation and Mold Risk in Residential Buildings

Condensation and mold formation are among the most persistent and underestimated challenges affecting the performance and healthiness of residential environments, particularly in hot-humid or mixed-arid climates like those found in many regions of Saudi Arabia [12]. Condensation occurs when humid air comes into contact with cooler surfaces, causing water vapor to transition into liquid. In buildings, this typically arises on surfaces such as external walls, windows, ceilings, or within enclosed zones such as built-in wardrobes, particularly when insulation is inadequate or ventilation is absent [13]. Prolonged surface moisture provides an ideal environment for microbial growth, most notably fungi such as *Aspergillus*, *Penicillium*, and *Cladosporium*, which are commonly associated with respiratory illnesses and allergic responses (Figure 1) [14].



Figure 1. Aspergillus, Penicillium, and Cladosporium Fungi in Saudi Villas

In Saudi Arabia, where air conditioning is ubiquitous and outdoor relative humidity can exceed 80% in coastal cities such as Dammam and Jeddah, the risk of condensation within building interiors is exacerbated by significant temperature differences between the outdoor environment and mechanically cooled indoor air [15]. This thermal stratification forms condensation in concealed or passive areas like built-in closets when paired with poorly ventilated or thermally bridged zones. A recent survey of construction defect litigation in the Kingdom found that moisture-related damage accounted for over 16% of claims in multi-unit residential buildings, much of which stemmed from hidden condensation and subsequent mold infestation [16].

Multiple international studies have emphasized that surface relative humidity should remain below 80% to prevent fungal colonization, with ISO 13788 (2012) further recommending that corrosion-prone materials be kept below 60% RH [17]. However, maintaining these thresholds in humid climates becomes difficult without carefully designed ventilation, continuity, and moisture-resistant construction detailing. Moreover, building materials commonly used in closets, such as medium-density fiberboard (MDF), plywood, or gypsum, are highly porous and susceptible to fungal attack under sustained moisture conditions [18]. However, most residential design and construction practices in Saudi Arabia do not incorporate microclimatic analysis in passive zones, leaving a critical research and regulatory gap.

Previous literature focused mainly on mold occurrence in kitchens and bathrooms, where water usage is frequent and ventilation is often prescribed [19]. However, the semi-enclosed microenvironments of built-in wardrobes or storage compartments present a more complex challenge. These spaces are typically located against external walls or under rooflines, where thermal gradients are most severe and airflow is minimal [20]. Even moderate indoor humidity can result in localized condensation and mold development in such environments, particularly in buildings emphasizing airtightness for energy conservation without a corresponding ventilation strategy [21]. Given the health implications and long-term material degradation caused by undetected mold, there is a pressing need for building science research that addresses condensation risk beyond the traditionally monitored spaces. Future efforts should involve sensor-based environmental monitoring, moisture risk mapping, and detailed modeling of airflow and temperature profiles within concealed architectural zones. This will help inform regulatory standards and practical design solutions suited to the Kingdom's evolving residential construction practices and climatic conditions.

2.2. Climatic, Environmental, and Regulatory Context in Saudi Arabia

In Saudi Arabia, issues related to condensation and mold in residential environments, particularly enclosed spaces such as built-in wardrobes, have received increasing attention due to their impact on occupant health, material degradation, and building performance [22]. Although the Saudi Building Code (SBC 501) addresses moisture protection and thermal insulation as part of its general design criteria, it does not currently include specific performance standards to prevent surface condensation or regulate microclimatic conditions in semi-enclosed interior spaces [23]. This regulatory gap is notable given the climatic realities of the Kingdom, where regions such as Dammam, Jeddah, and Al Khobar experience extended periods of high humidity, often exceeding 80% during summer months, combined with high daytime temperatures and intensive use of mechanical cooling systems [24]. These conditions promote significant temperature gradients and localized condensation, particularly in areas with limited air circulation.

While extensive research has been conducted in Saudi Arabia on indoor air quality, energy-efficient building envelopes, and HVAC system performance, studies addressing condensation and mold formation inside non-mechanically ventilated storage areas remain scarce. This is even though built-in closets are highly susceptible to trapped moisture due to their positioning against external walls, insufficient insulation continuity, and stagnant air volumes [25]. Observations in new residential developments suggest thermal bridging and high absolute humidity contribute to surface wetting and mold growth, especially where closets lack sufficient air exchange with the main room environment [26].

As such, there is a pressing need to establish empirical data and performance benchmarks tailored to the Saudi climate and construction typologies [27]. This study aims to address this gap by collecting in situ data on temperature, relative humidity, and absolute humidity levels inside built-in storage areas within recently constructed apartment complexes. The findings will be critically examined against the best international practices to support the development of

condensation-prevention strategies that align with the Kingdom's regulatory framework and environmental conditions.

3. Methodology

This study investigated the microclimatic conditions inside built-in closets in Saudi apartment buildings during the summer, focusing on temperature, relative humidity, and absolute humidity [0]. The selected test unit was a ground-floor apartment in Al Khobar, built in 2000. No air conditioning or dehumidification systems were used during the measurement period to reflect typical occupant behavior in naturally ventilated spaces.

The closet, equipped initially with a louvered gallery door, was modified by sealing it with polyethylene vinyl to simulate a conventional solid panel door—commonly found in Saudi residential interiors [0]. The experiment aimed to compare internal environmental conditions under two configurations: (1) with the gallery door open and (2) with it sealed. Additionally, the presence of commercial silica gel desiccants was introduced as a third variable to evaluate passive moisture control.

Measurements were conducted over 72 hours in July 2025. Temperature and relative humidity sensors were installed inside the closet and recorded data at 10-minute intervals, beginning 24 hours after sensor placement to ensure stabilization. To detect thermal gradients, surface temperatures were logged at five points within the closet. The data was analyzed to assess conditions against ISO 13788 mold risk thresholds, providing foundational insight into condensation behavior in semi-enclosed residential spaces under hot-humid Saudi conditions.

4. Results and Analysis

The field measurements conducted in a residential apartment in Al Khobar during peak summer conditions provided insight into built-in closets' thermal and hygrothermal behavior under varying ventilation and moisture-control strategies (Figure 2). The internal surface temperature of the built-in closet was found to range between 24.8°C and 26.5°C, while the calculated dew point temperature varied from 16.1°C to 24.3°C. The fact that the surface temperature consistently remained above the dew point across all test conditions indicates that no active surface condensation occurred during the measurement period. This outcome confirms that condensation risk can be effectively managed under certain microclimatic conditions despite the high ambient humidity typical of Saudi Arabia's Eastern Province.

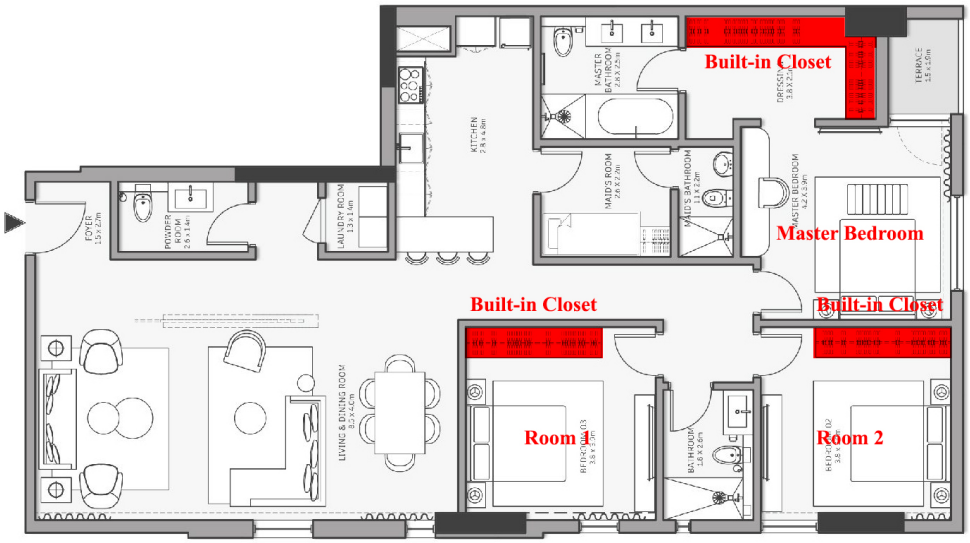


Figure 2. 3-bedroom apartment and locations of built-in closets



Figure 3. Surveyed Built-in Closets

When the built-in closet was equipped with a louvered gallery door, simulating a well-ventilated configuration, the absolute humidity inside the closet exhibited a strong correlation with the room air and ambient external humidity (Figure 3). This condition allowed for a relatively free moisture exchange between the closet and its surroundings. In Case 3—where bedding was stored inside the closet—absolute humidity was reduced by approximately 0.1 to 1.1 g/kg. In Case 4, where bedding and a portable dehumidifier were used, the reduction ranged from 0.2 to 0.5 g/kg. These relatively modest reductions are explained by the fact that the ventilated design permitted continuous inflow of moisture-laden air from the surrounding environment, thereby diminishing the effectiveness of localized humidity control interventions (Table 1).

Table 1. Experiment Conditions

Category	Gallery Door Sealed	Gallery Door Used
Dehumidifier not installed	Case 1	Case 3
Dehumidifier installed	Case 2	Case 4

In contrast, a significant difference in hygrothermal performance was observed when the gallery door was tightly sealed to replicate the conditions of a typical solid-panel closet door, commonly found in Saudi residential architecture. In Case 1 (bedding only), the reduction in absolute humidity ranged from 0.4 to 0.8 g/kg, while in Case 2 (bedding and dehumidifier), it increased substantially to a range of 1.0 to 1.9 g/kg. These results demonstrate that under reduced ventilation scenarios, using a dehumidifier is crucial in lowering humidity levels and mitigating mold risk. This is particularly important in built-in closets where airflow is minimal and thermal bridges may promote localized dew point proximity.

International standards, including *BS 5250:2021* and *ISO 13788:2012*, define critical thresholds for microbial growth. Both recommend keeping surface relative humidity below 80% to prevent mold proliferation and maintaining RH below 60% to prevent material corrosion. The present study monitored RH levels relative to these thresholds. In Case 3 and Case 4 (gallery door configuration), relative humidity levels frequently exceeded 80%, especially during early morning and late evening hours when ambient humidity peaks. These exceedances are indicated by the red dotted threshold line in Figure 4 and Figure 5.

The results underscore the limitations of passive ventilation in climates with persistent high outdoor humidity, such as the Gulf region. Naturally ventilated closets may remain above critical

RH thresholds unless air exchange is controlled, even when equipped with dehumidifiers. Conversely, enclosed closets—though at greater risk of stagnant air—benefit significantly from mechanical or passive moisture-control interventions such as desiccant packs or compact dehumidifiers. The data suggest that the design of built-in wardrobes in Saudi apartments must incorporate a combination of architectural foresight (e.g., insulation, vapor barriers) and user practices (e.g., desiccant use, intermittent ventilation) to manage indoor moisture effectively.

These findings are particularly relevant for residential developers, architects, and policymakers focused on sustainable housing performance under Saudi Arabia's Vision 2030 framework. The interaction between design choices, indoor environmental quality, and building durability highlights the need for updated design guidelines that consider microclimatic variations within spaces traditionally overlooked in HVAC and insulation strategies.

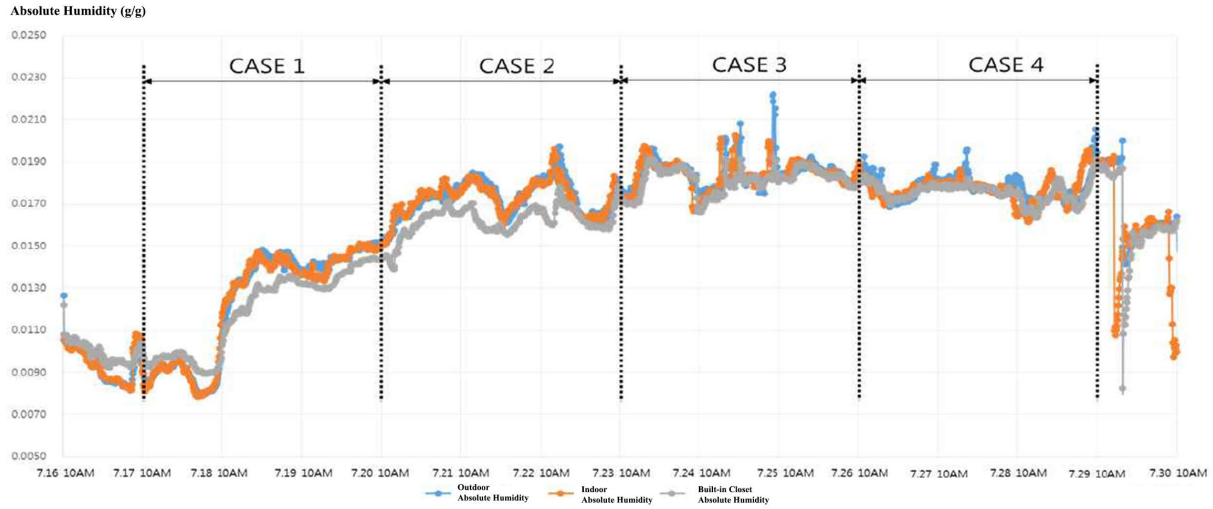


Figure 4. Measurement Result: Absolute Humidity

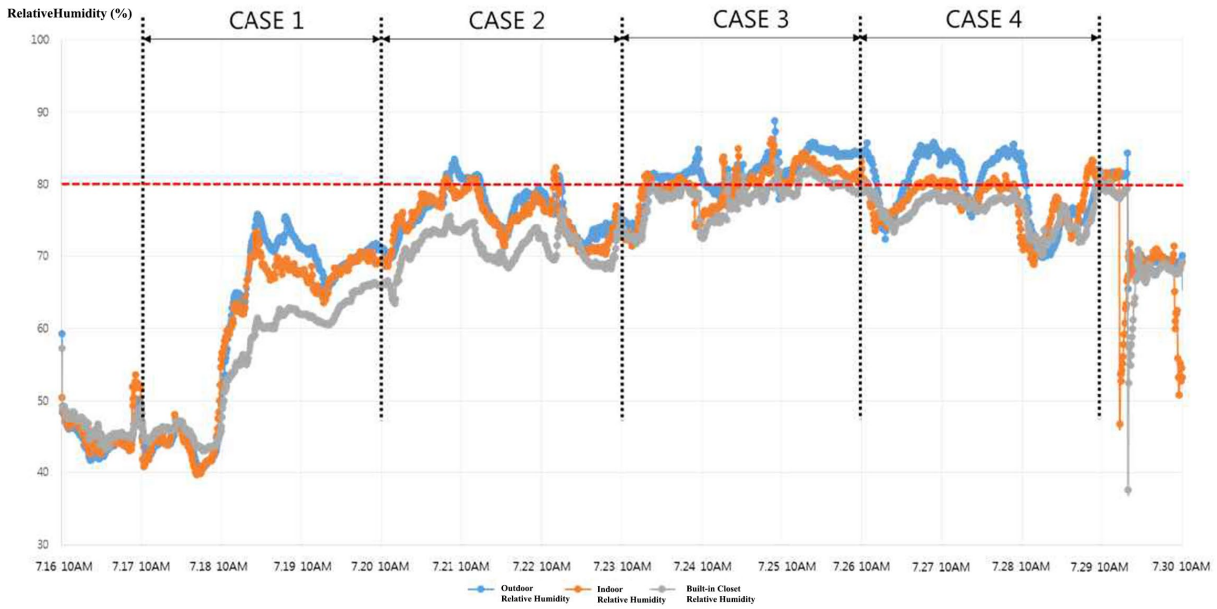


Figure 5. Measurement Result: Relative Humidity

5. Discussion

The findings of this study provide critical insights into the hygrothermal behavior of built-in closets in Saudi residential apartments and underscore the complex relationship between ventilation strategies, moisture control, and microclimatic stability in enclosed spaces. Although no direct surface condensation was observed, given that internal temperatures remained above dew point values across all cases, relative humidity levels frequently exceeded the critical 80% threshold, particularly in closets fitted with ventilated gallery doors. This condition is well-documented in BS 5250 and ISO 13788 as conducive to fungal proliferation, highlighting an often-overlooked vulnerability in local residential design. While gallery doors promoted airflow, they also permitted unregulated vapor ingress, limiting the effectiveness of desiccants and dehumidifiers. Conversely, closets with sealed doors demonstrated improved moisture control when mechanical or passive drying interventions were applied, achieving absolute humidity reductions of up to 1.9 g/kg. These results reveal the limitations of passive ventilation strategies in Gulf climates characterized by prolonged high humidity, emphasizing the importance of targeted moisture management in semi-enclosed interior zones. The study exposes a regulatory gap in the Saudi Building Code. Despite their susceptibility to thermal bridging and moisture entrapment, it does not currently address microclimatic performance criteria for built-in storage spaces. As residential architecture in the Kingdom continues to evolve toward airtight, energy-efficient construction in line with Vision 2030, these findings call for updated guidelines that integrate insulation continuity, vapor barrier application, and controlled ventilation. This research contributes foundational data to inform such reforms and supports the development of evidence-based design strategies that enhance indoor environmental quality, prevent mold risks, and extend material durability in Saudi Arabia’s hot-humid housing environments.

6. Conclusion

This study has demonstrated that built-in closets in Saudi Arabia's residential apartments, particularly those in coastal, high-humidity regions, are vulnerable to elevated relative humidity levels that can foster mold growth, even without visible condensation. Through in situ monitoring of closets under different door configurations and moisture-control strategies, it was confirmed that surface temperatures remained above the dew point during summer, thus preventing direct condensation. However, the relative humidity in gallery-door closets frequently exceeded the critical 80% threshold, reinforcing the risk of microbial contamination in ventilated but uncontrolled environments. Sealed closet doors, combined with desiccants or dehumidifiers, showed significant potential in reducing absolute humidity levels by up to 1.9 g/kg, highlighting the importance of managing enclosed microclimates through targeted interventions. These findings point to a critical regulatory and design gap in Saudi residential architecture, as current codes like SBC 501 do not specifically address moisture control in semi-enclosed zones. As the Kingdom advances toward energy-efficient and airtight building envelopes under Vision 2030, it is imperative to revise building guidelines to incorporate condensation prevention strategies for enclosed interior spaces. This includes improved insulation continuity, vapor barriers, mechanical ventilation provisions, and user education on humidity management. By addressing these design and policy gaps, Saudi Arabia can better safeguard material durability, reduce maintenance costs, and protect occupant health in future residential developments.

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Evaluating Ventilation Protocols for Healthy Housing: A Survey of Flush-Out Implementation in Saudi Arabia

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Keywords: Indoor Air Quality (IAQ), Flush-Out Protocol, Residential Ventilation, Sick Building Syndrome (SBS), Saudi Housing Standards

Abstract. This study examines post-construction flush-out practices and indoor air quality (IAQ) management in newly built residential apartment complexes across Saudi Arabia. A structured survey was conducted with 13 major construction firms that delivered over 1,000 housing units between 2023 and 2025. The results revealed significant inconsistencies in flush-out duration (ranging from 48 to 120 hours), lack of standardized Testing, Adjusting, and Balancing (TAB) procedures, and minimal use of IAQ monitoring tools such as VOC or PM2.5 sensors. Built-in closets, especially in coastal cities, exhibited elevated relative humidity, posing risks of mold growth despite the absence of visible condensation. The absence of national IAQ regulations has led to procedural gaps, despite increasing awareness within the industry. The findings underscore the urgent need for Saudi-specific flush-out standards and verification protocols to improve occupant health and align with Vision 2030's goals for sustainable and livable urban environments.

1. Introduction

Volatile organic compounds (VOCs), commonly emitted from interior building materials, paints, sealants, composite wood products, and household appliances, are increasingly recognized as significant contributors to indoor air pollution in newly constructed residential units across Saudi Arabia [1]. These emissions are linked to a range of health issues, collectively termed "Sick Building Syndrome (SBS)," which include symptoms such as headaches, dizziness, nausea, eye irritation, and exacerbation of respiratory diseases like asthma and atopic dermatitis [2]. In Saudi Arabia's arid climate, where buildings are typically designed to be airtight to ensure thermal efficiency and reduce dust infiltration, the lack of natural ventilation often leads to accumulating indoor pollutants, further aggravating this issue [3].

Despite rapid modernization and expansive residential development under Vision 2030, especially in urban centers such as Riyadh, Jeddah, and Dammam, there remains a notable regulatory gap in mandatory indoor air quality (IAQ) standards targeting the emission of VOCs [4]. Unlike in regions with established environmental building codes, Saudi Arabia has yet to enforce a national framework that compels construction companies to implement systematic flush-out procedures—ventilation protocols designed to expel accumulated airborne contaminants before occupancy [5]. In practice, developers often prioritize mechanical and aesthetic completion

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over post-construction air quality measures, resulting in apartments being handed over to residents while still containing elevated levels of harmful substances [6].

This study explores the current status of IAQ management practices among residential developers in the Kingdom, focusing on newly built apartment complexes completed after 2020. Through targeted surveys with construction project managers, site engineers, and facilities maintenance teams, alongside indoor environmental quality assessments in selected units, the research investigates whether any form of flush-out or post-construction ventilation has been voluntarily implemented, and if so, to what extent it aligns with global best practices [7,8]. Preliminary findings indicate that while some high-end developments incorporate HVAC systems with advanced filtration, flush-out procedures remain inconsistent and largely unregulated across the broader housing market [9].

The absence of enforceable standards has implications for occupant health and the long-term sustainability of Saudi Arabia's residential construction sector [10]. As the government intensifies efforts to enhance livability and environmental performance under the Quality of Life Program, formulating national IAQ guidelines—including flush-out duration, ventilation rates, and VOC concentration thresholds—is becoming increasingly critical [11]. This paper argues for integrating scientifically grounded IAQ measures into building handover procedures and municipal approval workflows [12]. Establishing such criteria would provide tangible health protections for future occupants while fostering greater accountability and innovation within the construction industry [13].

Ultimately, a robust, Saudi-specific IAQ policy framework—anchored in empirical evidence and informed by the experiences of countries with mature building health standards—can play a transformative role in improving residential indoor environments and supporting the broader goals of sustainable urban development in the Kingdom.

2. Literature Review

2.1 Sick Building Syndrome (SBS)

SBS refers to a set of symptoms experienced by occupants of a building that are linked to time spent indoors, but where no specific illness or cause can be identified [14]. Common manifestations include headaches, fatigue, respiratory irritation, dry skin, and difficulty concentrating, which tend to improve or disappear shortly after leaving the building [15]. SBS is primarily associated with poor IEQ, including elevated concentrations of VOCs, inadequate ventilation, poor thermal regulation, biological contaminants, and insufficient natural lighting [16]. In Saudi Arabia, SBS presents unique challenges due to climate-adaptive architectural practices that often prioritize energy efficiency over ventilation [17]. Given the region's harsh desert climate, residential buildings are typically sealed and heavily reliant on mechanical ventilation or air conditioning systems. This design paradigm, while effectively reducing thermal loads, can significantly limit natural air exchange, thereby intensifying the concentration of indoor pollutants. Moreover, the increasing use of synthetic construction materials and prefabricated furniture in rapidly built residential developments under Vision 2030 adds to the risk of VOC accumulation and subsequent SBS manifestations (Table 1).

Table 1. Sick Building Syndrome in Residential Buildings in Dubai (Source: Chuloh Jung)

Question	Often	Sometimes	Never	Mean	Standard Deviation
Fatigue	45.98%	42.53%	11.49%	1.66	0.68
Severe headache	19.54%	24.14%	56.32%	2.37	0.79
Headache	27.38%	53.57%	19.05%	1.92	0.68
Nausea/dizziness	7.23%	33.73%	59.04%	2.52	0.63
Difficulty concentrating	27.59%	48.28%	24.14%	1.97	0.72
Itching, burning, irritation of the eyes	15.29%	32.94%	51.76%	2.36	0.74
Irritated, stuffy or runny nose	14.12%	34.12%	51.76%	2.38	0.72
Dry throat	11.90%	44.05%	44.05%	2.32	0.68
Cough	7.14%	48.81%	44.05%	2.37	0.62
Dry or flushed facial skin	11.49%	29.89%	58.62%	2.47	0.70
Scaling/itching scalps/ears	6.10%	17.07%	76.83%	2.71	0.58
Dry hands/itching read skins	9.52%	14.29%	76.19%	2.67	0.65
Others	5.71%	8.57%	85.71%	2.80	0.53

Recent studies conducted in the Gulf region have revealed that indoor environments in newly constructed housing units frequently exceed recommended thresholds for total VOC concentrations [18]. For instance, ElSharkawy (2024) measured average total VOC levels of 320–480 μg/m³ in air-conditioned residences in Saudi Arabia, well above the 200 μg/m³ comfort guideline recommended by international standards such as those from the European Union and the US EPA [19]. Although direct data for Saudi Arabia remains limited, similar building typologies, material sourcing, and climatic conditions suggest parallel risk levels, particularly in high-density urban developments such as Riyadh's Al Malaz and Jeddah's Al-Safa districts [20].

Significantly, the lack of enforceable national IAQ standards in Saudi Arabia has delayed both recognition and mitigation of SBS. No mandatory flush-out or indoor air testing procedures are currently integrated into municipal building handover protocols. This regulatory vacuum affects residents' health and productivity and undermines the long-term sustainability and livability objectives embedded in Saudi Arabia's Quality of Life Program and National Urban Strategy.

Therefore, recognizing SBS as an emerging health and design issue is critical for developing healthier residential environments in Saudi Arabia. Incorporating SBS mitigation measures—such as enhanced mechanical ventilation systems, low-emission building materials, flush-out protocols, and mandatory IAQ monitoring—into building regulations could significantly reduce health risks and align residential construction with global best practices in indoor environmental quality.

2.2 IAQ Regulations in Saudi Arabia

IAQ has emerged as a critical public health concern in Saudi Arabia, particularly due to the country's arid climate, rapid urbanization, and the prevalent use of airtight, mechanically ventilated buildings [21]. Despite the growing awareness of IAQ's significance, the Kingdom lacks comprehensive, enforceable regulations specifically addressing IAQ in residential settings [22]. The primary legislative framework governing air quality in Saudi Arabia is the Executive Regulations for Air Quality, issued by the Ministry of Environment, Water, and Agriculture (MEWA) [23]. These regulations focus predominantly on ambient (outdoor) air quality, setting standards for pollutants such as particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ozone (O_3) [24]. However, they do not extend to indoor environments, leaving a regulatory gap concerning IAQ in homes and other indoor spaces.

Empirical studies have highlighted the implications of this regulatory void. For instance, research conducted in the Eastern Province revealed that indoor concentrations of total volatile organic compounds (TVOCs) and sulfur dioxide in residential homes were comparable to outdoor levels, indicating significant infiltration and accumulation of pollutants indoors [25]. Another study in Abha reported that PM concentrations in residential buildings exceeded international health guidelines, posing potential health risks to occupants [26]. In the absence of national IAQ

standards, some organizations and service providers in Saudi Arabia have adopted international guidelines, such as those from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the International Organization for Standardization (ISO), to inform their practices. For example, companies offering IAQ assessment services often reference ASHRAE Standard 62.1 and ISO 16000 series standards to evaluate and improve indoor environments.

Initiatives aimed at raising awareness and promoting best practices have been launched to recognize the importance of IAQ [27]. Educational campaigns and professional services emphasize the role of regular maintenance of HVAC systems, the use of low-emission building materials, and the implementation of effective ventilation strategies to enhance IAQ in residential and commercial buildings. National IAQ standards are urgently needed to align with Saudi Vision 2030's objectives of quality of life and sustainable development. Establishing comprehensive regulations would provide clear guidelines for construction practices, material selection, and building maintenance, ultimately safeguarding public health and enhancing indoor environmental quality across the Kingdom.

3. Methodology

This study employed a structured survey to investigate the implementation of IAQ management practices—particularly post-construction flush-out procedures—by major residential construction firms in Saudi Arabia. The focus was on companies that completed over 1,000 apartment units between January 2023 and March 2025 in key urban areas such as Riyadh, Jeddah, and Dammam. This period reflects increased attention to occupant health and environmental performance under the Kingdom's Vision 2030 initiatives. An initial pool of 22 construction and development firms was identified using data from the Ministry of Municipal and Rural Affairs and Housing (MoMRAH) and real estate publications. Sixteen companies met the inclusion criteria, and 13 responded to the survey, yielding an 81.25% response rate.

The survey consisted of 46 questions across three categories: (1) awareness and internal policy on IAQ, (2) application of flush-out and low-emission material practices, and (3) implementation challenges. This paper focuses on 14 key questions that provide direct insight into on-site execution of IAQ protocols in newly built apartments. All responses were anonymized and analyzed using descriptive statistics to identify trends and gaps. This approach provides a clear understanding of current industry practices and informs future regulatory recommendations for healthier residential environments in Saudi Arabia (Table 2).

Table 2. Survey Contents

Number of Key Questions	Survey Categories
2	Survey respondent information
10	Current status of operation related to housing construction standards
5	Compliance with the application standards for housing construction
5	Construction company's policy on flushing out
22	Current status of flushing out in newly constructed apartment complexes
5	Improvement requirements

4. Results and Analysis of Flush-Out Implementation in Saudi Residential Developments

This section presents the survey findings regarding the implementation of flush-out procedures by major construction firms engaged in the development of large-scale residential complexes across Saudi Arabia. The analysis draws attention to the lack of standardization in IAQ practices, particularly in relation to mechanical ventilation commissioning, system operation protocols, and post-construction environmental preparation prior to occupancy. Figure 1 illustrates construction companies' operational policies related to flush-out implementation. The survey explored several technical aspects of the process, including: (1) the frequency and method of opening fixed interior

furnishings such as closets and cabinetry to facilitate pollutant discharge, (2) the timing of Testing, Adjusting, and Balancing (TAB) procedures for mechanical ventilation systems, (3) the sequencing of flush-out activities across residential units, and (4) the procedures for handling and replacing ventilation filters post-implementation.

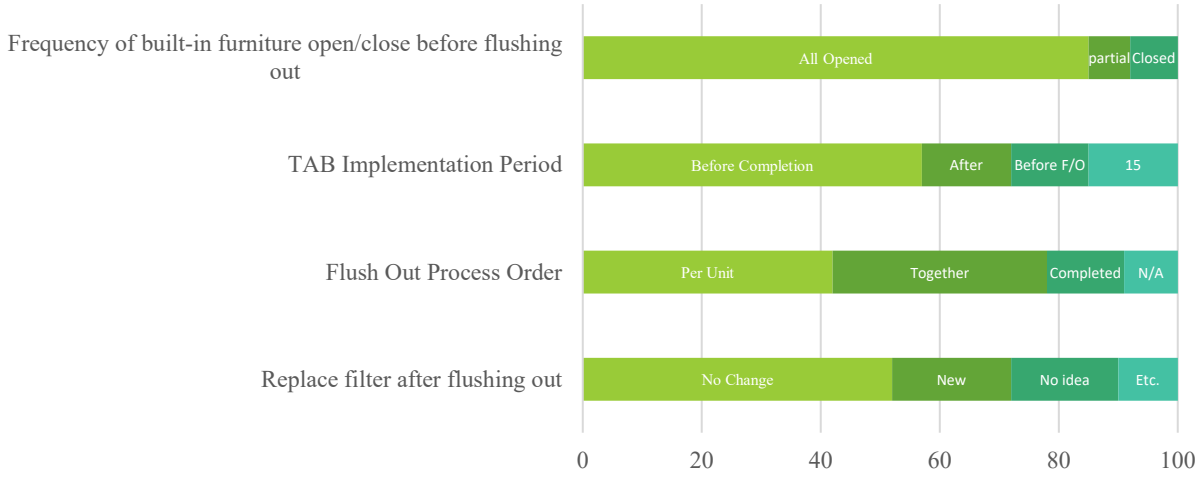


Figure 1. Construction Company's Policy on Flushing Out

Results indicated that the TAB timing remains vague or unstructured in most firms' workflows, leading to uncertainty about whether the calculated air volume for proper flushing—necessary to remove accumulated VOCs and airborne particles—was adequately achieved before residents moved in. In particular, many developers rely on default equipment commissioning schedules without correlating them with the actual implementation of the flush-out process. This gap raises concerns about compliance with global IAQ benchmarks, such as those outlined in ASHRAE 62.2, and suggests an urgent need for localized procedural guidance tailored to Saudi construction timelines, climate, and HVAC system specifications.

Figure 2 presents findings related to the flush-out implementation practices at the building site level, focusing on apartment complexes completed between 2023 and early 2025. Survey items addressed critical technical variables: (1) the type of ventilation system employed (e.g., centralized, decentralized, mixed-mode), (2) the methodology used to determine the required outdoor air supply—particularly efforts to meet or approximate the widely recommended minimum of 400 m^3 of fresh air per square meter of floor area, (3) the actual duration of flush-out operations per apartment unit, (4) the use of auxiliary strategies such as natural ventilation openings or temporary HVAC operation for indoor temperature regulation, (5) humidity control methods to prevent mold formation during extended flush-out periods, (6) whether indoor environmental monitoring (e.g., VOC levels, PM2.5, CO_2) was conducted during the procedure, and (7) the configuration and duration of mechanical fan operation during the flushing period.



Figure 2. Current Status of Flushing Out in Newly Constructed Apartment Complexes

Survey responses revealed considerable variation across companies in how the flush-out procedure was executed. While mechanical ventilation systems were universally employed, there was no consensus on the fan runtime calculation, with periods ranging from 48 hours to over 120 hours depending on project timelines, perceived client expectations, and weather conditions. Some companies implemented additional cooling measures to maintain internal comfort during flushing, while others relied solely on passive ventilation without monitoring indoor air pollutant reduction levels. Only a few reported using real-time IAQ sensors to validate the effectiveness of the procedure, highlighting a widespread reliance on procedural assumptions rather than empirical verification. Given the Saudi climate—where outdoor temperatures can exceed 45°C and relative humidity can vary sharply across regions—the operational requirements for effective flush-out differ markedly from temperate contexts. This makes it imperative to develop region-specific guidelines that address the technical, environmental, and cultural dimensions of IAQ practices in the Kingdom.

Figure 3 summarizes the industry's collective perspective on the necessity for improved flush-out protocols and regulatory reform. The survey asked firms whether they believed formalized flush-out guidelines were necessary, what form such guidelines should take (e.g., national standard, design manual, checklist, enforcement requirement), and what additional improvements would support implementation. Findings indicate strong industry demand for clear, enforceable flush-out policies integrated into the building approval and occupancy process. Respondents

overwhelmingly supported the introduction of standardized documents detailing mechanical ventilation testing requirements, indoor air volume targets, humidity and temperature controls, and pollutant threshold levels. Several firms also recommended the inclusion of a certification process, similar to LEED or Estidama, that would reward projects demonstrating excellence in indoor air preparation and occupant health protection.

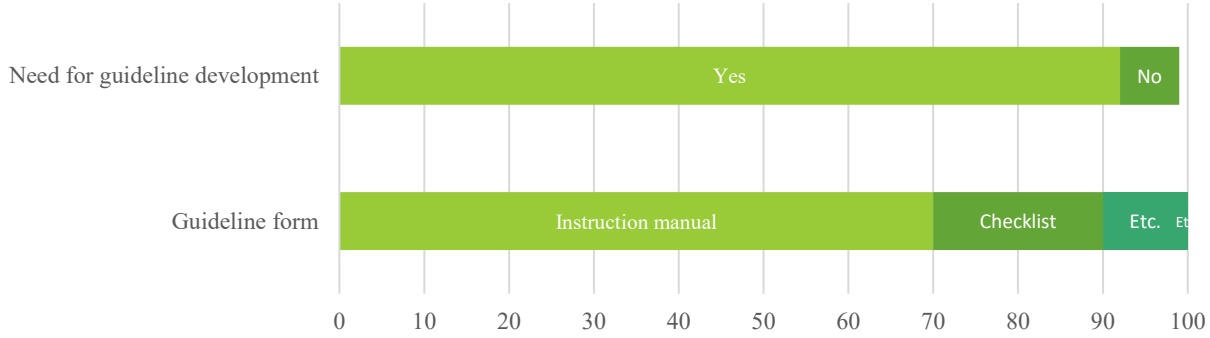


Figure 3. Improvement Requirements

While awareness of flush-out as a best practice is gradually increasing within Saudi Arabia's construction sector, current implementation remains inconsistent and highly dependent on individual company policies. The lack of national regulation, coupled with limited technical training and absence of mandatory IAQ commissioning protocols, undermines the reliability of current practices. This highlights the pressing need for the Ministry of Municipal and Rural Affairs and Housing (MoMRAH) and the Saudi Standards, Metrology and Quality Organization (SASO) to develop a nationally unified flush-out guideline that is technically rigorous, climatically appropriate, and enforceable within construction permitting and inspection frameworks.

5. Discussion

The study reveals a lack of standardization in flush-out practices across Saudi Arabia's residential construction sector. While awareness of IAQ is increasing, the absence of clear regulations has led to inconsistent implementation among construction firms. Notably, many companies lacked defined schedules for TAB ventilation systems, making it unclear whether adequate air exchange was achieved prior to occupancy.

Flush-out durations, ventilation methods, and environmental control strategies varied widely—from 48 to 120 hours—often without using monitoring tools such as VOC or PM2.5 sensors. This reliance on assumptions over empirical data weakens the effectiveness of pollutant removal, especially in Saudi Arabia's sealed, climate-controlled buildings, where poor air exchange can intensify VOC accumulation and humidity-related risks like mold, particularly in enclosed spaces like built-in closets.

The strong demand for formal guidelines - expressed by most surveyed companies - underscores the need for a national IAQ framework. Companies support the introduction of technical manuals, verification protocols, and optional certification schemes. Establishing flush-out standards tailored to Saudi conditions would strengthen construction quality and align housing development with the health and sustainability goals of Vision 2030.

6. Conclusion

This study examined the current status and variability of flush-out implementation practices across Saudi Arabia's residential construction sector, with a focus on IAQ management post-construction. The survey results revealed a general lack of standardization, with notable discrepancies in ventilation procedures, flush-out durations, and the use of air quality monitoring tools. These

inconsistencies are compounded by the absence of enforceable national guidelines tailored to Saudi climatic and architectural conditions.

Of particular concern is the observed vulnerability of built-in closets and enclosed spaces to elevated humidity levels, especially in coastal regions, which can foster microbial growth even in the absence of visible condensation. The findings underscore the need for scientifically grounded, Saudi-specific IAQ standards that include clearly defined flush-out protocols, performance verification requirements, and environmental controls.

As the Kingdom advances its Vision 2030 goals of enhancing public health and sustainable urban living, integrating flush-out procedures into the national building code—supported by regulatory enforcement and certification mechanisms—will be essential. Such measures would ensure healthier living environments for residents while promoting accountability and innovation within the construction industry.

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Toward a Housing Performance Evaluation Framework for Saudi Arabia: Lessons from Japan's Quality Assurance System

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Keywords: Housing Performance Evaluation, Building Lifecycle Assessment, Remodeling Policy, Aging Housing Stock, Saudi–Japan Comparative Study

Abstract. This study explores the applicability of Japan's housing performance evaluation system to the Saudi Arabian context, focusing on aging residential buildings and the need for structured lifecycle management. Japan's Housing Quality Assurance Act and Performance Labeling System provide a robust framework for evaluating housing quality, durability, and safety across both new and existing structures. In contrast, Saudi Arabia lacks a national system to assess the condition of its aging housing stock, much of which was built before modern building codes. Through comparative policy analysis and case study evaluation, the research identifies critical components—such as third-party inspections, performance grading, and maintenance diagnostics—that could be adapted to Saudi conditions. The paper proposes a localized evaluation framework tailored to Saudi Arabia's climate, construction practices, and Vision 2030 goals. Findings emphasize the importance of regulatory integration, data transparency, and institutional training to promote sustainable housing and proactive remodeling policies in the Kingdom.

1. Introduction

Japan's approach to managing its aging housing stock offers valuable insights for Saudi Arabia as it navigates urban development challenges and housing sustainability [1]. In Japan, as of 2025, there were approximately 6.13 million apartments for sale, representing over 10% of total households [2]. Notably, by 2025, 1.29 million of these units were over 30 years old and in need of remodeling [3]. Projections indicated that by 2033, the number of apartments exceeding 40 years in age would reach 2.64 million, highlighting the expanding scope of the housing inventory market [4]. Despite this, the average lifespan of a house in Japan is about 30 years, significantly shorter than the 55 years in the United States and 77 years in the United Kingdom [5]. In 2018, the Ministry of Land, Infrastructure, Transport and Tourism reported that used houses constituted 90.3% of the market in the U.S., 85.3% in the U.K., but only 13.5% in Japan, underscoring the need for policy interventions [6]. Consequently, Japan implemented the Act on Promotion of Distribution of Long-term Excellent Housing in 2019, emphasizing the importance of maintenance, repair, reinforcement, and remodeling of older buildings [7]. Furthermore, the "Housing Performance Labeling System" was introduced under the Act on Promotion of Housing Quality Assurance, categorizing houses into single and joint types and evaluating both new and existing buildings across 35 items in 10 fields.

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In Saudi Arabia, the average lifespan of residential buildings ranges between 25 to 50 years, influenced by factors such as construction quality and maintenance practices [8]. Recognizing the need for sustainable housing solutions, the Saudi Building Code was implemented in 2021 to enhance construction standards and extend the lifespan of properties [9]. Additionally, the Housing Program Delivery Plan (2021-2025) under Vision 2030 aims to increase homeownership rates and improve housing quality across the Kingdom.

Drawing parallels from Japan's experience, Saudi Arabia can benefit from establishing a comprehensive housing performance evaluation system. Such a system would assess the quality and durability of new and existing residential structures, promoting transparency and encouraging maintenance and renovation practices. Implementing standardized assessments can also facilitate the development of a robust secondary housing market, aligning with the Kingdom's objectives to diversify its economy and enhance the quality of life for its citizens.

2. Literature Review: Aging and Deterioration of Japanese Housing

Japan's approach to housing lifecycle management offers significant insight into the challenges of aging building stock and the implications for long-term urban sustainability [10]. According to the *2023 Housing and Land Statistics Survey* by Japan's Ministry of Internal Affairs and Communications, the nation's total housing stock stood at approximately 60.63 million units [11]. Of these, only 8% were constructed within the past eight years, while 31% were between 9 and 23 [12]. Notably, nearly 45.8% of the housing stock consisted of buildings older than 24 years, many of which required either significant renovation or complete reconstruction [13]. Additionally, 8% of buildings lacked age data, highlighting the systemic need for improved documentation and asset tracking in national housing registries (Figure 1).

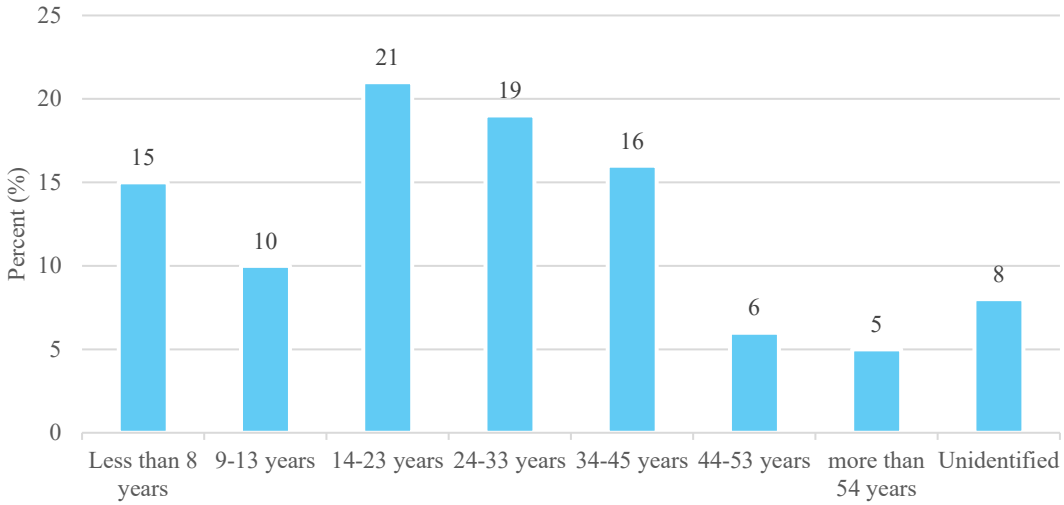


Figure 1. Housing Inventory by Years of Existence in Japan

The aging-related vulnerability of housing is further illustrated by findings from the *2023 Building Demolition Survey* by the Ministry of Land, Infrastructure, Transport and Tourism [14]. Of the 127,000 buildings demolished that year, 34% were removed due to structural aging and degradation [15]. This rate vastly outweighed demolitions caused by fire (2%), wind and flood damage (0.06%, or 70 buildings), and seismic or other natural disasters (0.025%, or 32 buildings). These statistics emphasize the significance of proactive lifecycle management and structural health diagnostics in preventing deterioration-driven demolition (Figure 2).

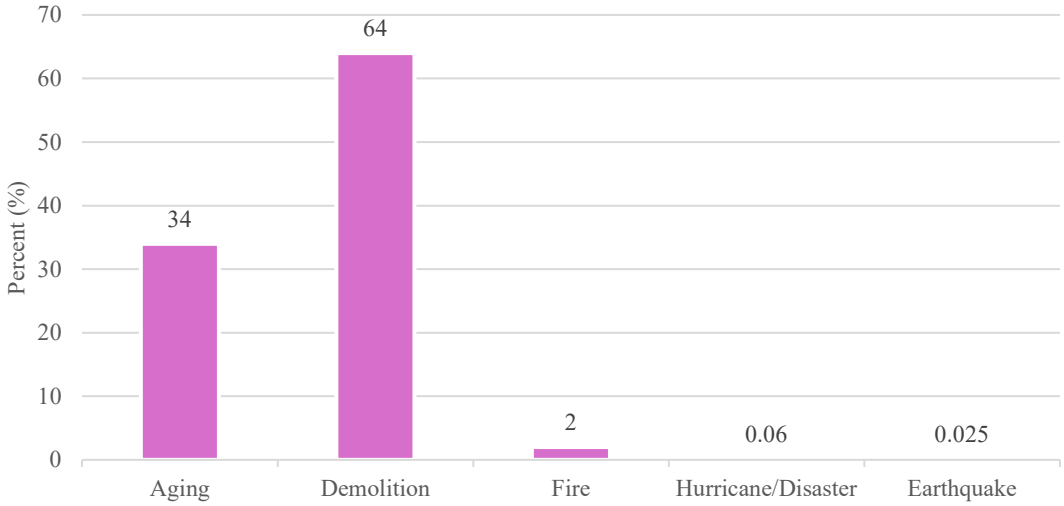


Figure 2. Causes of Housing Destruction

While Saudi Arabia is undergoing rapid urbanization and expansion, its housing sector faces an impending wave of aging buildings, particularly those constructed in the 1980s and 1990s before adopting modern building codes [16]. Unlike Japan, Saudi Arabia has no nationally implemented long-term housing performance tracking or deterioration monitoring system [17]. In Al Khobar and other urban centers, numerous medium-scale residential buildings are over 25 years old and may soon require rehabilitation or reconstruction. Moreover, the absence of a centralized, publicly accessible building age database complicates efforts to assess long-term urban resilience and housing security [18].

Using Japan's policy framework and data-driven methodologies, Saudi Arabia must establish national systems for building age classification, degradation assessment, and documentation [19]. Such systems would support proactive maintenance and contribute to efficiently developing a remodeling and secondary housing market, objectives aligned with the Kingdom's Vision 2030 goals for sustainable urban development [20].

3. Methodology

This study adopts a comparative analytical framework to examine the current status of building performance, evaluation protocols, and maintenance strategies in Japan and Saudi Arabia [21]. The research begins by outlining Japan's advanced performance evaluation systems, including condition diagnostics and long-term maintenance frameworks, which have been institutionalized through policies such as the Act on Promotion of Housing Quality Assurance and the Housing Performance Labeling System [22]. These tools offer structured approaches to assessing residential buildings' aging, safety, and renovation potential, particularly in a maturing housing inventory [23].

Building on this foundation, the study conducts a cross-national comparison with Saudi Arabia, where aging mid-scale residential buildings are increasingly becoming a concern, particularly in cities like Riyadh, Jeddah, and Al Khobar [24]. With approximately 40% of residential buildings in Saudi Arabia over 30 years old and built prior to the introduction of the national building code in 2007, the need for systematic evaluation and remodeling is urgent and underexplored [25].

Through qualitative field investigations and secondary data analysis, the research evaluates existing practices of structural assessment, maintenance frequency, and safety standards in small and medium-sized buildings, constituting a significant portion of the Kingdom's housing stock. Informed by Japan's diagnostic models, the study proposes a tailored diagnostic methodology and a comprehensive performance evaluation system applicable to the Saudi context [26]. This

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proposed framework assesses structural integrity, aging progression, seismic resistance (where relevant), and lifecycle maintenance needs [27].

Ultimately, the research aims to contribute to developing a strategic remodeling activation model in Saudi Arabia by recommending policy instruments, standardized evaluation criteria, and incentives that can stimulate the secondary housing market and promote sustainable building management in line with Vision 2030 housing quality objectives.

4. Analysis

4.1. Current Status of Housing Performance Evaluation in Japan

The Housing Performance Labeling System in Japan, established under the Housing Quality Assurance Act, is a regulatory and informational framework to promote acquiring high-quality, structurally sound housing. Its primary objective is to enhance consumer confidence by providing transparent and standardized performance data across multiple housing types. This system enables homebuyers and stakeholders to assess critical aspects of housing, such as structural integrity, fire resistance, energy efficiency, and durability, in a clear and accessible format.

In addition to facilitating informed decision-making, the system functions as a legal reference for dispute resolution bodies, offering objective criteria to expedite the resolution of conflicts that may arise during property transactions. One of its most significant contributions is instituting a mandatory 10-year basic structural defect warranty for newly constructed residential properties, ensuring long-term accountability in construction quality and builder responsibility.

Japan has fostered a market environment emphasizing quality assurance, lifecycle maintenance, and consumer protection by integrating performance evaluation into the real estate and construction sectors. These measures are especially critical as Japan faces a rapidly aging housing stock, with nearly half of all homes exceeding 24 years old.

For Saudi Arabia, where a substantial portion of the housing stock is aging and maintenance practices remain inconsistent, implementing a similar performance-based evaluation framework could enhance housing market transparency, reduce post-sale disputes, and stimulate investment in building rehabilitation. Such a system would align with Vision 2030 goals by improving construction standards, enabling data-driven policy interventions, and fostering trust among homeowners, developers, and public agencies.

4.2 Current Status of Housing Performance Evaluation in Japan

Japan’s housing performance evaluation system represents a mature, legally codified framework that has evolved to ensure residential architecture's long-term quality, safety, and adaptability. Established under Article 3, Paragraph 1 of the *Act on Promotion of Housing Quality Assurance* (Act No. 81 of 1999), the system initially applied only to newly built housing units. However, it was formally expanded in August 2002 to include existing dwellings. This shift marked a strategic policy evolution toward sustaining the value of aging housing stock and enhancing transparency in housing transactions.

The system is bifurcated by building typology—single-family homes and multi-family dwellings—and evaluated according to 35 items grouped into 10 performance categories (Table 1). These include structural stability (seismic and wind load resistance), fire safety, deterioration resistance, ease of maintenance, thermal insulation, air quality control, acoustic performance, lighting and ventilation, energy-saving features, and accessibility for the elderly or persons with disabilities (Table 2). Each item is assessed using a performance grading scale, generally from Grade 1 (basic compliance) to higher grades indicating superior performance. However, the boundaries between grades can be vague, and interpretation may vary among agencies, suggesting a need for further standardization of evaluative metrics.

Table 1. Performance Evaluation System of the Housing Performance in Japan

Performance Indications		New House		Existing House	
		Villa	Apartment	Villa	Apartment
Structural Safety	Earthquake resistance grade (prevention of structural collapse)	●	●	●	●
	Earthquake resistance grade (prevention of structural damage)	●	●	○	○
	Other (prevention of structural collapse and damage due to earthquake)	●	●	●	●
	Wind resistance grade (prevention of structural collapse and damage)	●	●	○	○
	Snow grade	●	●	○	○
	Allowable bearing capacity of ground and piles, etc. and their setting method	●	●	●	●
	Foundation structure method and type, etc.	●	●	●	●
Fire Safety	Detection alarm device installation level (in case of fire in townhouse)	○	○	○	○
	Detection alarm device installation level (in case of fire in other townhouses, etc.)	-	○	-	○
	Escape safety measures (in case of fire in ownhouses, etc., common hallway)	-	○	-	○
	Escape measures (in case of fire)	○	○	○	○
	Fire resistance level (areas with risk of combustion (openings))	○	○	○	○
	Fire resistance level (areas with risk of combustion (excluding openings))	○	○	○	○
	Fire resistance level (walls, floors)	-	○	-	○
Deterioration Reduction	Deterioration countermeasure level (structural body, etc.)	●	●	●	●
Maintenance and Updates	Maintenance Measures Grade (Exclusive Pipes)	●	●	●	●
	Maintenance Measures Grade (Public Pipes)	-	●	-	●
	Update Measures (Public Drains)	-	●	-	●
	Update Measures (Exclusive Section of Townhouses)	-	●	-	○
Thermal Environment	Insulation rating	●1	●1	●1	●1
	Primary energy consumption rating	●1	●1	●1	●1
Air Environment	Formaldehyde countermeasures (interiors and ceilings)	○	○	○	○
	Ventilation countermeasures	○	○	○	○
	Indoor air chemical substance concentration, etc.	○	○	○	○
Light & Visual Environment	Simple opening ratio	○	○	○	○
	Opening direction	○	○	○	○
Sound environment	Heavy floor impact sound insulation	-	○	-	○
	Light floor impact sound insulation	-	○	-	○
	Transmission loss rating (barrier)	-	○	-	○
	Transmission loss rating (exterior wall opening)	○	○	○	○
Elderly	Measures for the elderly, etc. (exclusive section)	○	○	○	○
	Measures for the elderly, etc. (public section)	-	○	-	○
Crime Prevention	Measures to prevent intrusion into openings	○	○	○	○

Table 2. Evaluation Items and Grades for the Elderly.in Japan

9. Evaluation items and grades for the elderly, etc.	
9-1. Measures for the elderly (exclusive section) / Single-family homes and apartment complexes	
- The extent of measures taken for the elderly in the home	
5	- Special measures to ensure the safe movement of elderly people, etc. - Special measures to facilitate basic daily life activities for wheelchair users
4	- Take measures to ensure safe movement of the elderly and others - Take measures to facilitate basic daily life activities for wheelchair users
3	- Only basic measures are taken to ensure that the elderly and others can move safely - Only basic measures are taken to ensure that wheelchair users can perform basic activities
2	- Implement basic measures to ensure the safety of elderly people and others
1	- Only measures to ensure safety during movement as stipulated in the Building Standards Act are taken.
9-2. Grade of measures considering the elderly (common areas) / Apartment complex	
- The extent of measures for the elderly, mainly from the entrance of the building to the front door of the home	
5	- Special measures to ensure safe movement of elderly people, etc. - Special measures to ensure easy access to the front door of a home for users of self-propelled wheelchairs
4	- Implement measures to ensure safe movement of the elderly and others - Implement measures to ensure that users of self-propelled wheelchairs can easily reach the front door of their homes
3	- Only basic measures are taken to ensure that the elderly and others can move safely.

	- Only basic measures are taken to ensure that self-propelled wheelchair users can reach the front door of their homes.
2	- Implementing basic measures to ensure safe movement of the elderly and others
1	- Only measures to ensure safety during movement as stipulated in the Building Standards Act are taken.

Evaluation is performed by third-party institutions designated as Registered Housing Performance Evaluation Agencies. These agencies operate under the oversight of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). They are responsible for both design-phase document review and on-site inspections during construction. Inspectors must conduct four site visits for buildings up to three floors to verify compliance and assess performance. In larger buildings (four floors or more), the number of inspections increases proportionally with height and complexity. Evaluators must be certified professionals who have completed rigorous training programs administered by the Housing Performance Evaluation Institute, a non-governmental but ministerially authorized organization. This ensures a standardized, technically sound evaluation process nationwide.

Importantly, the performance ratings are used not only by homebuyers and sellers but also by legal mediators in the event of post-occupancy disputes. Moreover, insurance companies, financial institutions, and government subsidy programs rely on these ratings to guide risk assessment and eligibility decisions. The system has thus become a cornerstone of Japan's housing policy ecosystem, fostering a culture of quality assurance and long-term asset value preservation.

4.3 Implications for Saudi Arabia

Saudi Arabia lacks a comparable national comprehensive housing performance evaluation system, especially for existing buildings. However, the need is increasingly urgent. With an aging housing stock, particularly in urban centers such as Riyadh, Jeddah, and Al Khobar, combined with rapid population growth and urban expansion, the risk of structural degradation and underperforming buildings is becoming more pronounced. According to regional surveys, many homes built in the 1980s and 1990s are nearing or exceeding their lifecycle thresholds. Yet, there is no mandated mechanism for evaluating their safety, durability, or functional adequacy.

Adopting a modified version of Japan's evaluation model could yield significant benefits. A Saudi Housing Performance Evaluation System (SH-PES) could be established under the Ministry of Municipal and Rural Affairs and Housing, supported by accredited third-party agencies operating under a national regulatory framework. Evaluation criteria should be localized to address specific climatic conditions (e.g., thermal insulation in extreme heat), regional construction practices, and cultural design expectations. For example, shading, ventilation, and water-use efficiency might be weighted more heavily in Saudi Arabia than in Japan.

Furthermore, SH-PES could serve as a policy tool to promote the secondary housing market by offering objective quality ratings for used properties. This would enhance buyer confidence, inform pricing strategies, and enable access to housing finance. Mandatory periodic inspections, especially for buildings over 20 years old, could also form part of a national maintenance regulation strategy, linked to insurance renewals or occupancy permits.

Training and certifying local evaluators through government-accredited institutions or technical universities would ensure implementation integrity. In parallel, a centralized digital database of performance ratings could support long-term housing policy planning and assist municipal authorities in prioritizing infrastructure investments.

Ultimately, such a system would align with Saudi Arabia's Vision 2030 objectives by elevating housing quality standards, strengthening consumer protection, and fostering a resilient, sustainable urban fabric.

5. Discussion

The comparative evaluation between Japan and Saudi Arabia reveals significant differences in the maturity of housing performance evaluation systems. Japan offers a well-institutionalized model through the Housing Quality Assurance Act and the Housing Performance Labeling System. These frameworks have enabled systematic maintenance, lifecycle management, and structural assessment of new and aging housing stock. In contrast, despite rapid modernization and regulatory improvements under Vision 2030, Saudi Arabia's housing sector lacks a standardized mechanism for assessing the performance of its aging residential inventory, particularly those built before the Saudi Building Code's full implementation in 2007. With approximately 40% of the current housing stock exceeding 30 years of age, the absence of a structured performance diagnostic framework poses risks to structural safety, occupant well-being, and housing market efficiency.

Implementing a Saudi Housing Performance Evaluation System (SH-PES) modeled on Japan's approach could offer transformative benefits. Localized criteria—considering heat resilience, ventilation strategies, and water efficiency—would ensure climatic and cultural relevance. Such a system could enhance consumer trust, support real estate transparency, and stimulate renovation activity in the secondary market. Moreover, integrating SH-PES with digital databases and third-party evaluator training could build institutional accountability and policy coordination. This strategy would directly contribute to Vision 2030 goals by improving housing quality, enabling preventive maintenance, and supporting data-driven infrastructure planning. The research thus reinforces the urgency of establishing a legally supported, performance-based housing evaluation framework to sustain long-term urban resilience in the Kingdom.

6. Conclusion

This study conducted a comparative analysis of Japan's housing performance evaluation system and its applicability to the Saudi Arabian context, focusing on aging residential buildings and long-term sustainability challenges. Japan's system—supported by the Housing Quality Assurance Act and the Housing Performance Labeling System—offers a structured, legally supported model for assessing building performance, safety, and durability. Its framework emphasizes standardized evaluation, periodic inspections, and third-party certification, contributing significantly to market transparency, lifecycle asset management, and consumer protection.

For Saudi Arabia, which is undergoing rapid urbanization and experiencing a growing share of aging housing stock, particularly in urban centers such as Al Khobar, introducing a Saudi Housing Performance Evaluation System (SH-PES) presents a strategic opportunity. Adapting to the Kingdom's climatic, cultural, and construction conditions, a localized system could strengthen regulatory oversight, encourage proactive maintenance, and revitalize the secondary housing market. By institutionalizing evaluation mechanisms and linking them to housing finance, insurance, and renovation policies, Saudi Arabia can enhance housing quality and safety while aligning with the broader goals of Vision 2030 to create resilient and livable urban environments.

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Sustainable Urban Living in Arid Climates: Indoor Air Quality Risk Modeling for Saudi Residential Developments

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Keywords: Indoor Air Quality (IAQ), Volatile Organic Compounds (Vocs), Health Risk Assessment, Sustainable Residential Design, Formaldehyde Exposure

Abstract. This study investigates the indoor air quality (IAQ) of newly constructed apartment complexes in Al Khobar, Saudi Arabia, with a focus on formaldehyde (HCHO) and volatile organic compounds (VOCs), including benzene, toluene, and xylene. Using the U.S. EPA's risk assessment framework, the study calculated hazard quotient (HQ) and excess cancer risk (ECR) values based on pollutant concentrations and exposure models. Results indicate that xylene frequently exceeded HQ thresholds within the first six months, while benzene and HCHO presented notable carcinogenic risks, with ECR values surpassing 1×10^{-5} and $1\times10^{-4,}$ respectively. Despite gradual reductions, pollutant levels often remained above WHO health protection guidelines. The findings underscore the need for a localized, health-based IAQ index and stricter sustainable housing policies in Saudi Arabia. This research contributes to evidence-based environmental health strategies aligned with the nation's Vision 2030 development goals.

1. Introduction

Formaldehyde (HCHO) and volatile organic compounds (VOCs) are persistent indoor air pollutants known to cause adverse health effects, including sick building syndrome, respiratory ailments, and neurological disorders [1]. In Saudi Arabia, rapid urbanization, extreme climatic conditions, and prevalent use of synthetic building materials exacerbate the risks associated with indoor air pollution [2]. The country's hot and arid climate often necessitates sealed indoor environments and extensive use of air conditioning, reducing natural ventilation and accumulating indoor pollutants [3].

Recent studies have highlighted the severity of indoor air pollution in the region [4]. For instance, an assessment in the Al-Baha region reported indoor formaldehyde concentrations ranging from 0.009 to 0.1 mg/m³, approaching the World Health Organization's recommended limit of 0.1 mg/m³ [5]. Additionally, total VOC levels in some residential settings have reached up to 0.8 mg/m³, indicating significant indoor air quality concerns [6].

Saudi Arabia lacks a comprehensive, health-based indoor air quality (IAQ) index specifically tailored for residential environments. Existing standards are often adapted from international guidelines without fully considering the Kingdom's unique environmental and cultural factors [7]. This gap underscores the need for localized research and the development of IAQ indices that accurately reflect the health risks associated with indoor pollutants in Saudi homes (Figure 1) [8].

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Figure 1. Indoor Air Quality in Saudi Arabia

This study aims to establish a foundational framework for a health-oriented IAQ index for residential buildings in Saudi Arabia. By applying risk assessment methodologies to empirical pollutant concentration data collected from newly constructed apartments across various regions, including Riyadh, Dammam, and Jeddah, the research seeks to quantify potential health risks and propose a recalibrated IAQ index [9]. The approach involves integrating exposure assessment, dose-response relationships, and population susceptibility factors to develop an index that is both scientifically robust and contextually relevant [10]. Furthermore, the study considers the effectiveness of various mitigation strategies. For example, implementing ventilation systems with rates between 0.3 and 0.8 air changes per hour has been shown to reduce formaldehyde and VOC concentrations by 30%–50% [11]. Such insights are crucial for informing building design and maintenance practices aimed at improving indoor air quality.

Developing a health-oriented IAQ index tailored to the Saudi Arabian context is imperative for safeguarding public health amid ongoing urban development [12]. This research contributes to the body of knowledge necessary for informed policy-making and the promotion of healthier indoor environments in the Kingdom.

2. Literature Review

In Saudi Arabia, applying human health risk assessment methodologies to indoor air quality (IAQ) is still in an emergent phase [13]. Unlike Japan and Korea, where regulatory frameworks are limited and typically reference international standards such as those of the United States Environmental Protection Agency (US EPA), the Kingdom has begun developing its national guidelines [14]. Nevertheless, in practice, many IAQ-related studies in Saudi Arabia continue to rely on the US EPA's four-step risk assessment model: hazard identification, dose-response assessment, exposure assessment, and risk characterization [15].

The risk assessment begins with identifying hazardous pollutants common in indoor environments, such as formaldehyde, volatile organic compounds (VOCs), and particulate matter (PM2.5 and PM10) [16]. In Saudi homes, especially in urban regions such as Riyadh, Dammam, and Jeddah, the prevalence of such contaminants is exacerbated by the arid climate, low ventilation

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rates, and widespread use of synthetic building materials [17]. For example, indoor formaldehyde (HCHO) concentrations in newly constructed Saudi homes have been found to range from 0.05 to 0.1 mg/m³, nearing the World Health Organization's recommended maximum exposure level of 0.1 mg/m³ [18]. Additionally, total VOC concentrations in some units have exceeded 0.6 mg/m³, particularly in spaces with recent furnishing and finishing.

The second risk assessment stage involves establishing dose-response relationships, where the toxicity reference values are used to evaluate how the body responds to specific pollutant concentrations over time [19]. However, these reference values are often adopted from WHO or EPA guidelines in Saudi Arabia, as no unified national toxicity database exists [20]. As a result, there is a gap between scientific modeling and localized health impact verification.

Exposure assessment constitutes the third component and is heavily influenced by the built environment [21]. The design of residential buildings in the Kingdom frequently features compact layouts, limited cross ventilation, and heavy reliance on mechanical cooling systems due to extreme heat. These characteristics contribute to the accumulation of indoor pollutants, particularly in sealed environments where ventilation rates fall below the ASHRAE-recommended minimum of 0.35 air changes per hour. Risk characterization synthesizes these elements to estimate the potential health impacts on occupants. Recent regional studies have indicated that prolonged exposure to indoor air pollutants in Saudi Arabia is associated with increased risks of respiratory disorders, allergic reactions, and potential neurocognitive impairment, especially among vulnerable populations such as children and the elderly. For instance, a 2023 study published in Frontiers in Built Environment demonstrated that poor IAQ in Saudi primary schools was linked to a 20% increase in reported respiratory symptoms among children during the summer months.

2.2. Exposure Assessment and Risk Determination

Exposure assessment is typically conducted using the lifetime average daily dose (LADD) estimation model, as represented in equation (1) [22]. For non-carcinogenic substances, exposure is evaluated based on the average daily intake throughout the exposure period (ED) [23]. In contrast, the assessment considers the cumulative dose over an assumed lifetime, generally set at 70 years, for carcinogenic substances, by international standards. Accordingly, for non-carcinogens, the averaging time (AT) is equal to the exposure duration (ED), whereas AT corresponds to the average lifespan for carcinogens.

$$LADD\left(\frac{mg}{kg}/day\right) = \frac{CA \times IR \times EF \times ED}{BW \times AT} \quad \text{Equation (1)}$$

$$ECR = SF \times LADD \quad \text{Equation (2)} \qquad \text{HQ} = \frac{LADD}{RfC \times \frac{IR}{BW}} \quad \text{Equation (3)}$$

CA: Exposure concentration [mg/m^3] BW: Body weight [kg]
IR: Respiratory rate [m^3/hr] AT: Mean time [day]
EF: Exposure frequency [hr/day] SF: Carcinogenicity [(mg/kg day)$^{-1}$]
ED: Exposure duration [day] RfC: Exposure reference value [mg/m^3]

The key parameters involved in the estimation include pollutant concentration (CA) and exposure duration (ED), suggesting that the overall exposure can be conceptualized as a function of both concentration and time [24]. In practice, exposure durations applied in field surveys are often derived from hypothetical exposure scenarios or statistical assumptions based on activity patterns [25]. Refining these assumptions through empirical validation could significantly enhance the accuracy and applicability of predictive IAQ models, particularly for use in future simulations and risk projections.

The hazard quotient (HQ) for non-carcinogenic effects and the excess cancer risk (ECR) for carcinogenic outcomes are calculated in the subsequent risk characterization phase [26]. These are determined using the slope factor (SF) derived from the unit risk values reported in the United States Environmental Protection Agency's Integrated Risk Information System (US EPA IRIS). An HQ value equal to or exceeding 1 indicates the potential for adverse health effects, while ECR reflects the probabilistic risk of cancer development over a lifetime. The US EPA advises that HQ values remain below one and recommends an acceptable ECR range between 10^{-6} and 10^{-4}, with a preferred target of 10^{-6} or lower to ensure minimal carcinogenic risk.

3. Methodology

This study investigates indoor air quality conditions in newly constructed apartment buildings in Al Khobar, Eastern Province of Saudi Arabia, focusing on the concentrations of HCHO and TVOCs following project completion after 2024. Al Khobar was selected due to its rapid urban growth and distinct environmental conditions, including elevated ambient temperatures and high humidity levels that influence indoor pollutant dynamics.

Air samples were collected in newly completed units before occupancy, ensuring the measurement of initial pollutant concentrations associated with off-gassing from construction and furnishing materials [27]. The measurement protocol adhered to internationally recognized procedures to guarantee consistency, and pollutant concentrations were analyzed in compliance with residential indoor air quality monitoring guidelines.

To evaluate potential health risks, toxicity reference values were applied. These included the inhalation reference concentration (RfC) for non-carcinogenic assessment and the slope factor (SF) for carcinogenic risk analysis. Both values were extracted and converted from the U.S. Environmental Protection Agency's Integrated Risk Information System (IRIS) database. These benchmarks were instrumental in guiding the exposure and risk assessment stages.

Exposure levels were calculated using standard physiological parameters recommended by the World Health Organization (WHO) in its Exposure Factors Handbook. The inhalation rate was set at an average of 14.25 cubic meters per day, representing a mean daily breathing volume for adult males and females under moderate activity. A mean body weight of 62.8 kilograms was also used, reflecting demographic profiles relevant to the Saudi adult population. These values were used to estimate each pollutant's lifetime average daily dose (LADD).

The resulting dose values were then used to calculate the hazard quotient (HQ) for non-carcinogenic effects and the excess cancer risk (ECR) for carcinogenic pollutants. An HQ value greater than or equal to 1 indicates potential adverse health effects, while the ECR value quantifies the probability of developing cancer over a lifetime. According to U.S. EPA standards, acceptable ECR values fall from 1×10^{-6} to 1×10^{-4}, with a target of 1×10^{-6} or less.

The analysis acknowledges that the environmental context in Al Khobar, where sealed indoor spaces and reliance on mechanical ventilation are predominant, directly impacts pollutant accumulation. As such, the methodology was designed to reflect the international risk assessment framework and the localized conditions of the Saudi built environment. This dual approach ensures that the findings are globally informed and regionally applicable.

4. Analysis

4.1. Setting the Target and Conditions of Risk Assessment

This study analyzed indoor air quality conditions in newly constructed apartment complexes in Al Khobar, Saudi Arabia, completed after 2024. The investigation focused on measuring concentrations of HCHO and TVOCs during the post-construction, pre-occupancy period to assess the baseline levels of chemical pollutants commonly emitted from construction materials, adhesives, furnishings, and synthetic finishes (Table 1). Sampling was conducted using the best international practices to ensure methodological consistency and accuracy.

Table 1. IAQ Pollutant Concentration Values (μg/m³) based on Literature Review

Authors	Toluene ($C_6H_5CH_3$)	Benzene (C_6H_6)	Xylene (C_8H_{10})	Formaldehyde (HCHO)	Measurement Duration
Jung & Awad (2021)	158.00	12.00	34.00	372.50	3 Months
Cheng et al. (2022)	58.00	9.00	467.00	150.00	4–6 Months
Arar et al. (2022)	209.13	1.73	19.77	70.77	3 Months
Wei et al. (2022)	92.56	0.11	17.97	270.02	12 Months
Pei et al. (2024)	101.00	1.85	9.35	515.70	3 Months
Baeza_Romero et al. (2022)	137.92	.255	68.05	133.45	12 Months
Alonso et al. (2022)	397.50	2.30	200.40	113.21	3 Months
Zhang et al. (2021)	272.82	3.05	137.92	71.68	3 Months
Jung et al. (2024)	254.04	1.59	137.53	212.24	3 Months
	141.11	0.93	93.32	184.15	4–6 Months
	83.21	2.21	42.42	93.64	12 Months
Passi et al. (2022)	230.42	2.03	75.26	829.10	12 Months
	216.24	2.18	57.92	360.42	24 Months
	161.51	1.42	74.52	26.32	36 Months
Kumar et al. (2023)	471.88	3.86	55.81	232.62	3 Months
Nandan et al. (2021)	77.44	2.74	448.17	104.02	3 Months
Bralewska et al. (2022)	95.75	1.74	62.02	495.40	3 Months
Vasile et al. (2024)	154.96	4.69	159.92	190.36	3 Months

The toxicity reference values for each pollutant, including the inhalation reference concentration (RfC) and slope factor (SF), were adopted from the U.S. Environmental Protection Agency's Integrated Risk Information System (IRIS) and converted for applicability in local assessments (Table 2). These values served as critical benchmarks for calculating potential health risks, distinguishing between non-carcinogenic and carcinogenic effects. The World Health Organization's Exposure Factors Handbook applied standard physiological and behavioral parameters for the exposure assessment. The average respiratory rate was 14.25 cubic meters per day, representing the mean for adult males and females under light physical activity. In contrast, an average body weight of 62.8 kilograms was used to reflect typical values for the regional adult population.

Table 2. Reference Values for Dose-response Assessment of Target IAQ Pollutants

Category	Toluene ($C_6H_5CH_3$)	Benzene (C_6H_6)	Xylene (C_8H_{10})	Formaldehyde (HCHO)
RfC(mg/m^3)	5.0	0.03	0.1	-
SF$(mg/kg \cdot day)^{-1}$	-	3.6×10^{-2}	-	4.6×10^{-2}

Using these parameters, each substance's lifetime average daily dose (LADD) was estimated. The derived values were then applied in the risk characterization stage. The hazard quotient (HQ) was calculated for non-carcinogenic analysis, with any result exceeding one indicating a potential health concern. In parallel, the excess cancer risk (ECR) was computed to evaluate long-term carcinogenic impact, with acceptable risk thresholds guided by U.S. EPA standards set between 1×10^{-6} and 1×10^{-4}, and a preferred target of 1×10^{-6} or lower. These thresholds provide an evidence-based framework to interpret the degree of health risk associated with measured pollutant concentrations.

The selection of Al Khobar as a case study site reflects its strategic significance as a growing urban hub in Eastern Province and its environmental context. The region's high ambient temperatures, elevated humidity levels, and dependence on sealed, mechanically ventilated indoor environments collectively influence the persistence and concentration of indoor pollutants. This analysis provides valuable insights into the IAQ profiles of Saudi residential developments and forms a foundation for future guidelines to safeguard occupant health in rapidly urbanizing desert climates.

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4.2. Setting the Target and Conditions of Risk Assessment

The investigation revealed that none of the measured volatile organic compound (VOC) concentrations exceeded the established guideline thresholds. However, among the six primary VOCs analyzed, hazard quotient (HQ) values were highest for xylene, followed by benzene and toluene, prompting a focused assessment on these specific compounds. The outcomes of the health risk analysis based on these pollutants are presented in Figure 2. While the HQ values for both toluene and benzene remained consistently below the critical threshold of 1, xylene frequently exceeded this limit during the initial six months following construction completion, indicating potential short-term non-carcinogenic health risks.

Regarding carcinogenic risk, most measurements failed to meet the U.S. Environmental Protection Agency's (EPA) recommended excess cancer risk (ECR) benchmark of 1×10^{-6}. Benzene exhibited values slightly above this threshold, typically in the range of 1×10^{-5}, whereas formaldehyde (HCHO) exceeded even the upper boundary of the acceptable range, with values surpassing 1×10^{-4}. Nonetheless, after a six-month post-construction period, HCHO levels generally declined to concentrations below those defined by the World Health Organization's (WHO) indoor air quality guidelines for health protection.

Although toluene was often present in the highest concentrations among the VOCs studied, benzene demonstrated significant toxicity even at low exposure levels. Xylene, by contrast, exhibited both elevated concentrations and toxicity, thereby representing a critical pollutant in the early post-construction phase. Moreover, the elevated reference threshold established for HCHO, due to the practical challenges of mitigating emissions in real-world conditions, suggests that even nominal compliance may not equate to sufficient health protection. The frequent exceedance of this standard further underscores the need for enhanced monitoring and stricter control strategies, particularly in the early occupancy phase of newly constructed residential buildings.

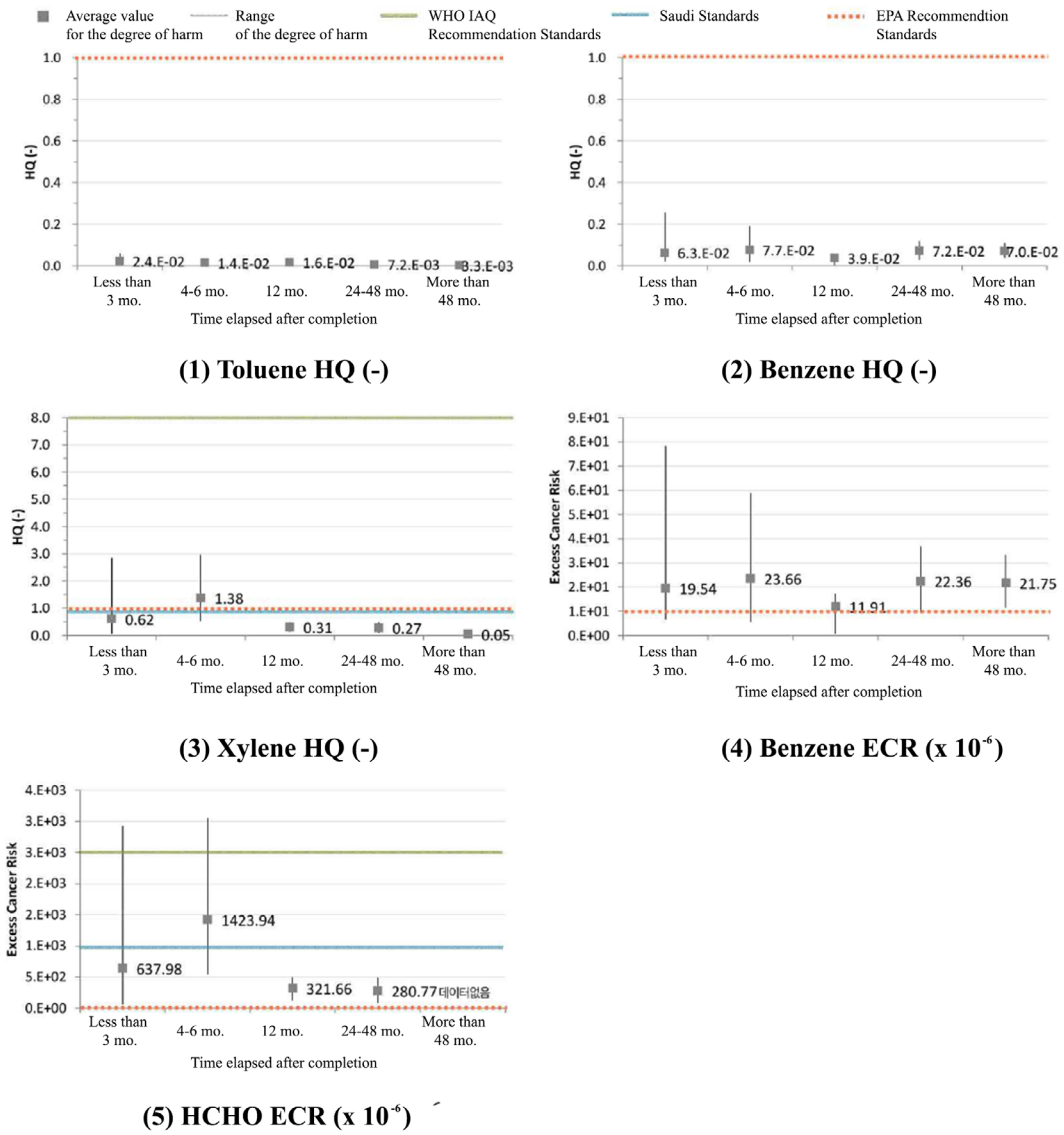


Figure 2. Risk of New Apartment Complexes according to the Time Elapsed after Completion

5. Discussion

The findings from this study highlight the critical need to reassess IAQ standards in Saudi Arabia's residential sector, particularly during the early post-construction phase. Among the six major VOCs evaluated, xylene exhibited the highest hazard quotient (HQ), frequently exceeding the threshold of 1 within six months after completion, indicating a potential short-term health risk. While toluene appeared in the highest concentrations, benzene and formaldehyde (HCHO) demonstrated higher toxicity even at lower levels. Notably, benzene surpassed the EPA's excess cancer risk (ECR) benchmark of 1×10^{-6}, reaching 1×10^{-5}, and formaldehyde exceeded 1×10^{-4}, reflecting substantial carcinogenic potential. Although HCHO concentrations declined after six months, the persistence of elevated levels above WHO recommendations suggests current IAQ regulatory limits may be insufficient for occupant health protection.

These results emphasize that existing reference values—often derived from feasibility considerations—do not adequately account for localized risks in arid, sealed indoor environments like those in Al Khobar. The study's risk modeling approach, using LADD, HQ, and ECR, effectively contextualized pollutant exposure; however, improved assumptions regarding occupant behavior and ventilation dynamics are essential for greater predictive accuracy. To ensure health

resilience in new housing developments, Saudi Arabia must develop a national IAQ index tailored to its environmental and cultural context, updated standards, and post-construction mitigation strategies, including mandatory flush-out periods, low-emission material regulations, and embedded IAQ monitoring systems.

6. Conclusion

This study comprehensively evaluated indoor air quality in newly constructed apartment buildings in Al Khobar, focusing on HCHO and major VOCs such as benzene, toluene, and xylene. Through the application of internationally recognized risk assessment methodologies, including the LADD, HQ, and ECR, the study revealed that while pollutant concentrations often fell within formal guideline limits, several compounds, particularly xylene and HCHO, frequently exceeded health-based thresholds during the first six months after construction. These findings indicate that even without regulatory exceedances, health risks may persist due to the toxicity and behavior of specific pollutants in sealed and mechanically ventilated environments typical in the region.

The study underscores the urgent need for Saudi Arabia to adopt a localized, health-oriented IAQ index tailored to its unique climatic and construction conditions. Such an index should be accompanied by updated ventilation standards, mandatory post-construction flush-out protocols, and enforcing low-emission material use in residential projects. By aligning national policy with empirical risk evidence, urban development in the Kingdom can move toward a more sustainable and health-conscious trajectory, particularly in support of Saudi Vision 2030 and the goal of enhancing quality of life in rapidly urbanizing communities.

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Balancing Daylighting and Thermal Control: Experimental Analysis of Window Films under Saudi Climatic Conditions

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Keywords: Solar Control Window Films, Building Energy Efficiency, Hot-Arid Climate Retrofit, Optical Performance Analysis, Sustainable Building Envelope

Abstract. This study investigates the optical performance of eight commercially available solar control window films (SCWFs) to assess their applicability for retrofitting building façades in Saudi Arabia's hot-arid climate. Spectral transmittance and reflectance measurements were conducted using a high-resolution spectroradiometer under simulated solar conditions. Results show significant variation in performance among the films, with Products B and C demonstrating optimal balance, reducing infrared transmittance by approximately 85% while maintaining visible light transmittance near 55%. Reflectance analysis across multiple angles of incidence confirmed that high-performing mirrored films increased glare potential, while Products B and C maintained moderate angular reflectivity suitable for dense urban environments. The findings emphasize that film selection should consider energy efficiency and visual comfort. This research supports the integration of SCWFs into national retrofitting strategies, aligning with Saudi Vision 2030 and building code requirements, and highlights the need for simulation-based design tools that incorporate local climate and building typologies.

1. Introduction

Globally, the building sector accounts for a substantial proportion of energy consumption and carbon emissions, responsible for approximately 36% of final global energy use and nearly 39% of energy-related carbon dioxide (CO_2) emissions [1]. In response, many nations have elevated the energy performance of buildings to a national priority, leveraging a combination of regulatory frameworks, technological innovation, and market-based incentives [2]. Among the strategies gaining prominence is applying solar control technologies to mitigate thermal loads and improve envelope efficiency, which is particularly critical in regions with intense solar exposure [3].

In the Kingdom of Saudi Arabia, which is characterized by a harsh desert climate with extended summer periods and ambient temperatures often exceeding 45°C, the issue of heat gain through building envelopes is especially pronounced [4]. Solar radiation contributes significantly to the cooling load in buildings, leading to peak electricity demand [5]. Data from the Saudi Energy Efficiency Center (SEEC) indicate that approximately 70% of total electricity consumption in Saudi residential buildings is attributed to air-conditioning systems. In this context, passive strategies that reduce solar heat gain through façades, particularly fenestrations, are desirable and essential [6].

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Window glazing is a primary pathway for solar radiation ingress in buildings [7]. Given its typically lower thermal resistance and higher exposure to direct sunlight, it often becomes the most significant source of heat gain, glare, and ultraviolet (UV) degradation of interior materials [8]. To address this, retrofitting with solar control window films (SCWFs) has gained global traction as a feasible and economically viable method. These films are designed to reduce the solar heat gain coefficient (SHGC) by blocking infrared (IR) and ultraviolet (UV) radiation while maintaining high visible light transmittance (VLT) [9]. This enables natural daylighting and exterior view preservation, an important feature in urban housing and office typologies, while improving indoor thermal comfort [10].

In Saudi Arabia, where many existing buildings, particularly those constructed before enforcing modern energy codes, suffer from poor envelope performance, adopting SCWFs presents a compelling retrofit opportunity [11]. As the government pursues sustainability objectives under the Vision 2030 framework and the Green Saudi Initiative, improving building energy performance through envelope enhancements has become a key pathway [12]. Moreover, the updated Saudi Building Code (SBC 601: Thermal Insulation and SBC 602: Energy Efficiency) mandates performance-based energy standards, which increasingly favor the incorporation of advanced glazing or retrofit treatments such as SCWFs to meet compliance. Beyond energy savings, SCWFs also offer benefits such as glare reduction, improved visual comfort, and protection of interior furnishings from UV-induced degradation—factors particularly relevant in high-rise urban housing developments in cities like Riyadh, Jeddah, Dhahran, and Al Khobar, where glass façade systems are prevalent [13]. Despite these advantages, there remains a lack of empirical data quantifying the thermal and optical performance of various SCWF types under local climatic conditions [14].

This study aims to examine the effectiveness of solar control window films in reducing solar heat gain and improving optical performance within the Saudi context. A series of controlled laboratory experiments was conducted to analyze the spectral properties, such as reflectance, transmittance, and absorptance, of commercially available SCWFs. By quantifying their thermal impact, the study intends to provide evidence-based recommendations to policymakers, designers, and facility managers to promote deploying these passive retrofit solutions in alignment with national energy efficiency goals.

2. Literature Review

2.1. Principle of Solar Control Window Films

In the context of energy-efficient architecture, the thermal behavior of window systems plays a crucial role in determining overall building performance [15]. Fenestrations are particularly vulnerable to unwanted heat gain and loss due to their relatively low thermal mass and high exposure to solar radiation [16]. Heat transfer through windows occurs primarily via conduction, convection, and radiation. Among these, solar radiation-driven heat transfer dominates in hot-arid regions such as Saudi Arabia, where average solar insolation exceeds 6.5 kWh/m²/day and ambient summer temperatures frequently surpass 45°C. In such extreme climates, windows without thermal control measures can significantly intensify indoor cooling demand [17]. To mitigate this effect, solar control window films (SCWFs) have emerged as a viable, passive, and cost-effective retrofitting solution, capable of enhancing the energy performance of existing glazing systems (Figure 1).

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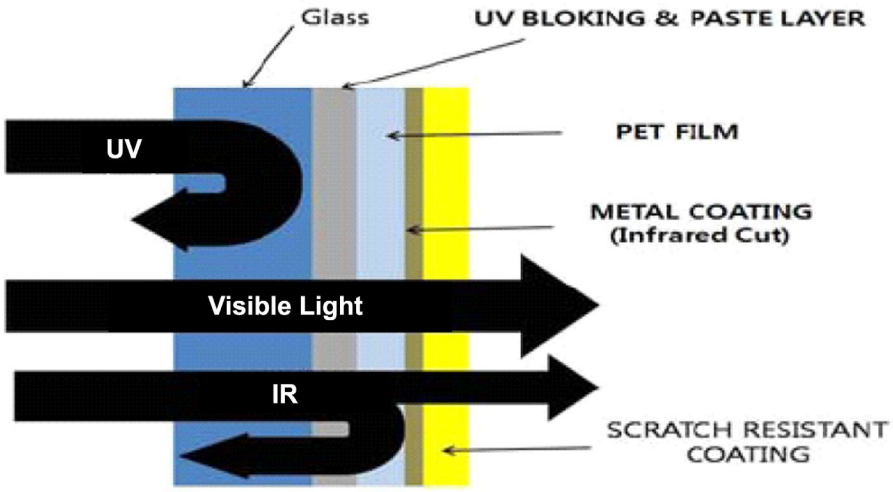


Figure 1. Principles of Solar Control Window Films

SCWFs are thin, multi-layered films composed of polyester, metallic, or ceramic nanomaterials, designed to manage the transmission of solar radiation through the window selectively [18]. These films maintain high visible light transmittance to ensure daylighting and external view retention, while selectively filtering ultraviolet (UV) and infrared (IR) radiation, wavelengths primarily responsible for heat gain and material degradation. Technically, this selective filtration reduces the window assembly's solar heat gain coefficient (SHGC) and mitigates the thermal load imposed on cooling systems [19]. Studies conducted in similar desert climates have shown that high-performance window films can reduce cooling energy use by 10% to 23% annually, depending on factors such as orientation, glazing type, and shading conditions [20]. Moreover, films incorporating low-emissivity coatings can reflect long-wave infrared radiation into the interior space, offering a degree of thermal insulation during cooler periods—an added benefit in regions such as Abha or Taif, where winter temperatures can fall significantly below national averages [21].

The working principle of SCWFs is based on spectral selectivity. When solar radiation strikes a window coated with the film, a portion of the energy is transmitted as visible light [22]. At the same time, the UV and IR components are either absorbed or reflected. The absorbed energy increases the temperature of the glass-film interface [23]. Heat is then dissipated inwardly into the building or outward into the external environment, depending on the film's thermal emissivity and conductivity characteristics [24]. This dynamic behavior influences both the surface temperature of the glazing and the internal heat load experienced by the building. ISO 9050 standards define the optical and thermal metrics used to evaluate such materials, including transmittance, reflectance, and absorptance across the solar spectrum [25].

In the Saudi Arabian context, where a significant portion of the building stock was constructed before implementing energy efficiency codes, the application of solar control window films presents a practical intervention. Unlike complete glazing replacement, SCWF installation is non-invasive, requires minimal operational downtime, and does not compromise the architectural façade—a key consideration in heritage-sensitive or aesthetically regulated developments [26]. Widespread adoption of SCWFs aligns with national policy directions, including Saudi Vision 2030, the Green Saudi Initiative, and the requirements of the Saudi Building Code (SBC 601 and 602), all of which emphasize reducing energy consumption and improving indoor environmental quality [27]. As the Saudi Energy Efficiency Center (SEEC) expands its efforts to retrofit inefficient buildings and reduce peak electricity loads, SCWFs represent a high-impact, low-cost technology capable of contributing significantly to the Kingdom’s sustainability targets.

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3. Methodology

To assess the optical performance of solar control window films (SCWFs) relevant to the Saudi Arabian climate, an experimental study was conducted using eight types of commercially available SCWFs commonly used for retrofitting. Each film was applied to 6 mm clear float glass, reflecting typical glazing in pre-code Saudi buildings. Measurements focused on spectral transmittance and reflectance across the ultraviolet (UV), visible, and infrared (IR) bands.

A high-resolution spectroradiometer (Avaspec-ULS2048, Avantes) was used under a controlled light source simulating standard solar radiation (ASTM G173). To evaluate changes in optical characteristics, the performance of each treated glass specimen was compared to a baseline untreated sample. The analysis focused on visible light transmittance (VLT), total solar energy transmittance (TSET), and solar heat gain coefficient (SHGC), which were calculated from the spectral data.

This methodological framework provides empirical insight into how SCWFs can reduce cooling loads and improve envelope performance in Saudi Arabia's hot-arid conditions. The measured values are input parameters for future dynamic simulations of building energy performance using region-specific weather data.

4. Analysis

4.1. Transmittance by Type of Window Film for Solar Control

The transmittance characteristics of the tested solar control window films (SCWFs) were quantitatively evaluated by separating the solar spectrum into the visible light range (380–780 nm) and the infrared range (780–2500 nm). These two ranges are critical to understanding the dual goals of maintaining visual comfort and reducing solar heat gain. Table 1 presents the measured transmittance values for each of the eight film types applied to 6 mm float glass, while Figure 2 visualizes the spectral performance across both wavelength regions.

Table 1. Principles of Solar Control Window Films

Film Type	Visible Light Transmittance (VLT, %)	Infrared Transmittance (IRT, %)	UV Transmittance (%)	Relative Performance Summary
Uncoated Glass	89.2	86.5	75.4	Baseline condition
Product A	42.7	19.6	5.3	Substantial IR reduction, moderate VLT
Product B	55.8	12.9	2.8	Balanced: High VLT, excellent IR rejection
Product C	56.2	13.4	3.2	Balanced: High VLT, excellent IR rejection
Product D	33.4	11.2	2.1	Low VLT, good IR rejection
Product E	22.8	8.7	1.6	High IR rejection, low daylighting
Product F	24.5	7.9	1.1	Maximum IR rejection, poor visibility
Product G	48.9	23.5	4.6	Moderate performance in all ranges
Product H	19.2	7.1	1.1	Strong IR and UV blocker, very low VLT

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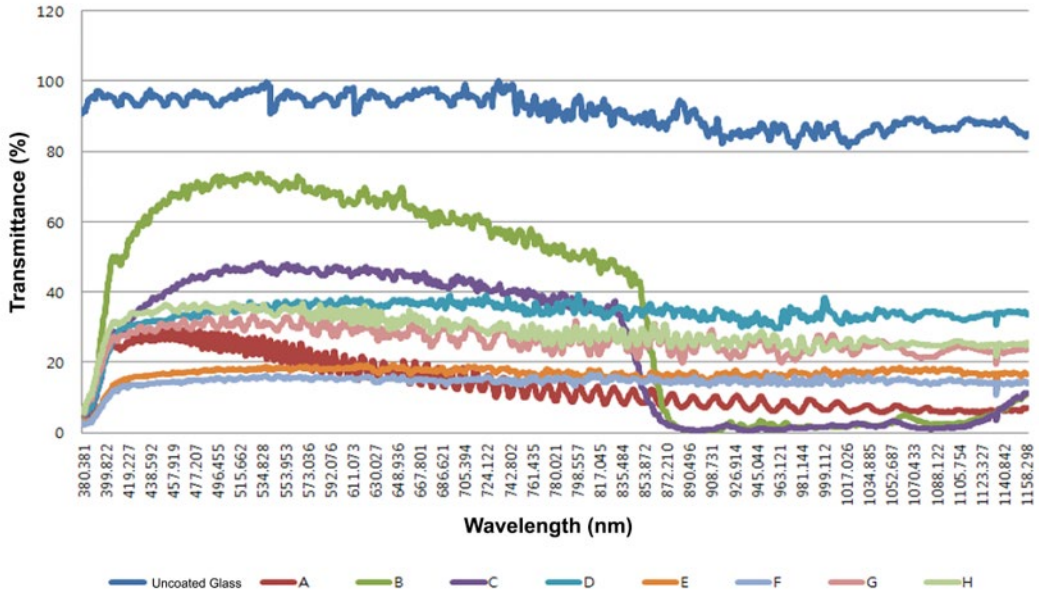


Figure 2. Transmittance by Type of Window Film for Solar Control

Products B and C emerged as the most effective in balancing daylighting performance and thermal control. These two films demonstrated a visible light transmittance (VLT) reduction of approximately 37% compared to the uncoated glass benchmark, maintaining high transparency. However, they significantly reduced infrared transmittance—approximately 85%—thereby minimizing the inflow of long-wave radiation responsible for internal heat gain. This selective spectral filtering allows buildings to reduce cooling loads while preserving natural lighting and external views, essential for occupant comfort and visual ergonomics, especially in educational or office settings where daylight quality influences productivity and well-being.

In contrast, other tested film types, particularly Products E, F, and H, exhibited higher infrared rejection, reaching IR transmittance reductions of over 90%, but at the cost of substantially reduced visible light transmission, falling below 25% in some cases. While this may enhance solar heat control, it also diminishes daylight penetration and creates a potential dependency on artificial lighting systems. In Saudi Arabia, where solar radiation is intense year-round, excessive suppression of natural light can lead to increased internal lighting energy demand and may cause psychological discomfort due to inadequate indoor brightness.

The data underscores the importance of selecting SCWFs based on project-specific priorities. In residential and institutional buildings requiring thermal comfort and visual transparency, such as schools, healthcare facilities, and high-rise housing, products with moderate VLT and high IR rejection (like B and C) are preferable. Furthermore, the ability of these films to maintain outward visibility during daytime hours is an added benefit in high-density urban environments like Riyadh, Jeddah, or Dammam, where privacy and external view retention are valued.

Ultimately, the comparative analysis reveals that the energy-saving potential of solar control window films cannot be assessed solely based on IR rejection. The interplay between visible transmittance, thermal absorptance, and user comfort must be considered holistically in Saudi Arabia’s hot-arid context. These findings guide film selection criteria in future building retrofit policies and green building certification frameworks, such as those aligned with the Saudi Green Building Code and the SEEC's national retrofit initiatives.

4.2. Reflectance by Type of Window Film for Solar Control

To assess the angular reflectance characteristics of solar control window films (SCWFs), the spectral reflectivity of each film was measured across multiple angles of solar incidence (0°, 30°, 45°, and 60°), with particular focus on the visible and near-infrared (NIR) regions. This analysis is critical for buildings in Saudi Arabia, where intense solar radiation occurs throughout the day and from varying solar angles due to extended daylight hours. The results are presented in Table 2 and visually compared in Figure 3.

Table 2. Angular Reflectance (%) by Film Type and Wavelength Range (Measured at 550 nm for visible and 1500 nm for near-infrared; glass: 6 mm float with SCWF applied)

Film Type	0° Incidence	30° Incidence	45° Incidence	60° Incidence	Notes
	VIS/NIR	VIS/NIR	VIS/NIR	VIS/NIR	
Uncoated Glass	8.5 / 7.2	10.3 / 9.1	12.7 / 11.4	16.9 / 15.5	Baseline reference
Product A	13.4 / 17.2	16.8 / 20.3	21.1 / 24.7	28.3 / 31.6	Moderate IR reflection
Product B	11.1 / 13.9	14.3 / 17.4	18.5 / 21.5	24.7 / 27.9	Balanced reflectance
Product C	10.9 / 14.1	14.0 / 17.6	18.3 / 22.1	24.2 / 28.5	Low-glare performance
Product D	16.7 / 20.4	21.2 / 25.1	26.9 / 30.8	34.5 / 38.7	High solar rejection
Product E	19.3 / 26.8	24.8 / 31.4	31.0 / 37.2	38.9 / 44.3	Mirrored, high reflectance
Product F	20.1 / 28.6	26.4 / 33.9	32.7 / 39.5	40.8 / 46.2	Strong thermal barrier
Product G	14.7 / 18.5	18.9 / 22.7	23.6 / 27.1	30.4 / 34.9	Moderate reflective behavior
Product H	22.5 / 30.3	28.6 / 36.4	35.4 / 42.8	43.9 / 50.6	Maximum solar reflection

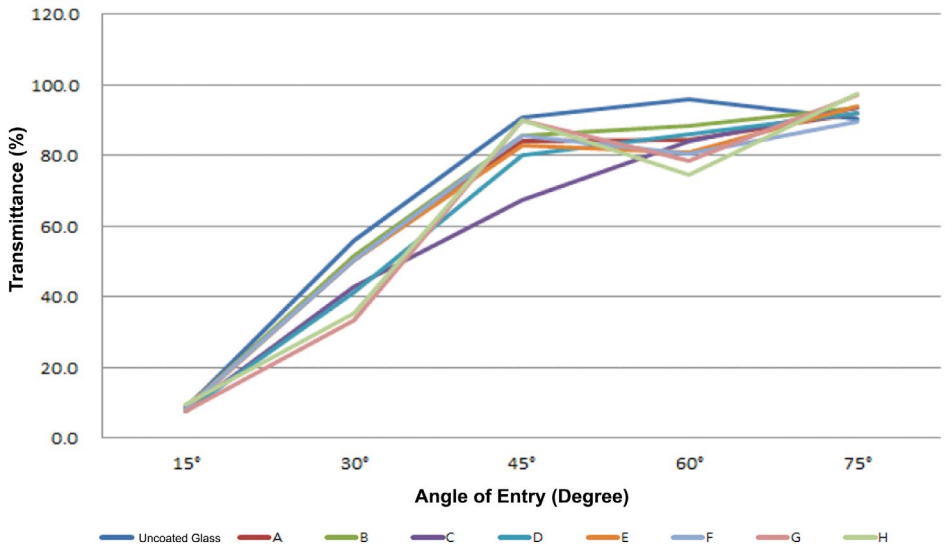


Figure 3. Reflectance vs. Incident Angle by Type of Window Film for Solar Control

As expected from principles of optical physics, the reflectance of all SCWF types increased progressively with the angle of incidence across all wavelengths. This trend is attributed to the Fresnel effect, where reflectivity at the air–film interface rises sharply at oblique angles. At normal incidence (0°), most films demonstrated relatively low reflectance in the visible range to preserve outward transparency and daylighting. However, as the angle approached 60°, visible and NIR reflectance increased, with the most reflective products (such as Products E, F, and H) showing values exceeding 35% in the NIR spectrum.

Differences in reflectance behavior were also observed across the various film types due to differences in coating composition, surface finish, and base material. Products B and C, which previously showed optimal transmittance balance, maintained moderate reflectance across all angles, making them suitable for urban Saudi settings where external visual privacy, glare control, and façade aesthetics are considerations. In contrast, films with metallic or mirrored coatings (e.g.,

Product H) exhibited higher reflectance levels, which, while beneficial for thermal performance, could introduce glare issues on building exteriors and contribute to urban light pollution, an important factor in high-density districts such as Riyadh and Jeddah.

These findings suggest that angular reflectance should be a key consideration when selecting SCWFs for buildings in Saudi Arabia. High reflectivity at steep angles may increase glare for adjacent buildings or public areas, potentially impacting visual comfort in the surrounding urban context. Thus, the optical behavior of films under varied solar incidence must be evaluated alongside their energy performance to ensure holistic sustainability and urban integration.

5. Discussion

The findings of this study demonstrate that solar control window films (SCWFs) exhibit varied optical performances that directly impact their suitability for building retrofits in Saudi Arabia. Products B and C showed the most balanced performance among the eight tested films, combining effective infrared rejection (approximately 85%) with moderate visible light transmittance (around 55%). This dual capability is critical for reducing cooling loads, particularly in a climate where air-conditioning accounts for nearly 70% of household energy use, without compromising daylight access or visual comfort.

Reflectance analysis also revealed that angular reflectivity increases with the solar incidence angle, with mirrored films such as Products E, F, and H exhibiting high reflectivity at steep angles. While beneficial for heat rejection, excessive reflectance may cause glare and light pollution in dense urban areas. In contrast, Products B and C maintained moderate reflectance across all angles, making them more compatible with the aesthetic and environmental requirements of Saudi cities like Riyadh and Jeddah.

These results confirm that optimal SCWF selection must consider thermal performance and visual impact. Integrating high-performance films into national retrofit initiatives and green building policies can support Saudi Arabia's Vision 2030 sustainability goals.

6. Conclusion

This study has empirically evaluated the optical performance of eight commercially available solar control window films (SCWFs) to determine their suitability for retrofitting building façades in Saudi Arabia's hot-arid climate. The research identified key performance variations across film types through spectral analysis of transmittance and reflectance. Products B and C emerged as optimal solutions, offering substantial infrared rejection (~85%) while preserving moderate visible light transmittance (~55%). These films effectively minimized solar heat gain without compromising natural lighting or visual comfort.

Angular reflectance data further revealed that mirrored films, though thermally efficient, could introduce visual glare and urban light pollution at high angles of solar incidence. This highlights the need to balance energy savings with visual and urban integration concerns when selecting retrofit solutions. As Saudi Arabia intensifies efforts to enhance building energy efficiency under Vision 2030, SCWFs present a practical, scalable, and low-disruption intervention for improving envelope performance in existing and new developments.

The findings support the inclusion of SCWFs in national retrofit programs and building code recommendations, particularly within initiatives led by the Saudi Energy Efficiency Center and under the Green Saudi Initiative. Future work should integrate these optical parameters into dynamic simulation models to quantify whole-building energy impacts across various typologies and orientations in the Saudi context.

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Environmental Performance of *rawashin* in the Traditional Hijazi Houses of Historic Jeddah: A Comparative Simulation Study of Beit Al-Sharbatly and Beit Baeshen

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Keywords: *Rawashin*, *Rawashin*, *Mashrabiyya*, Hijazi Architecture, Historic Jeddah, Building Performance Simulation, Thermal Comfort, Daylighting, Natural Ventilation, Passive Cooling, Vernacular Architecture, Saudi Arabia

Abstract. Traditional architecture in hot-arid regions embodies generations of passive environmental design knowledge. In Historic Jeddah, a UNESCO World Heritage Site, wooden lattice screens known as *rawashin* are a defining feature of Hijazi architecture. This study investigates the environmental performance of *rawashin* in two traditional houses, Beit Al-Sharbatly and Beit Baeshen, using building performance simulation tools. The analysis examined four parameters: thermal comfort (operative temperature, Predicted Mean Vote PMV and Predicted Percentage of Dissatisfied PPD); solar heat gains through windows; daylighting (Daylight Factor and illuminance distribution); and natural ventilation (air changes per hour ACH and airflow velocity). Both buildings were compared with and without *rawashin*. It was shown that *rawashin* positively affect building performance with respect to each of the selected parameters. In particular, *rawashin* contribute to the decrease of solar gains from 25% up to 71%, as well as lowering indoor operative temperature by approximately 1.1°C in extreme summer conditions, decreasing PMV and PPD scores by 0.53 and 4.9% correspondingly; however, the environment in the building remains uncomfortable. Also, *rawashin* reduced the maximum Daylight Factor from 24% - 27% down to 10% - 22%; thus, more uniform daylighting and glare avoidance are achieved, while deep spaces experience insignificant effect. *Rawashin* do not limit air flow (ACH=1.5-2.85). The findings obtained are relevant for both studied buildings despite their different designs.

Introduction

Concerns about sustainable development and climate change have brought vernacular architecture into prominence again. Traditional building techniques, evolved over the years, provide solutions in design for thermal comfort and energy conservation in line with local climates [1, 2]. Hot and dry conditions along the Red Sea coast feature numerous traditional buildings characterized by an abundance of passive cooling systems compared to modern buildings with air conditioning facilities [3]. Historic Jeddah (Al-Balad), inscribed as a UNESCO World Heritage site in 2014, constitutes a classic example of an historic town in a coastal hot climate [4]. Architectural identity of this region reflects itself in multi-storey houses made of coral stone and ornamental wooden balconies and window grills known as *rawashin* (plural) or rawshan (singular) [5]. These architectural elements represent an integral part of an environmental control system in addition to providing protection and ventilation [6]. Rawshan can be defined as a special kind of Mashrabiyya, a typical component in Islamic architecture. It comprises an orielt window enclosed in a wooden

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lattice [7, 8]. Among other examples of Mashrabiyya, Jeddah's *rawashin* exhibit uniqueness owing to their size, craftsmanship and ability to cope with adverse climatic conditions (**Fig. 1**). Besides offering visual appeal and privacy, the *rawashin* help protect the house by providing a layer of shading and admitting diffuse light inside the building [9]. There are few quantified studies on the environmental performance of the *rawashin* despite their significance to the historic buildings in Jeddah. Most of the existing research on Mashrabiyya focuses on different climates zones and generic designs and pays little attention to specific characteristics of Hijazi architecture or traditional architecture of Jeddah [10-12]. The current research attempts to fill this gap by presenting a comparative study of the environmental impacts of two authentic traditional houses in Historic Jeddah on the basis of simulation experiments. Although there is ample literature on Mashrabiyya designed under generic assumptions or adapted to other climates different from those of Jeddah, this research will provide a new outlook on the issue in terms of multi-performance comparative analysis in the authentic Hijazi architecture of Jeddah. The objectives of this study are: (1) to quantify the environmental performance of *rawashin* in two traditional Hijazi houses through building performance simulation; (2) to compare the performance of *rawashin* across two buildings with different architectural characteristics; (3) to assess the effectiveness of *rawashin* in improving thermal comfort, reducing solar heat gains, enhancing daylighting, and maintaining natural ventilation; and (4) to provide evidence-based recommendations for the conservation and adaptive reuse of traditional houses in Historic Jeddah.

Literature Review

Vernacular Architecture and Lessons in Sustainability:

Various studies have shown the higher adaptability of traditional houses compared to modern houses. A study in Nepal conducted by Bodach, Lang [11] explained the use of bioclimatic design concepts in traditional houses, while a study conducted in the Asir Region of Saudi Arabia showed that the traditional houses constructed of mud were capable of maintaining the indoors at a comfortable level in all seasons compared to modern houses [11, 13-15]. Historic Jeddah (Al-Balad) is an example of vernacular architecture skillfully designed to function effectively in hot-arid coastal regions [4, 5]. The architecture of Al-Balad is marked by multi-story “tower houses,” with architectural features including coral limestone (Al-Mangabi), which has high thermal mass, stabilizing changes in indoor climate and protecting from outdoor temperature fluctuations [16, 17]. The study on a traditional Jeddah house, Beit Baeshen, showed that its thick walls constructed of coral stones effectively created a strong thermal mass up to five-hour lag effect; in summer, however, the time lag was 1. 25 hours due to extreme thermal conditions. [1]. Further studies were conducted on the passive design principles of Saudi traditional buildings, such as thermal mass and shading, and their impact on energy performance and cooling [18].

The Rawashin - A Multifunctional Climate-Adaptive Device:

A great deal of research literature exists concerning simulation analysis to evaluate the efficiency of latticework screens in the Islamic world. In Egypt, Elwan [19] used CFD simulations to show that *Mashrabiyya* geometry greatly impacts pressure differential forces for intensified single-sided ventilation with maximum velocities of up to 3.5 m/s. In Algeria, research on kinetic *Mashrabiyya* by Ben Bacha and Bourbia [20] showed that adaptive shading brought a potential decrease of 43% in building energy use and up to a 4.8°C drop in indoor temperature. The *Mashrabiyya* design includes other forms of latticework screens like *jaali* screens in regions like India. Rehman and Surapaneni [21] showed how *jaali* screens are optimized for a well-lit and thermally pleasant environment with no glare inside spaces by optimizing solid/void ratios and depth of screens. In the case of Saudi Arabia and the Hijaz region, simulation studies have verified these advantages specifically in the case of *rawashin*. Taki and Kumari [22] illustrated their effectiveness in reducing peak solar gains by 77.8%, and operative temperature by 14%. In the study conducted by

Bagasi, Calautit [9] in Jeddah, simulation and field measurements revealed the important cooling potential of *rawashin* in decreasing indoor temperatures up to 2.4°C and its crucial role in the natural ventilation. Related experimental work has also shown the potential of integrating *Mashrabiyya* with passive and evaporative cooling techniques in hot climates [23]. Moreover, Alelwani, Ahmad [3] utilized genetic algorithms to optimize the design of *rawashin* and demonstrated up to 16.6% reduction of energy consumption without reducing daylight adequacy.

Building Performance Evaluation Through the Use of a Simulation Approach:
Despite the well-known benefits of *rawashin* described above, their quantitative assessment is crucial for today's application. Building Performance Simulation offers a reliable toolset for this purpose. DesignBuilder is a program that connects to EnergyPlus, used to simulate energy consumption, thermal loads, comfort levels, convective and radiative heat transfers, solar shading, conduction in massive facades, and air flow dynamics [24]. Thermal comfort is quantified using widely accepted criteria of Predicted Mean Vote and Predicted Percentage Dissatisfied, as part of ASHRAE 55 and ISO 7730 standards [25, 26]. Van Hoof [27] conducted a thorough review of the PMV theory and emphasized its wide adaptability to various climatic zones. Further evidence of the applicability of PMV for evaluating warm zones without air conditioning systems was presented in Fanger and Toftum [28]. Cheung, Schiavon [29] investigated reliability of PMV-PPD model in predicting thermal comfort levels, using ASHRAE Global Thermal Comfort Database II. As for air flow and ventilation efficiency evaluation, Computational Fluid Dynamics simulations can be employed alongside building energy modeling, to analyze air flow dynamics and assess performance of ventilation systems with great spatial accuracy. Ramponi and Blocken [30] established key requirements for CFD analyses of cross-ventilation systems and experimentally validated relevant simulation parameters. Moreover, Van Hooff, Blocken [31] made a comparison of cross-ventilation using RANS and LES numerical approaches and proposed a thorough methodology.

Methodology
In the current study, the quantitative comparison technique involving Building Performance Simulation is employed to evaluate the environmental effectiveness of *rawashin* in the context of Hijazi architecture. Two representative dwellings located in Jeddah are modeled using Autodesk Revit software, followed by BPS using DesignBuilder V7 (with EnergyPlus being a simulation engine). All simulations were performed under identical environmental conditions, where focus was placed on four major parameters: (1) thermal comfort measured by operative temperature, PMV, and PPD; (2) solar heat gains through fenestrations; (3) daylighting performance estimated by Daylight Factor and illuminance distribution; and (4) natural ventilation evaluated in terms of ACH and air flow velocity distribution. Two main scenarios were selected in order to isolate the effect of the *rawashin*: 1. A base case without *rawashin*, where simple glazed windows with no shading devices replaced the wooden *rawashin*; and 2. The actual case with *rawashin*, where the entire *rawashin* are incorporated in the model as external shades in front of the window opening. Comparing the results of these two scenarios enabled direct quantification of the contribution and consistency of the *rawashin* to building performance on all four key indicators. The research framework is shown in **Fig. 2**.

Climate of Jeddah:
Jeddah is located at 21.5°N, 39.2° E along the Red Sea coast in Saudi Arabia and has a hot-arid desert climate (BWh, Köppen classification), with very hot summers and warm winters (**Fig. 3 [**32-34**]**). The summer months are marked by high temperatures, often above 38-40 °C, and humidity levels above 50%, which remain high throughout the year because of its close proximity to the Red Sea. It is important to mention that the Koppen classification only considers the

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precipitation not the relative humidity. The solar radiation is high throughout the year, increasing the heat gain through glazing; winds are moderate, mainly from the N-NW direction. The climatic information required for this analysis was obtained from the EnergyPlus Weather (EPW) file for Jeddah.



***Fig. 1**. Traditional Houses in Historic Jeddah (Al-Balad district) featuring Rawashin. (The author)*

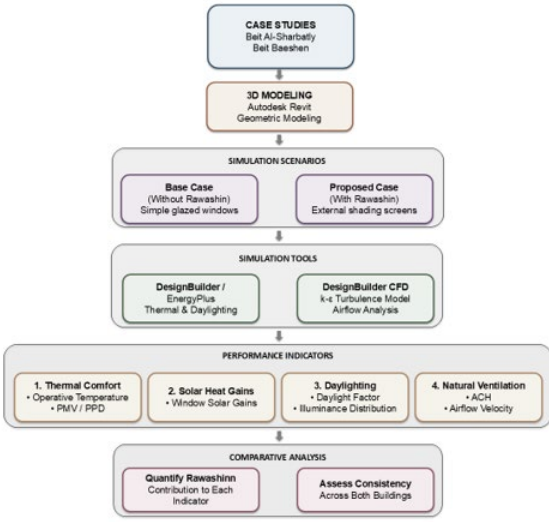


***Fig. 2**. Research Framework*

Case Study Selection:

Two well-known traditional houses in Historic Jeddah (Al-Balad district) were selected as case studies (**Fig. 4)** : Beit Al-Sharbatly, a large residential building known for its size, high status and elaborate *rawashin* decoration; and Beit Baeshen, a well-conserved Hijazi tower house, previously studied in academic literature, and thus provides a basis for evaluating its thermal performance [1]. While they share common Hijazi architectural features (coral stone, tower design), the two houses have some differences in architectural features and dimensions. These variations help in carrying out a more comprehensive analysis of the benefits of *rawashin* across several configurations.

Modeling and Simulation Tools:

Three-dimensional models of both houses were developed in Autodesk Revit based on architectural drawings and field measurements (**Fig. 4**). They were then imported to Design Builder V7 (EnergyPlus simulation engine), using GBxml Revit file export, to model the *rawashin*, assign materials and assess the environmental parameters. Airflow simulation was performed in DesignBuilder using the CFD analysis. Important modeling parameters are illustrated in **Table 1**. The walls are 70-80 cm thick coral stone (Al-Mangabi limestone). The *rawashin* were simplified but preserved the similar porosity based upon their lattice pattern.

Table 1. Building Modeling Parameters

Parameter	**Beit Al-Sharbatly**	**Beit Baeshen**
Total Floor Area (m²)	850	620
Number of Floors	4	5
External Wall Thickness (cm)	70	70
Internal Wall Thickness (cm)	70	70
Wall Material	Coral Stone (Al-Mangabi)	Coral Stone (Al-Mangabi)
Roof Construction	Timber joists with wooden planks	Timber joists with wooden planks
Finishing	Lime plaster	Lime plaster

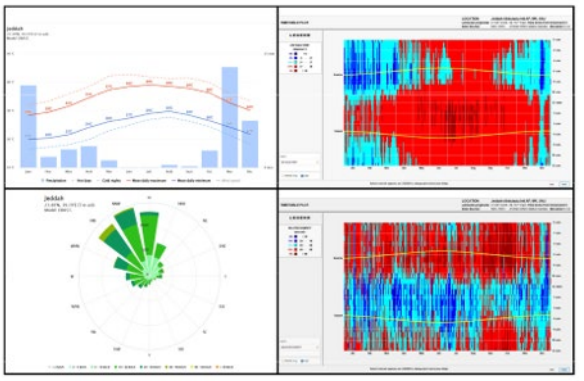


Fig. 3. Climate of Jeddah (Saudi Arabia). Monthly temperature and precipitation, hourly dry-bulb temperature timetable plot, wind rose, and hourly relative humidity timetable plot.

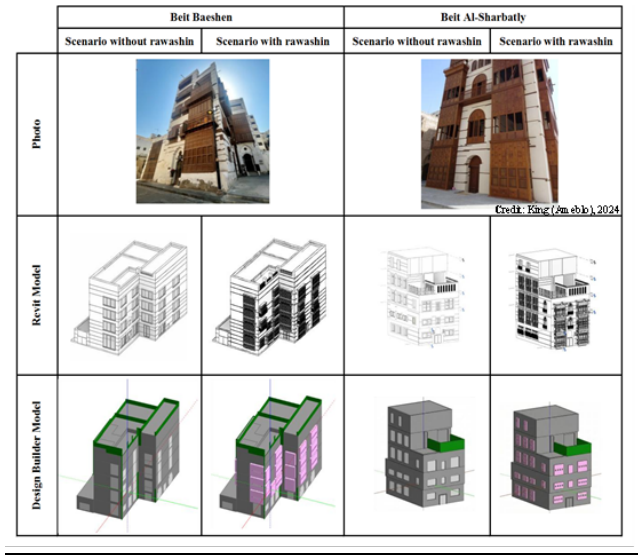


Fig. 4. Photographs, Revit models, and DesignBuilder simulation models of Beit Baeshen and Beit Al-Sharbatly, without and with Rawashin. (Authors)

Performance Parameters:

Thermal Comfort:

Thermal comfort was assessed using the operative temperature, PMV and PPD, as standardized in ISO 7730 and ASHRAE 55 [25, 26]. Operative temperature (T_o) considers air temperature and mean radiant temperature:

$$T_o = (h_r \times T_r + hc \times T_a) / (h_r + hc) \quad \text{Equation (1)}$$

For typical indoor conditions with low air velocities, this simplifies to:

$$T_o \approx (T_a + T_r) / 2 \quad \text{Equation (2)}$$

The PMV index predicts the mean thermal sensation vote of a large group of people on a 7-point scale ranging from -3 (cold) to +3 (hot), with 0 representing thermal neutrality. The acceptable range is between -1 and +1. It is calculated based on the heat balance of the human body [28]:

$$PMV = [0.303 \times e^{(-0.036 \times M)} + 0.028] \times L \quad \text{Equation (3)}$$

Where M = Metabolic rate (W/m²), L = Thermal load on the body (W/m²) as a function of six variables: air temperature (T_a), mean radiant temperature (T_r), relative air velocity (v), relative humidity (RH), metabolic rate (M), and clothing insulation (Icl). The PPD index predicts the percentage of occupants who would be thermally dissatisfied. It is associated with the PMV and the minimum PPD value is 5%, occurring at PMV = 0.

$$PPD = 100 - 95 \times e^{[-(0.03353 \times PMV^4 + 0.2179 \times PMV^2)]} \quad \text{Equation (4)}$$

Solar Heat Gains:

Solar heat gain through windows ($Qsol$) is calculated using [24]:

$$Qsol = Aw \times SHGC \times It \quad \text{Equation (5)}$$

Where *Aw* = Window area (m²), *SHGC* = Solar Heat Gain Coefficient of the glazing system (dimensionless), *It* = Total incident solar radiation on the window surface (W/m²)

Daylighting: Daylight Factor:
The Daylight Factor (DF) is a ratio that expresses the amount of daylight available inside a building relative to the unobstructed external illuminance [3]:

$$DF = (Ein / Eout) \times 100\% \quad \text{Equation (6)}$$

Where *Ein* = Internal illuminance at a point on the work plane (lux), *Eout* = Unobstructed external horizontal illuminance under overcast sky conditions (lux)

Natural Ventilation Performance:
Natural ventilation effectiveness was assessed using Air Change per Hour (ACH) and airflow velocities and distribution obtained through CFD simulation. ACH measures how many times the entire air volume in a space is replaced with fresh air per hour [30, 31, 35]:

$$ACH = Q / V \quad \text{Equation (7)}$$

Where Q = Airflow rate (m³/h), V = Room volume (m³) The CFD simulations employed the standard k-epsilon (k-ε) turbulence model for indoor airflow analysis, which is a widely used RANS model [30, 36]. The model is based on two transport variables: the turbulence kinetic energy (k), and its dissipation rate (ϵ).

$$k = (3/2) \times (U \times I)^2 \quad \text{Equation (8)}$$

$$\varepsilon = (C\mu^{0.75} \times k^{1.5}) / L \quad \text{Equation (9)}$$

$$\nu_t = C\mu \times k^2 / \varepsilon \quad \text{Equation (10)}$$

Where k = turbulence kinetic energy (m²s⁻²), ε = turbulence dissipation rate (m²s⁻³), I = turbulence intensity (%), U = mean flow speed (ms⁻¹), $C\mu$ = model coefficient for turbulent viscosity, equal to 0.09, L = reference length scale (m), ν_t = turbulent viscosity (m²s⁻¹)

Simulation Settings:
The parameters were standardized across the two case studies to maintain a comprehensive comparison. For the hourly climatic data, the research utilized the Jeddah (King Abdulaziz International Airport) EPW weather file. The simulation period was during the peak summer design week from August 1st to August 7th.The analysis was carried out without the HVAC system being enabled (cooling, heating and DHW were turned off) to test the passive performance of the building envelope and the *rawashin.* Standard template of residential schedules for occupancy, lighting, and equipment was applied to the models. Natural ventilation was enabled, with windows assumed to be operable. The simulation outputs were configured to generate daily and period reports for key performance indicators, and the CFD simulation was set to the standard k-ε turbulence model. The CFD simulation settings are illustrated in **Table 2**; it was run until the primary residuals reached convergence (< 10^{-4}), as shown in **Fig. 5**.

Table 2. CFD Simulation Parameters

Parameter	Value
Turbulence Model	Standard k-ε
Grid Resolution	0.1 m (fine mesh near openings)
Discretization Scheme	1-Upwind
Maximum Number of Iterations	4000
Relaxation Factor	1.000
Convergence Criteria	$1.0 \times 10^{-}4$
Boundary Conditions - Inlet	Velocity inlet (from EPW wind data)
Boundary Conditions - Outlet	Pressure outlet
Wall Treatment	Standard wall functions

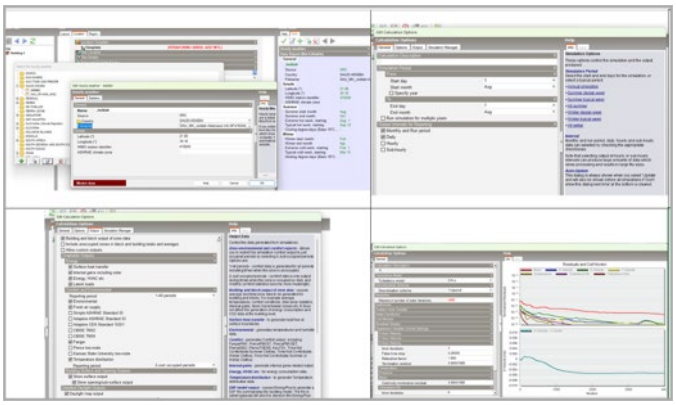


Fig. 5*. Simulation setup, calculation options, simulation outputs and CFD settings in Design Builder for Jeddah.*

Results

Beit Al-Sharbatly:

Thermal Comfort:

As shown in **Table 3** and illustrated in **Fig. 6**, *rawashin* improved the thermal comfort conditions during the peak summer week. The mean operative temperature was lowered by 1.08°C. As a result, the PMV index decreased from +3.35 (hot) to +2.82 (warm). The PPD decreased by around 5%, from 99.50% to 94.63%. Although *rawashin* reduced the thermal discomfort, PMV did not reach the acceptable comfort range (between -1 and +1) under peak summer conditions in Jeddah. This usually requires the use of additional strategies, like mechanical cooling, and improved airtightness of the building envelope.

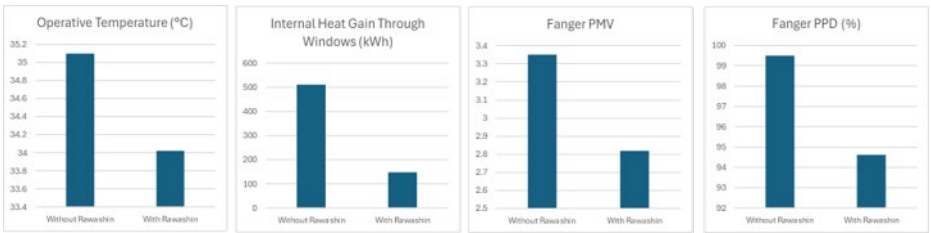


Fig. 6. *Beit Al-Sharbatly Results of Thermal Comfort and Heat Gain Through Windows.*

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Table 3. Beit Al-Sharbatly Results of Thermal Comfort and Heat Gain Through Windows

Parameter	Without *Rawashin*	With *Rawashin*	Reduction	Change (%)
Operative Temperature (°C)	35.10	34.02	1.08 °C	-3.08%
Total Fresh Air ACH (ach/h)	2.13	1.45	0.68 ach/h	-31.92%
Fanger PMV (-)	3.35	2.82	0.53	-15.82%
Fanger PPD (%)	99.50	94.63	4.87 %	-4.89%
Internal Heat Gain Through Windows (kWh)	510.35	147.21	363.14 kWh	-71.16%

Solar Heat Gain Through Windows:
A major thermal benefit of the *rawashin* was its efficiency in blocking solar heat gain through windows (**Table 3**, **Fig. 6**). The simulation results indicated a considerable reduction by around 71%, from 510.35 kWh to 147.21 kWh.

Daylighting Performance:
The *rawashin* provided effective control over daylight and glare (**Table 4**). The average Daylight Factor (DF), illustrated in **Figure 7**, was reduced from 3.24% to 1.15%. Notably, the maximum DF decreased from 27.5% to 22.0%. The percentage of floor area exceeding the daylight threshold was reduced from 38.1% to 31.9% only. The results show that even with lower illumination, the *rawashin* provide more uniform levels and controls strong sun near the windows.

Table 4. Daylighting Performance for Beit Al-Sharbatly

Parameter	Without *rawashin*	With *rawashin*	Change
Average Daylight Factor (%)	3.24	1.15	-2.09%
Maximum Daylight Factor (%)	27.51	21.99	-5.52%
Floor Area above DF Threshold (2%)	38.09	31.93	-6.16%

Natural Ventilation Performance:
CFD results (**Fig. 8**) showed that the *rawashin* enhanced the efficiency of natural ventilation. In the reference case, the airflow was ununiform while in the case with the *rawashin*, the airflow became more uniform and continuous. The lattice holes functioned as jets and helped to guide and intensify airflow, pushing them further inside the interior. Although the Air Changes per Hour (ACH) had reduced from 2.13 to 1.5 (**Fig. 8**), they remained in the residential ACH levels (0.35) according to ASHRAE [35].

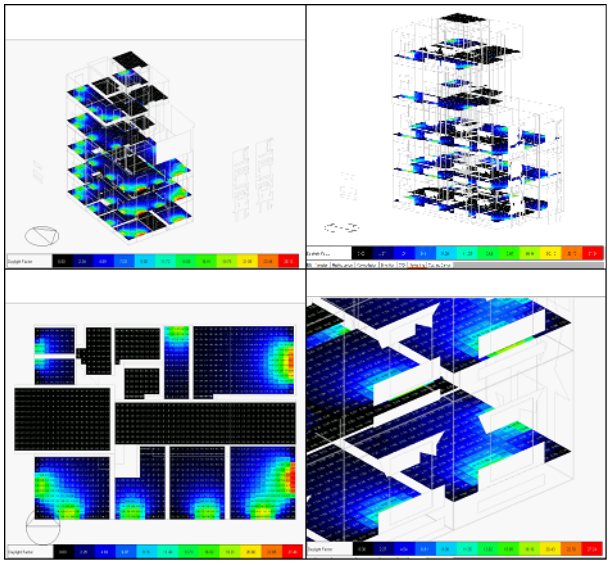


Fig. 7. The average Daylight Factor (DF) in Beit Al-Sharbatly without Rawashin (left) and with Rawashin (right).

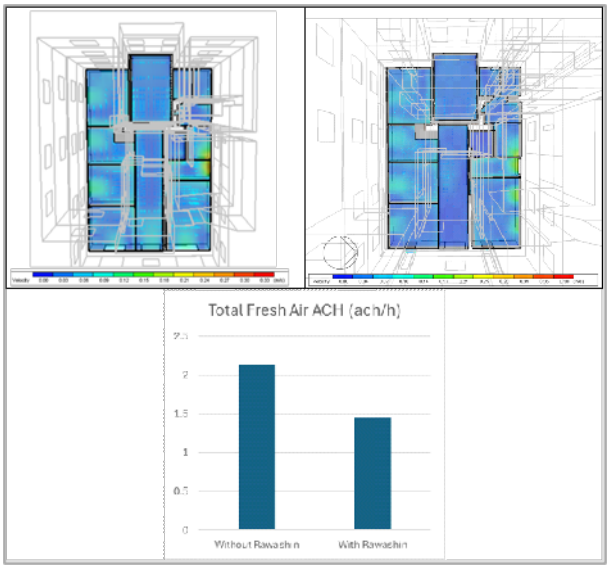


Fig. 8. The CFD results in Beit Al-Sharbatly without Rawashin (upper left), with Rawashin (upper right), and the ACH results (below).

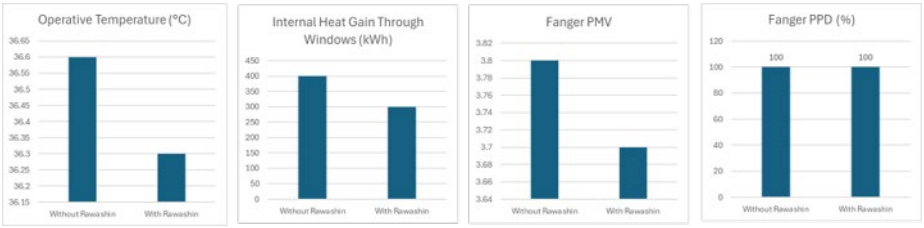


Fig. 9. Beit Baeshen Results of Thermal Comfort and Heat Gain Through Windows.

Beit Baeshen:

Thermal Comfort:

Similar to Beit Al-Sharbatly, the *rawashin* in Beit Baeshen resulted in a slight but important improvement in the thermal comfort level (**Table 5, Fig. 9**). The operative temperature was reduced by 0.8°C. PMV was improved from a range of +3.8 / +4.1 to +3.3 / +3.9. The PPD remained close to 100% and the space remained uncomfortable under summer peak conditions.

Table 5. Beit Baeshen Results of Thermal Comfort and Heat Gain Through Windows

Parameter	**Without *Rawashin***	**With *Rawashin***	**Reduction**	**Change (%)**
Operative Temperature (°C)	36.85	36.05	0.8 °C	-2.17%
Total Fresh Air ACH (ach/h)	3.00	2.85	0.15 ach/h	-5.00%
Fanger PMV (-)	3.8	3.7	0.1	-2.63%
Fanger PPD (%)	100	100	0 %	0.00%
Internal Heat Gain Through Windows (kWh)	400	300	100 kWh	-25.00%

Solar Heat Gain:

The results showed a 25% reduction in the mean daily values of solar gains through the windows from 400 kWh (without *rawashin*) to about 300 kWh (with *rawashin*) (**Table 5**, **Fig. 9**).

Daylighting:

Similar to Beit Al-Sharbatly, the *rawashin* in Beit Baeshen provided good glare control and enhanced daylight uniformity (**Table 6, Fig. 10**). The maximum DF decreased from 24.3% to

10.6% and its average was reduced from 1.84% to 0.36%. However, the percentage of floor area exceeding the daylight threshold was reduced from 45.23% to 41.7% only. Although light penetration in deeper areas was similar, (below 2% DF), *rawashin* created a balanced lighting, which is consistent with the performance of traditional Indian *jaalis* [21].

Table 6. Daylighting Performance for Beit Baeshen

Parameter	Without *rawashin*	With *rawashin*	Change
Average Daylight Factor (%)	1.84	0.36	−2.2%
Maximum Daylight Factor (%)	24.27	10.62	−13.65%
Floor Area above DF Threshold (2%)	45.23	41.70	−3.53%

Natural Ventilation Performance:

The rate of air change per hour was relatively unaffected; it was reduced from 3 to 2.85 and remained in the residential ACH levels air changes per hour (**Fig. 11**). At the same time, the airflow patterns have improved, and the air velocity was better distributed, leading to concentrated air jets entering the rooms (**Fig. 11**). The base case witnessed high velocities near the windows with very low velocities in deeper parts. In the scenario with *rawashin*, the peak air velocities decreased from 1.2 m/s to 0.6-0.8 m/s, while air distribution uniformity did not change. This result corresponds with the findings of the Egyptian *mashrabiyya*, where the lattice helped creating more effective ventilation within the space [19].

Discussion

Interpretation of Key Findings:

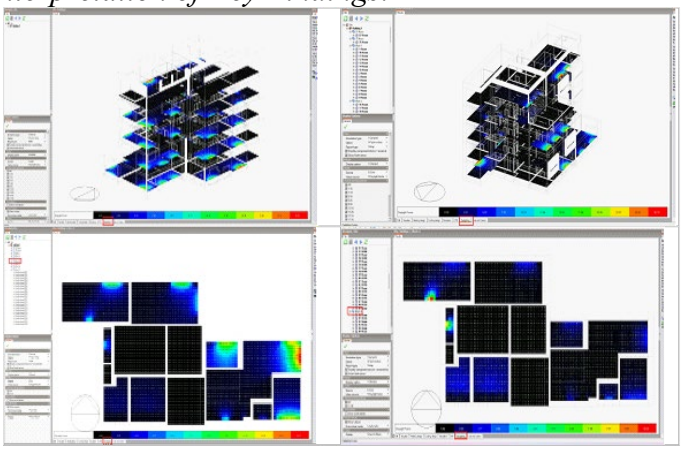


Fig. 10. The average Daylight Factor (DF) in Beit Baeshen without Rawashin (left) and with Rawashin (right).

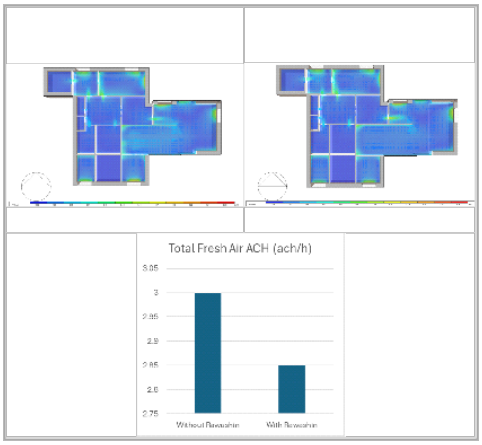


Fig. 11. The CFD results in Beit Baeshen without Rawashin (upper left), with Rawashin (upper right), and the ACH results (below).

According to the results, *rawashin* lower indoor operative temperatures by about 0.8°C to 1.1°C. Yet, this remains insufficient to ensure full thermal comfort in peak summer conditions (design week), as PMV values remain > +2.8, aligning with other studies on traditional buildings in hot climates that often recommend additional cooling systems such as mechanical ventilation [11, 13]. The improvement in PMV and PPD can reduce mechanical cooling loads; however, despite significant reductions in solar gains through windows, shading alone in hot-arid climates remains insufficient to achieve comfort under high ambient temperatures and humidity. Therefore, instead of ensuring maximum comfort from temperature aspects alone, the primary purpose of *rawashin* is to lessen the negative impact of the sun's radiation, which makes it more comfortable to be indoors than outdoors. The reduction in solar heat gain varied from 25 to 71%, which agrees

with previous computer simulations of traditional lattices. These findings correlate with those made by Taki and Kumari [22], who concluded that the use of mashrabiyya and *rawashin* could reduce cooling load in building envelopes. Nevertheless, the results point to an obvious tradeoff between daylight availability and the prevention of glare. *Rawashin*s were shown to reduce peak DF from 24 to 27% to 10 to 22 while mitigating glare close to windows. Likewise, it was found that jaalis – perforated screens – in India contribute to increased daylighting without significant darkening of the deep spaces [21]. Therefore, *rawashin* can also serve as a daylight filter. In contrast to one's expectations, CFD analysis showed that *rawashin* promote better efficiency of ventilation. Data on natural ventilation proves that *rawashin*s do not interfere with airflow distribution, which is vital for the quality of ventilation and evaporative cooling. Values of Air Changes per Hour (ACH) of 1.5 to 2.85 are within the recommendations set by ASHRAE Standard 62.1 [35] for naturally ventilated buildings. Thus, *rawashin*s do not hinder the flow of ventilation, unlike the expected. Besides, *rawashin*s provided a more penetrating and uniform pattern of airflow. It was stated earlier that the modulation of airflow is among functions of such lattice structures. Indeed, previous studies have found out that geometrical features of Egyptian mashrabiyya increase airflow velocity and mixing [3], and the geometry of Persian Badgirs promotes effective airflow through redirection [37]. As such, *rawashin* operate as airflow modulators rather than barriers. Another objective of the research was to determine whether the advantages of *rawashin*s would remain applicable for both houses. The results prove the hypothesis. Despite differences in size, planning, and orientation of houses, the two cases had similar patterns for all four criteria.

Limitations of the Study

One limitation is the fact that the simulations were performed only during a one-week peak summer design period, i.e., August 1–7, representing the case of maximum thermal stress; a yearly study might have been better at capturing a complete picture. Secondly, the CFD analysis was performed separately from the thermal analysis, focusing on airflow alone. Thirdly, the current investigation is dedicated solely to evaluating the performance of the existing *rawashin* and does not consider variations like porosity. Finally, some simplifications were made in terms of the *rawashin* geometry and material parameters, and a digital model is used in place of the actual physical processes. Although very well-tested software is used, it still represents a simplified representation of a highly complicated process.

Implications for Contemporary Design

Passive shading devices such as the *rawashin* may be considered means for enhancing both the thermal and visual performance. Lowering solar gains due to the use of fenestration helps lower the cooling demand, which becomes a necessary step in sustainable design in the Gulf region. In addition, the current research highlights the importance of considering multiple performance aspects. *Rawashin* represent a holistic device that considers issues related to solar radiation, lighting, ventilation, and privacy, thus fulfilling several roles at once. One more conclusion made based on the results obtained is that *rawashin* cannot guarantee comfortable temperatures in extremely hot summer weather, which makes the need for hybrid solutions that use both old and new approaches absolutely necessary. Finally, a consistency in results obtained from both of the investigated houses implies a positive role heritage guidelines can play in Historic Jeddah by recommending keeping or reconstructing the *rawashin*s as a part of the design solution.

Conclusion

In this paper, the environmental performance of *rawashin*, an iconic wooden screen of the traditional Hijazi architecture, has been quantitatively analyzed using simulation software based on a comparison of two historic buildings in Jeddah. From the results, the environmental benefits

of *rawashin* can be inferred. *Rawashin* is a highly effective passive design element whose use improves the performance of indoor environments in four key aspects in hot-arid climates. With regards to thermal comfort, *rawashin* helps decrease the operative temperature inside the house by about 1.1 degrees C, thus providing improved levels of PMV and PPD. Furthermore, it is a highly effective shading device which decreases the amount of solar heat gain by 25-71%. As for day lighting factors, they show that *rawashin* minimizes the issue of glare and bright daylight by reducing the maximum daylight level by 24-27% down to 10-22% and diffusing light, creating more pleasant visual environments. *Rawashin* also serve as airflow conditioners, ensuring even air distribution and proper air change rate (ACH) of 1.5-2.85. However, despite their advanced functions, *rawashin* cannot guarantee thermal comfort in hot summer days since PMV value is more than +2.8. It seems consistent with research on traditional architecture in hot regions that emphasizes the use of mechanical systems alongside *rawashin* [11, 13]. Hence, one can argue that *rawashin* mitigate the negative impacts of direct sunlight, making indoor environments more tolerable, and minimizing the use of AC. In addition, it has been demonstrated in modern practice that sustainable design does not necessarily imply the implementation of innovative ideas, but may involve the use of classical concepts such as shading, filtered light, and ventilation.

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Assessing Regional Identity Strategies in Contemporary Saudi Architecture: A Survey-Based Study of Professional Architects

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Abstract. This study operationalizes regional architectural identity in contemporary Saudi architecture by identifying and ranking the strategies through which architects integrate environmental, cultural, and human-centered determinants into modern design practice. A structured Likert-scale survey was administered to 132 professional Saudi architects across private, governmental, and academic sectors. The instrument translated regional identity into eleven measurable strategy categories derived from literature-based construct mapping. Data were analyzed using descriptive statistics, Relative Importance Index (RII), Pearson correlation, Cronbach's alpha ($\alpha = 0.886$), and inferential tests (ANOVA and t-tests). Results indicate that climatic responsiveness (RII = 0.85) and integration of local cultural values (RII = 0.84) are the highest-ranked determinants, followed by human-centered and user-responsive design strategies. Direct replication of traditional forms and supra-regional references ranked lowest. The study contributes a structured multidimensional model for assessing regional architectural identity, providing decision-support guidance for culturally grounded contemporary architectural practice.

Introduction

Architecture reflects culture by embodying a society's values, history, and traditions in its design and structure . It shapes and is shaped by national, community, and personal identities, serving as a tangible expression of these aspects. This viewpoint serves as both a preventative measure and a source of inspiration for the greatest architects to return to their origins. In traditional Arabian constructed environments, deeply ingrained understandings of cultural practices, basic necessities, and environmental conditions were used by local master builders and decision-makers to design urban fabrics and buildings instead of using precise geometrical correlations [1]. Local architecture and architectural heritage are valuable products with perfectly rational solutions and community satisfaction; they are dependent on one another and carry the local identity with its many distinctive variables, but the central element that unites them is belonging [2]. Human Identity is expressed through both architecture and art. Humanity has consistently demonstrated a commitment to its artistic heritage. Maintaining architectural identity through the US Standards for culture preservation involves clearly differentiating new modern techniques from the original structure and preserving character-defining features. Constructing an identity relies significantly on humans' capacity for reflexive self-awareness, which involves an individual's ability to reflect on and understand their own existence, behaviors, and their relation to their place in any place in world. This self-awareness is a fundamental aspect of identity formation, allowing people to interpret and integrate their experiences, cultural heritage, and personal values into a coherent sense of self. In our case, this reflexive self-awareness translates into the way communities design

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and build their environments to reflect their unique identities, cultural traditions, and social values. The neglect of identity and tradition in regional architecture can have far-reaching consequences on society, the economy, and the environment. Al-Naim [3] observed that a "lack of identity in contemporary architecture in Saudi Arabia" had become apparent by the late 20th century, raising questions about how to preserve continuity amid rapid change. Prioritizing generic designs over contextually sensitive ones can lead to unsustainable buildings and urban spaces that fail to meet the needs of local communities. Moscatelli [4] observes that the unchecked adoption of Western models in Riyadh "accelerated the traditional loss of identity" in architecture, and she argues that new development must integrate local cultural elements to avoid this outcome. This disconnect can result in the loss of cultural heritage and identity, impacting not only the physical appearance but also the social and psychological aspects of the built environment. In Saudi Arabia, preserving and valuing distinct regional architecture has been a significant challenge [5]. Protecting modern heritage buildings is essential for increasing public appreciation and understanding of modernist architecture and preserving valuable cultural resources [6]. However, by incorporating cultural and heritage elements into designs, architects can create spaces that resonate with residents, fostering a sense of belonging and continuity with the past [7]. As Abowardah [8] argues, socio-cultural sustainability achieved by blending traditional design elements with innovation not only reinforces national identity but also enhances community cohesion and well-being in Saudi architecture. This integration can enhance well-being, as environments rich in cultural elements promote positive emotions, social interactions, and a stronger sense of pride and identity. As Sirror [9] shows in the case of Al-Ula Village, vernacular design strategies were inherently sustainable and their preservation today can "strengthen social and cultural identity" while improving environmental comfort Maintaining a country's identity in a globalized world involves showcasing its traditional elements, identity and rich cultural history, both of which are reflected in its architecture [10]. Balancing modernity with the preservation of cultural heritage is essential for Saudi architects to create a built environment that is both modern and reflective of the country's unique identity. Mazzetto and Vanini's [11] findings support this by illustrating how sustainably reusing heritage sites can achieve modern functionality while preserving unique local identity a direct affirmation of the introduction's claim Architectural spaces are influenced by a multitude of factors, including material, environmental, functional, and cultural aspects. The qualities and accessibility of building materials, developments in building science and technology, and financial concerns that affect the viability and sustainability of construction projects are examples of material variables. These factors determine things like ventilation, insulation, and overall harmony with the landscape. Functional aspects integrate biological and technical concerns to improve comfort and usefulness by addressing the behavioral patterns and spatial requirements of the planned activities in the space. Architectural identity and space symbolism are shaped by a variety of variables, many of which are cultural in nature. These include aesthetic preferences, customs, values held by society, and inventions. A society's collective memory, beliefs, and identity are reflected in the functional structure and symbolic representation of architectural design, which are enhanced by historical and cultural settings [12]. Regrettably, a lot of architects have a tendency to ignore socio-cultural factors, placing more importance on new technology, building costs, and aesthetics [1].

Despite extensive theoretical discourse on architectural regionalism and identity, there remains a critical methodological gap in the empirical operationalization of regional architectural identity, particularly within rapidly developing non-Western contexts such as Saudi Arabia. Existing studies often conceptualize identity normatively or philosophically, yet few translate it into measurable indicators that can be systematically evaluated across professional practice. Moreover, limited quantitative evidence exists regarding how architects prioritize competing identity strategies or whether such priorities vary across professional sectors. This study addresses this gap by operationalizing regional architectural identity as a multidimensional construct composed of

eleven measurable strategy categories and empirically evaluating their relative importance through a structured survey of professional Saudi architects. By transforming an abstract theoretical notion into a ranked and statistically validated framework, the study contributes a structured assessment model capable of informing architectural education, design decision-making, and policy formulation in culturally sensitive and rapidly globalizing environments.

This study is guided by the following research questions:

RQ1: How can regional architectural identity be operationalized into measurable strategy categories grounded in theoretical and contextual literature?

RQ2: What is the relative importance of the identified regional identity strategies according to professional Saudi architects?

RQ3: Are there statistically significant differences in the prioritization of regional identity strategies across professional sectors (academia vs. practice) and levels of experience?

Literature Review

To systematically derive the eleven regional identity strategy categories, a structured qualitative content analysis was conducted on selected theoretical and empirical studies addressing architectural identity, regionalism, and contextual design. Studies were included based on three criteria: (1) explicit discussion of architectural identity or regionalism, (2) identification of measurable or operational design determinants, and (3) relevance to environmental, cultural, or human-centered dimensions of architecture. Each study was coded for recurring identity-related determinants using open coding, followed by axial grouping into higher-order conceptual dimensions. Saturation was considered achieved when no new identity determinants emerged across the reviewed studies. The resulting coded determinants were consolidated into eleven distinct strategy categories, which were subsequently operationalized into survey items.

Research on architectural identity, regionalism, and sustainability has evolved across diverse cultural and climatic contexts; however, comprehensive frameworks integrating environmental, cultural, and human dimensions remain limited. Previous studies as revealed in **Table 1** shows two key trajectories: one focusing on theoretical and philosophical interpretations of architecture, and the other grounded in empirical, contextual, and practice-based applications. Collectively, these works illustrate a progressive convergence between environmental responsiveness, cultural identity, and human-centered design.

From a theoretical perspective, Hosseini et al. [13] and Malpas [14] positioned architecture as a dialogue between humans and their environment. Hosseini et al. developed a framework linking regional architectural principles to sustainability through qualitative and inductive reasoning, emphasizing responsiveness to climate and topography. Malpas explored the notion of place and spatial experience through a phenomenological lens, arguing that architecture fosters belonging and identity through the relationship between interior and exterior spaces. Yadav [15] advanced this discourse by defining ecological regionalism, asserting that sustainable architectural identity emerges from the integration of environmental, cultural, and regional determinants. Together, these theoretical studies establish that architecture's identity is rooted in its responsiveness to ecological and social contexts.

Complementary contextual and cultural studies emphasize how tradition and social values shape architectural expression. Ettehad et al. [12] examined cultural influences on Iran's architectural evolution, highlighting how responsiveness to natural light and environmental conditions preserves cultural meaning. Torabi and Brahman [16] identified spatial organization, materials, and context as key factors in defining architectural identity, stressing that modern reinterpretations must uphold cultural integrity. Similarly, Salman [17] explored vernacular architecture and sustainability in the Arab world, demonstrating how traditional Arab design

embodies ecological wisdom and social symbolism, advocating for vernacular adaptation to sustain cultural continuity.

Empirical studies in Saudi Arabia expand this understanding through regional application. Alnaim and Bay [5] analyzed the Salmaniah Architectural Style and King Salman Charter, linking cultural heritage, human needs, and modern design values, while Lucchi et al. [6] developed a documentation framework to preserve Riyadh's modern architectural identity. Both emphasize human-centered and culturally adaptive design. In a Western context, Akande [18] assessed retrofitting in England's heritage churches, balancing sustainability with historical integrity, illustrating how environmental performance can coexist with cultural preservation.

Table 1 Summary of similar previous studies.

No.	Study	Context	Methodological Approach	Identity Determinants Identified	Derived Strategy Category
1	Hosseini et al. (2023) [13]	Global	Qualitative content analysis; thematic framework	Climatic adaptation; topographic responsiveness	Respond to site natural and climatic conditions
2	Ettehad et al. (2014) [12]	Iran	Documentary and case study analysis	Environmental conditions; natural light; cultural context	Environmental responsiveness; cultural integration
3	Malpas (2012) [14]	Global	Phenomenological textual analysis	Spatial continuity; inside–outside relationship; sense of place	Environmental responsiveness; human-centered design
4	Alnaim & Bay (2023) [5]	Saudi Arabia	Surveys; interviews; case analysis	Local values; behavioral patterns; vernacular adaptation (direct/indirect); contemporary contextualization; regional references; human needs; building regulations	Cultural integration; direct traditional use; indirect traditional use; contemporary localization; supra-regional referencing; human-centered design; regulatory alignment
5	Lucchi et al. (2023) [6]	Saudi Arabia	Field surveys; documentation framework	Preservation of cultural patterns; quality of life; well-being	Cultural integration; human-centered design
6	Salman (2018) [17]	Arab World	Qualitative comparative analysis	Vernacular sustainability; social symbolism; place-based identity	Cultural integration; direct traditional use
7	Akande (2018) [18]	England	Interviews; benchmarking; performance evaluation	Sustainability; adaptive reuse; user functionality	Functional responsiveness; human-centered design
8	Torabi & Brahman (2013) [16]	Iran	Comparative descriptive analysis	Cultural continuity; temporal representation; reinterpretation of tradition	Indirect traditional use; contemporary localization
9	Yadav (2008) [15]	Global	Conceptual ecological regionalism analysis	Use of local materials; environmental harmony	Material localization; environmental responsiveness

Methodology

This study adopts a mixed-methods approach that integrates both quantitative and qualitative data to evaluate and prioritize the parameters influencing architectural identity in Saudi Arabia. As illustrated in **Figure 1**, the methodological framework combines an in-depth literature review with a structured questionnaire survey, enabling a comprehensive understanding of the key strategies shaping regional architectural identity among Saudi architects.

The qualitative phase comprised an extensive review of theoretical and empirical studies related to regionalism, cultural identity, and contemporary Saudi architecture. This phase identified eleven primary architectural strategies encompassing aspects such as climatic responsiveness, cultural integration, vernacular adaptation, material use, building codes, and human-centered design. These categories formed the conceptual foundation for the survey design and the study's analytical framework.

The questionnaire was developed through a structured construct operationalization process derived from the literature review and qualitative content coding. Each of the eleven regional

identity strategy categories was translated into a single declarative statement measured on a five-point Likert scale (1 = Not Important at All; 5 = Very Important).

The study employed a non-probability convenience sampling strategy targeting professional Saudi architects across private practice, governmental organizations, and academic institutions. Participants were recruited through professional networks, institutional mailing lists, and direct distribution within architectural offices. The survey was administered both digitally (Google Forms) and in printed format to maximize accessibility. A total of 148 responses were received, of which 132 were complete and valid for analysis, resulting in an effective response rate of 89.2% after data screening.

Participation was voluntary and anonymous. Respondents were informed of the research purpose prior to participation, and completion of the questionnaire was considered informed consent. No personally identifiable information was collected, and all data were stored securely and analyzed in aggregated form solely for academic research purposes.

The collected data were analyzed using the Statistical Package for the Social Sciences (SPSS) software. Statistical tests included descriptive analysis to summarize respondent profiles and mean importance scores; Pearson correlation to assess construct validity among the 11 strategy categories; and Cronbach's Alpha to determine the internal reliability of the questionnaire. Additionally, a one-way ANOVA and independent-samples t-tests were conducted to examine the impact of professional experience and work background on respondents' perceptions. The Relative Importance Index (RII) and weighted mean were also calculated to rank the relative significance of each architectural strategy.

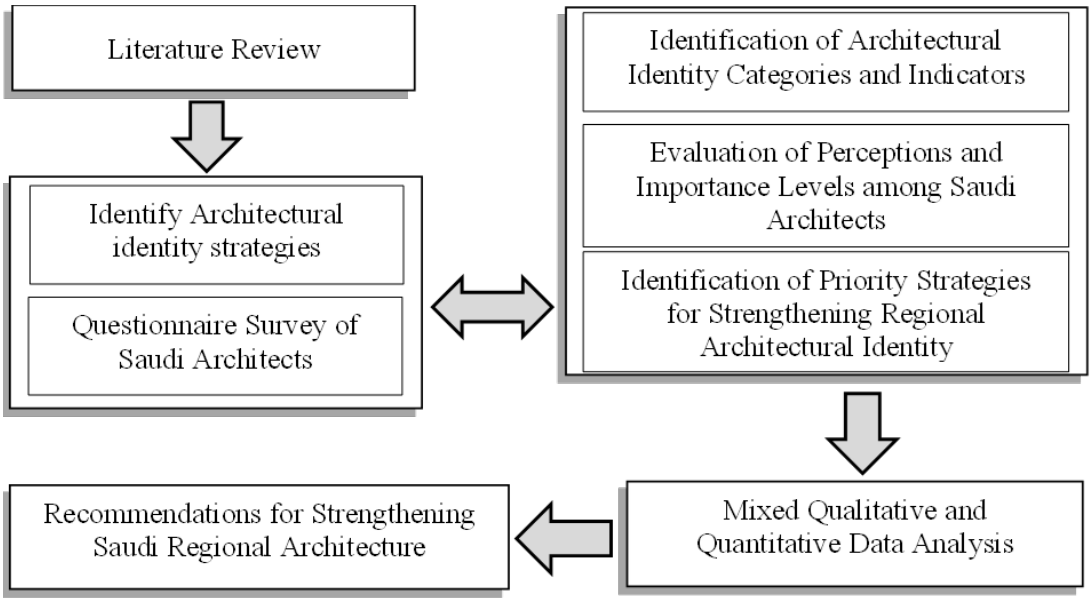


Figure 1 The Study's theoretical framework design

Results

As shown in **Table 2**, a total of 132 Saudi architects participated in the study. Regarding employment sector, 53.0% (n = 70) were practicing architects in private offices, 25.8% (n = 34) were employed in public or non-profit organizations, and 21.2% (n = 28) were engaged in academia. In terms of professional roles, most respondents identified as designers (69.7%, n = 92), followed by project managers (13.6%, n = 18), site architects (9.1%, n = 12), and consultants (7.6%, n = 10).

Table 3 shows Inter-item Pearson correlation coefficients were computed to examine the degree of association among the eleven regional identity strategy categories. Correlations ranged from r = .36 to r = .79 ($p < .01$), indicating moderate to strong positive associations. These results suggest

conceptual coherence among the strategy categories while maintaining sufficient differentiation across dimensions.

Figure 2 illustrates the distribution of respondents' perceived importance levels across the 11 investigated architectural strategy categories. Overall, the results reveal a clear tendency toward prioritizing context-responsive and human-centered design strategies. Responding to site natural and climatic conditions received the strongest endorsement, with the highest proportion of "Very Important" responses (60.6%), followed closely by local culture and values of the region (56.1%). Similarly, strategies related to responding to user/client needs and incorporating human design aspects attracted high combined percentages of "Important" and "Very Important" ratings, indicating broad professional consensus on their relevance.

In contrast, strategies associated with symbolic or referential approaches showed more polarized or neutral evaluations. The use of elements from the larger region (e.g., Gulf or Islamic world) recorded the highest combined share of neutral and lower-importance responses, suggesting limited perceived relevance. Direct use of traditional architectural elements also attracted a substantial neutral response, whereas indirect references were evaluated more favorably.

Table 2 Sample of Characteristic's

Variable	Options	N	%
Type of Work	Practicing Architect in Offices	**70**	53.00%
	Architect in other organization	**34**	25.80%
	Academic Field	**28**	21.20%
	Total	**132**	100%
Type of Title	Designer	**92**	69.70%
	Site Architect	**12**	9.10%
	Consultant	**10**	7.60%
	Project Manager	**18**	13.6%
	Total	**132**	100%
Experience	0-2 Years	**40**	30.30%
	3-5 Years	**8**	6.06%
	6-10 Years	**14**	10.60%
	11-15 Years	**24**	18.20%
	16+ Years	**46**	34.80%
	Total	**132**	100%

Table 3 *Inter-item Pearson Correlation Matrix Among Regional Identity Strategy Categories (N = 132)*

Correlation Analysis of categories	Respond to site natural and climatic conditions	Respond to local culture and values of the region	Use elements from traditional architecture of the Kingdom in a direct way	Use elements from contemporary Saudi architecture	Use of local materials	Use of local materials	Use relevant local building codes	Use elements of the larger region	Use relevant contemporary principles, forms, and materials	Incorporate human design aspects and factors	Focus on responding to user/client needs
Respond to site natural and climatic conditions	1										
Respond to local culture and values of the region	0.42	1									
Use elements from traditional architecture of the Kingdom in a direct way	0.47	0.41	1								
Use elements from traditional architecture of the Kingdom in an indirect way	0.4	0.36	0.41	1							
Use elements from contemporary Saudi architecture	0.52	0.42	0.45	0.57	1						
Use of local materials	0.46	0.41	0.42	0.44	0.53	1					
Use relevant local building codes	0.44	0.45	0.44	0.52	0.58	0.6	1				
Use elements of the larger region	0.55	0.48	0.54	0.48	0.62	0.56	0.61	1			
Use relevant contemporary principles, forms, and materials that reflects the spirit of the era	0.47	0.5	0.51	0.55	0.56	0.56	0.63	0.69	1		
Incorporate human design aspects and factors	0.56	0.54	0.54	0.6	0.66	0.64	0.67	0.72	0.73	1	
Focus on responding to user/client needs	0.55	0.54	0.57	0.59	0.69	0.61	0.71	0.7	0.73	0.79	1

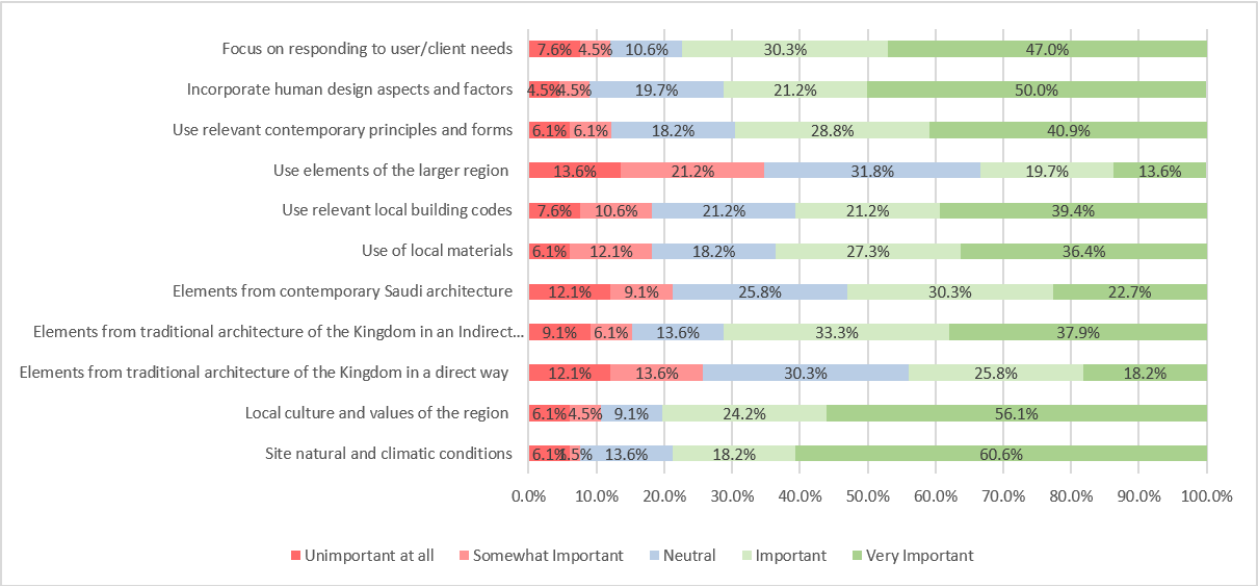


Figure 2 Percentages of users' importance with the 11 investigated categories

Table 4 shows that the highest ranked category was responding to site natural and climatic conditions, which achieved a weighted mean of 4.26, a Relative Importance Index (RII) of 0.85, and a first-place rank, indicating strong agreement among respondents on its critical role in architectural practice. This was followed closely by responding to local culture and values of the region (M = 4.20, RII = 0.84), and incorporating human design aspects and factors (M = 4.08, RII = 0.82), both of which reflect the significance placed on human-centered and context-aware design. The focus on responding to user/client needs (M = 4.05, RII = 0.81) and the use of relevant contemporary principles and materials (M = 3.92, RII = 0.78) also ranked highly. Conversely,

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lower levels of perceived importance were associated with strategies such as using elements from traditional architecture in a direct way (M = 3.24, RII = 0.65), contemporary Saudi architecture (M = 3.42, RII = 0.68), and especially using elements of the larger region (e.g., Gulf or Islamic world) (M = 2.99, RII = 0.60), which was ranked last. These rankings suggest that while respondents strongly value environmental and cultural responsiveness, there is relatively less emphasis placed on broader regional references or overt historic replication.

Table 4 Weighted means of architects importance level and RII of the 11 investigated categories.

	Weighted Mean	Std. Deviation	RII	Rank
Respond to site natural and climatic conditions	4.258	1.137	0.85	1
Respond to local culture and values of the region	4.197	1.162	0.84	2
Use elements from traditional architecture of the Kingdom in a direct way	3.242	1.249	0.65	10
Use elements from traditional architecture of the Kingdom in an indirect way	3.848	1.251	0.77	6
Use elements from contemporary Saudi architecture	3.424	1.273	0.68	9
Use of local materials	3.758	1.236	0.75	7
Use relevant local building codes	3.742	1.288	0.75	8
Use elements of the larger region	2.985	1.229	0.60	11
Use relevant contemporary principles, forms, and materials that reflect the spirit of the era	3.924	1.176	0.78	5
Incorporate human design aspects and factors	4.076	1.137	0.82	3
Focus on responding to user/client needs	4.045	1.203	0.81	4

Table 5 presents the results of independent-samples t-tests comparing architects in other organizations and those in academia regarding perceived importance of architectural identity strategies. Academics consistently reported higher mean scores across most categories, with statistically significant differences in overall importance ($p = .007$), responding to local culture and values ($p < .001$), indirect use of traditional architecture ($p = .037$), contemporary Saudi architecture ($p = .014$), use of local materials ($p = .044$), local building codes ($p = .019$), and contemporary principles reflecting the spirit of the era ($p = .008$). No significant differences were observed for site and climate responsiveness, direct traditional references, larger regional elements, human design aspects, or user/client needs. Overall, the findings indicate that academic architects place greater emphasis on culturally and conceptually driven identity strategies than practitioners in other organizations.

Table 5 Results of the independent sample t-test to examine the difference between architects in other organization and architects in academic field respondents regarding their level of importance.

	Mean for Architects in other organizations (N=34)	Mean for Architects in Academic Field (N=28)	Sig. (2-Tailed)
Overall Importance	3.44	4.01	0.007
Respond to site natural and climatic conditions	4.00	4.50	0.090
Respond to local culture and values of the region	3.65	4.71	0.000
Use elements from traditional architecture of the Kingdom in a direct way	2.82	3.21	0.180
Use elements from traditional architecture of the Kingdom in an indirect way	3.52	4.14	0.037
Use elements from contemporary Saudi architecture	3.11	3.78	0.014
Use of local materials	3.47	4.07	0.044
Use relevant local building codes	3.29	4.00	0.019
Use elements of the larger region	2.76	3.07	0.302
Use relevant contemporary principles, forms, and materials that reflect the spirit of the era	3.64	4.42	0.008
Incorporate human design aspects and factors	3.82	4.21	0.160
Focus on responding to user/client needs	3.82	4.00	0.563

Conclusion

The ranking analysis demonstrates a clearly structured hierarchy within the multidimensional framework of regional architectural identity. Environmental responsiveness emerged as the highest-ranked determinant (RII = 0.85, Rank 1), indicating that architects overwhelmingly prioritize climatic and site-specific adaptation as the primary foundation of identity formation. The high weighted mean and strong concentration of "Very Important" responses suggest a broad professional consensus that contextual ecological integration constitutes the most fundamental expression of regional identity. Rather than perceiving identity as a stylistic or symbolic construct, respondents associate it first with environmental performance, site sensitivity, and climate-responsive design strategies.

Closely following environmental responsiveness, cultural integration ranked second (RII = 0.84, Rank 2). Respondents emphasized the importance of aligning architectural design with local values, traditions, and socio-cultural patterns. Notably, statistically significant differences were observed between academic architects and practitioners ($p < .001$), with academics assigning greater importance to cultural responsiveness. This divergence suggests that theoretical exposure and research engagement may strengthen emphasis on cultural continuity as a central identity determinant. Importantly, the prioritization of cultural integration reflects a perception of identity as socio-cultural embeddedness rather than superficial visual replication. Identity, in this context, is interpreted as alignment with behavioral norms, spatial practices, and contextual symbolism rather than ornamental referencing.

A secondary priority cluster emerged around human-centered and functional responsiveness (RII = 0.82–0.81, Ranks 3–4). The categories "incorporate human design aspects and factors" and

"focus on responding to user/client needs" both received high mean values, indicating that experiential quality and usability are strongly associated with regional identity. The inter-item correlation matrix further supports this interpretation, revealing strong positive associations (r up to .79) between user-oriented strategies and other identity dimensions. These findings suggest that architects conceptualize identity not only as contextual or cultural alignment but also as a relational and experiential construct shaped by human comfort, spatial adaptability, and user satisfaction.

Contemporary contextualization ranked fifth (RII = 0.78), with respondents favoring the use of relevant contemporary principles, forms, and materials that reflect the spirit of the era. This result indicates that regional identity is not perceived as static or historically fixed but rather as dynamically negotiated within present-day architectural expression. The preference for contextual modernization over direct historical replication underscores a forward-looking interpretation of identity, wherein architectural authenticity is achieved through adaptation to contemporary conditions rather than preservationist literalism.

A notable contrast emerged between indirect and direct vernacular adaptation. Indirect reinterpretation of traditional architectural elements (RII = 0.77) ranked significantly higher than direct replication (RII = 0.65, Rank 10). This pattern suggests a professional preference for adaptive continuity—reinterpreting traditional principles within modern frameworks—rather than formal historicism or literal stylistic imitation. The comparatively lower ranking of direct traditional replication indicates that overt reproduction of heritage forms is not widely regarded as an effective strategy for reinforcing contemporary regional identity.

Material and regulatory localization (RII = 0.75, Ranks 7–8) occupied a mid-tier position within the hierarchy. The use of local materials and adherence to relevant local building codes were recognized as important but not dominant identity drivers. These findings suggest that such strategies are perceived as supportive or enabling mechanisms that reinforce contextual authenticity, rather than primary generators of identity meaning.

Finally, supra-regional referencing (RII = 0.60, Rank 11) received the lowest importance rating. The limited prioritization of broader Gulf or Islamic regional elements indicates that architects distinguish between localized identity formation and generalized regional symbolism. This suggests that contemporary Saudi architects conceptualize identity as rooted in specific environmental and cultural conditions rather than transnational stylistic markers or pan-regional aesthetic references.

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Sustainable Construction Practices in Taif City: The Role of Building Materials

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Abstract. Sustainable construction has gradually become the basis of environmental-economic improvement in the built environment. Building materials play a pivotal role in realizing sustainable development, which is addressed in this study, based on the construction industry of Taif City, Saudi Arabia, in terms of thermal regulation, energy consumption, and ecological footprint. Using a descriptive–analytical approach, this article incorporates a comprehensive review of local urban planning regulations in combination with an examination of construction operations. It evaluates alignments of the conventional and contemporary materials with the sustainability standards and investigates the possibility of adopting green concrete, thermally insulated bricks, as well as available resources on the ground. The authors conclude that sustainable material selection can greatly improve the quality of urban environments, occupant comfort, and low life cycle operational costs. The research concludes with a proposal for a regulatory and incentive-based framework in order to make it easier to use sustainable building materials and for innovation and research specific to Taif region's climatic and topographical conditions.

1. Introduction

Sustainability has been a topic of particular interest throughout the evolution of this technology, as it significantly influences the environment such as energy use, resource consumption and greenhouse gas emissions [1, 2]. International practices from sustainable design and construction seek to lower the external impact to the environment and to improve the social and economic functioning of construction assets [3]. The new paradigm that is emerging in the form of this paper focuses on the incorporation of environmentally responsive design principles, advanced materials, and innovative technologies with the goal of reducing the energy consumption, reducing resource use, and enhancing the well-being of the user throughout the building's full cycle of operational life [2,4].

A. Choosing Building Materials for Sustainability

Construction material selection is of paramount importance for implementing sustainable projects in the construction industry. One feature of these materials is the influence on thermal performance, embodied energy, and lifecycle costs as a result of these materials [5]. Materials sustainable for use, locally sourced, recyclable, low embodied carbon minimize environmental degradation and impact through activities such as construction. Life Cycle Assessment (LCA) methodologies also empower architects and engineers to systematically assess alternatives to materials and make decisions that maximize environmental functionality, economic viability, and functional lifespan of the building over the building lifespan [6].

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B. Taif City Specialiy: Climate and Urban Character:

Taif city has a moderate highland climate with a high altitude of about 1,800 m. Taif has relatively softer summers and cold winters than most of the cities of Saudi Arabia [7,8] . They are climatically and topographically unique, providing architectural challenges and opportunities, specifically in thermal comfort, and building material properties. The traditional architecture of Taif reflects the deep-rooted adaptation to the local environment that we have experienced, with stone sourced local to the region, the building's passive ventilation systems, and courtyards planted in shade [9]. Accordingly, by using sustainable materials and building techniques tuned specifically for Taif's specific climate, the energy efficiency of modern construction can be improved and thus the environmental blow reduced considerably [1, 10].

C. Research Problem and Research Questions:

Current construction practices in Taif still disproportionately depend on conventional building materials that may not meet long-term sustainability standards, even though the city adopts a unique environmental context. This concern raises the following central research question:

How do sustainable building materials contribute to the sustainability of the construction system in Taif City?

The following questions arise on the basis of this fundamental question:

- What are the predominant building materials used in current construction projects in Taif, and how well do they align with environmental and climatic suitability?
- What selection criteria are employed for building materials, and to what extent do they account for lifecycle performance and environmental impact?
- What are the comparative environmental and economic advantages of adopting sustainable materials over conventional alternatives?

D. Research Objectives

Main Objective:

To assess the contribution of sustainable building materials to the enhancement of efficiency and sustainability within Taif City’s construction sector.

Sub-Objectives:

- To evaluate the environmental and thermal performance of conventional building materials currently utilized in Taif’s construction projects.
- To identify sustainable material alternatives that are compatible with Taif’s local climatic conditions.
- To conduct a comparative analysis of the environmental and economic impacts of traditional versus sustainable materials.
- To develop a strategic framework or guideline for the integration of environmentally responsible building materials in Taif’s construction practices.

E. Research Hypotheses. The main ideas that inform this study are:

- Energy Efficiency and Resource Optimization – Sustainable building materials promote significant improvements in energy efficiency and saving resources utilized in the construction project of Taif City.
- Correlation of the choice of sustainable materials with environmental performance in the building is statistically significant under the harsh climate of Taif, because the choice of sustainable material is significant.
- Costs to implement: The relatively high initial costs of sustainable materials pose a barrier to widespread practice of sustainable materials in building process.

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- Knowledge and awareness Lack of awareness and technical knowledge of key stakeholders (engineers, contractors or developers) would negatively affect the sustainable building products' adoption rates in Taif.
- Regulatory impact: By implementing government policies and incorporating sustainability requirements in Saudi Building Code, the role of both regulatory and legislative powers can ensure that environmentally sustainable building materials are utilised more widely in the context of local construction.
- Supply Chain Optimization: Strengthening the local supply chain of sustainable materials could lead to a significant reduction in the cost of procurement and thus increase the economic viability of sustainable construction projects in Taif.

F. Research Methodology.

The study uses a Descriptive–Analytical Approach supplemented by the environmental and economic indicators to evaluate the sustainability of building materials. The methodology focuses on the below key stages:

Data Collection.

- Secondary Data
- Data were retrieved from: Existing literature, Saudi building codes and standards, environmental impact reports, and green building guidelines.
- Primary Data: Gathered through in-situ observations and structured interview or questionnaires addressing:
- Practicing engineers and builders in Taif City.
- Deputies of the local government bodies to include the Municipality in the discussion and Ministry of Municipal and Rural Affairs and Housing (where applicable).

Analysis of Existing Building Material Utilization.

- Analyze the dominant materials currently used in Taif's activities, namely but not limited to concrete, bricks, insulation systems, paints and finishing items.
- Analysis of these materials using important sustainability criteria:
- Energy consumption.
- Carbon emissions.
- Life of service and maintenance criteria.

Selection of Climate-Responsive Sustainable Alternatives.

• Selection by thermal climate analysis literature that is specific to Taif.

- Comparison study of conventional and sustainable materials by:
- Life Cycle Assessment (LCA)
- Benchmark environmental and economic performance.

Development of a Sustainability Guideline

Formulation of a strategic guideline to support the adoption of environmentally responsible building materials within Taif's construction sector, aligned with local climatic conditions and regulatory frameworks.

G. Literature Review:

Concept of Sustainability in the Construction Sector:

Sustainability within the construction sector represents a comprehensive and integrative approach to developing built environments that fulfill current functional and societal needs without

compromising the capacity of future generations to meet their own. This approach necessitates a balanced consideration of environmental, economic, and social dimensions throughout the entire lifecycle of a building. Key principles include the efficient utilization of natural resources, reduction in energy and water consumption, and minimization of carbon emissions, alongside the adoption of recyclable and low-impact building materials [2].

In the Gulf region, and in Saudi Arabia in particular, national strategies like Vision 2030 have sped up efforts to transition to sustainable construction practices. These projects focus on energy-efficient design principles and environmentally sound materials used in both public and private sector constructions [11]. Additionally, sustainable construction is not only concerned with environmental measures but also includes healthy, comfortable indoor spaces for occupants as well as the benefit of long-term savings in operating and maintenance costs [12].

Classification of Building Materials: Traditional vs. Sustainable

There are essentially two classes of construction materials: traditional and sustainable materials. Conventional materials, such as reinforced concrete, cement blocks, steel, and other industrial metals, are popular because of their structural reliability and market availability. Yet these materials are usually characterized by high energy consumption and significant carbon emissions at both manufacturing and operational levels [13]. On the contrary, sustainable materials refer to those which are natural, recycled, or low-emission, such as treated wood, locally quarried stone, compressed earth blocks, and cutting-edge thermal insulation materials with eco-friendly properties [2]. The use of materials such as natural stone and wood as part of the construction process in buildings built locally (Taif City, KSA), for instance, including Shubra Palace, provided thermal insulation and responsive architecture for Saudi Arabia and was an example of indigenous materials used in architecture and design that did not necessarily rely on mechanical systems to provide thermal insulation, as was the case throughout the history of Saudi-centered buildings in terms of architecture and energy and was not dependent on a mechanical cooling system.

Evaluation of the Environmental and Thermal Impact of Building Materials

Evaluating the environmental and thermal performance of building materials is a critical component in advancing sustainability within the construction sector, particularly in hot and arid climates such as that of Taif. These assessments focus on key material attributes including thermal conductivity, thermal mass, embodied energy, and carbon emissions throughout the material's lifecycle [14]. Research indicates that conventional materials such as reinforced concrete and cement blocks exhibit relatively poor thermal insulation properties, thereby increasing dependency on mechanical cooling systems and contributing to elevated energy consumption[15]. In contrast, indigenous materials like natural stone and compacted earth blocks, commonly found in Taif's heritage architecture, demonstrate significantly better thermal performance. These materials can reduce heat transfer by up to 40% compared to concrete, offering passive cooling benefits and enhanced indoor comfort [2].

Previous Research in Saudi Arabia or Other Climates in the Region:

Interest in Sustainable Construction in the Region In the past few years, sustainable construction and selection of materials suitable for hot and arid climate construction has been the focus of significant research attention across the region, with Saudi Arabia and the surrounding Gulf countries having led the way in researching sustainable building materials. This research always focuses on the role of choosing adaptable climate-responsive components to optimize energy efficiency and curb carbon emissions.

- Highlights of Regional Research

- Al-Homoud (2005) emphasized that the concordance between the selected building materials and the local climate gives huge returns for energy efficiency and building sustainability.
- Sultan et al. (2021) found that new construction methods in Saudi Arabia place significant emphasis on sustainability standards, in line with the Saudi Building Code and Vision 2030. They implement thermal insulation and low-emission building materials for better energy efficiency and thermal comfort inside.
- Ali and Al Nsairat (2009) conducted an analytical study on sustainable and natural materials use in buildings in Jordan, which is climatically similar to parts of Saudi Arabia, and indicated that application of sustainable and natural materials reduces energy consumption as well as the effects of energy consumption in buildings on long-lived environmental performance.
- The result is that these researchers all offer compelling reasons to shift the construction industry towards more sustainable materials in new projects, and they hint at the need for rethinking our construction processes altogether. Also, they emphasize the importance of adapting the materials selected to the climate related to each city (such as Taif) and use this approach in order to have durable and feasible responses to construction.

2. Characteristics of Sustainable Building Materials:

Sustainable building construction materials features. Sustainable building materials have low environmental effects, do not over-exploit resources and increase human healthcare and comfort during the life cycle of the building. Such materials are endowed with low embodied energy, recyclable, good longevity and, non-toxic substances in general [1]. Local sourcing is a great edge as it reduces transport pollution emissions and also supports local economic development [6]. In addition to these environmental benefits, sustainable materials lead to lower energy consumption in terms of improved thermal insulation and reflectivity, which reduce the necessity of heating and cooling systems[2]. Flexibility has been highlighted as one of its attributes: materials crafted to be dismantled, reapplied, or recycled very quickly have contributed significantly to transitioning to the circular economy [16]. These principles and embedded in building materials will promote environmental efficiency, long-term economic success, and social welfare from sustainable approaches. Their behaviors can thus be broadly divided into three sustainability dimensions: environmentally, economically, and socially.

2.1 Environmental Dimension

The environmental aspect of sustainable building material emphasizes carbon emissions, energy use, and waste reduction in the entire material life cycle, which spans extraction, manufacture, use, and end-of-life (EoL). These materials possess low embodied energy and carbon and are relatively durable, and they can be reused, recycled, or biodegraded, leading to lower overall environmental effects. One indispensable approach of assessing environmental performance during the entire lifespan from cradle-to-grave/cradle-to-cradle is Life Cycle Assessment (LCA), which allows for energy use quantification, carbon footprint estimation, and pollutant emissions identification [17]. Attainment of the embodied energy-carbon reduction process at the early stages of production is essential to minimise the emission of these substances [18]. Environmental impacts also can be minimized by utilizing recycled, reclaimed, renewable, and locally sourced materials, which reduce resource depletion, transport emissions, and dependency on fossil fuels whilst benefiting local economies [6]. Indoor environmental quality is key as well, non-toxic, low-VOC materials create better indoor air quality, occupant health, and comfort [19]. The sustainability of it in the long-term is material's robustness, maintenance, and lifetime, and consequently the replacement needs and save resources throughout construction life cycle [20]. End-of-life practices like

dismantling, recycling, and repurposing are examples as waste management and circular economy planning contribute to waste minimization [21], while prefabrication and streamlined construction practices also help to limit site wastage [22]. There are also environmental certification systems and standards that lead the designer in the selection of sustainable materials [1]. And climate-responsive materials, such as those used together with thermal performance and passive design, may help to achieve long-term eco-friendly energy efficient design suit to climatic suitability as well [23].

2.2 Social Dimension of Sustainable Building Materials:

More than just a technical property, a building's social sustainability means that aspects of environment such as health, cultural continuity, and community development will also be profoundly impacted. First of all, health and safety are an overarching key factor: the use of non-toxic, low-VOC (volatile organic compound) materials lead to sound indoor air quality – while not emitting harmful substances like formaldehyde, which can harm respiratory health, comfort and long-term well-being [19]. Cultural and aesthetic appropriateness is also significant as the inclusion of materials reflecting local styles and heritage is also beneficial for social acceptance, place identity and preventing cultural alienation within the community [24]. In addition to these material choices, they have direct socio-economic consequences at the local level: sourcing for job creation, promoting artisans and small-scale producers, promoting informal economic sectors, reducing social inequality [25]. The comfort and well-being of its people are also affected by the materials, which impact with its thermal, acoustic, and visual nature as well for its impact on mental health, productivity, and in house to work satisfaction [26]. Equitable access and cost must also ensure that sustainable materials are not only utilized in luxury projects but that lower-income groups have access to safe and healthy living conditions as well, staving off "green gentrification" and fostering social equity [1]. Integration of other communities into the design and selection of materials further enriches social cohesion, instills a sense of ownership, and means material selection is reflective of real user needs, values, and expectations [27]. Ethical concerns also must be considered in material production and extraction in which complying to international standards of labor, avoiding forms of exploitation (child labor and unsafe job) and ensuring equitable trade and labor rights along a construction supply chain are the focus of consideration [28]. Lastly, long-term social resilience and adaptability are promoted by flexible, expanding, re-used materials, enabling communities to respond easily to climatic, economic, or disaster changes, modular and adaptive materials, specifically, contribute to sustainable, socially resilient community-built environments [29].

2.3 Environmental Dimension:

Environmental Dimension of Sustainable Building Materials. And from an environmental point of view, sustainable building materials are those that have a smaller carbon emission, energy use, waste generation through the whole life cycle of their uses, including extraction, manufacture, use, and disposal [6]. Traditionally, these materials have low embodied energy, high durability and an ability to be recycled or biodegradable, which results in a smaller overall environmental impact. A Life Cycle Assessment (LCA) framework allows assessment of the environmental performance of materials and is used to quantify the impacts in different dimensions of a material such as extraction, manufacturing, transport, use, maintenance and end of life, and to highlight critical stages of improvement and to inform both cradle-to-grave and cradle-to-cradle approaches while including key elements of the environmental footprint, energy consumption and pollutant emission [17]. Embodied energy and embodied carbon are therefore critical factors to consider, as they encapsulate total energy use and CO_2 emissions arising from the materials' extraction, processing, manufacturing, and delivery, with particular effect on emissions at the construction phase [18]. Environmental considerations can be further improved by ensuring the consumption of recycled,

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reclaimed, rapidly renewable or naturally sourced materials, such as bamboo, cork, and straw bales, to mitigate the depletion of natural resources, environmental damage, and the production of embodied energy [1]. Localisation of materials for materials must also be considered, as this not only makes transportation emissions in a local area less, reduces the consumption of fossil fuels, and economic activities at small scale is also supported by locally based materials, by reducing the fossil fuel utilization, less of the external materials, the amount of power required and dependence on foreign ones [6]. Consider also indoor environmental quality, because in sustainable buildings non-harmful substances with fewer harmful, low emission of volatile organic compounds (VOC) have better air quality, occupant health and comfort [19]. The building's longevity for materials, along with its durability, low replacement rate, its low maintenance and long lifecycle, also is also an added value in the field with lower replacement and resource use costs and longer life cycle environmental effects, resulting from the sustainability of the building in the longer term [20]. End of life solutions, such as those related to disassembly design and product reuse or recycling, minimize landfilling and provide alignment with circular economy principles [21]. Construction waste generation can be reduced by means of prefabrication, modular building systems, and efficient construction design methods as well as on-site waste management strategies that reduce offcuts and material wastage during the construction phase [22]. Systems of environmental certification from LEED to BREEAM, WELL, Green Star to ISO 14001 and ISO 21930 offer clear guidelines on how best to choose eco-conscious materials and to support the developers and players decision-making on sustainability [1]. Lastly, the choice of materials has a substantial impact on climate responsiveness and energy performance, as materials possessing adequate thermal mass, insulation qualities, and passive design features reflective systems, cool roofs, phase change materials can substantially lower energy demand in operation and improve environmental performance of buildings over time [23].

2.4 Economic and Social Dimensions of Sustainable Building Materials:

Economically, sustainable building materials support economic efficiency across the building's life cycle, in terms of energy consumption and maintenance expenses, extending its life span, and with-it local production chains that reduce transportation costs [1]. The social dimension is of course also fundamental, beyond the economic consideration, to establish the sustainability of building materials. Occupant health and safety is a basic social attribute, non-toxic, low-volatile organic compounds (VOC) are predominantly used for indoor air preservation and prevent the emission of toxic chemicals such as formaldehyde, known to cause respiratory diseases and discomfort, as well as long-term health problems [19]. From a cultural and social point of view, materials should be in line with regional architectural traditions and heritage, for improving social acceptance, feeling 'at home', and reducing distance from communities [24]. Economically, the employment opportunities, preservation through long-established artisan crafts and indigenous small producers, and contribution towards inclusive economic development are all directly connected to the employment of locally produced materials via decreased social inequalities [25]. It is also obvious that design material selection plays a decisive role in user experience since thermal, acoustic, and visual comfort affect the mental health, productivity, as well as the satisfaction of residential, educational, and workplace users [26] .Equity mandates also that sustainable materials be affordable and accessible to varied social structures, ensuring health and safety gains do not fall solely on well-developed estates, as well as not enabling social exclusion and "green gentrification" [1]. Participation, as a way of drawing participation from future users and local communities in the choice of materials and design, promotes social solidarity, nurtures a sense of ownership, and confirms that materials are chosen to suit real social requirements and values [27]. Lastly, ethical and long-term aspects encompass labor rights and safe working conditions in the entire process of production and extraction of the material as well as the choice of materials that facilitate adaptability and resilience under changing climatic and socio-economic

conditions [28, 29]. Table (1) highlights the main social Sustainability Aspects and Criteria Related to Building Materials and the Built Environment.

Table (1): Social Sustainability Aspects and Criteria Related to Building Materials and the Built Environment[*2*, *30*, *31*, *32*, *33* ,*34*,*35*] .

Key Area	Focus
Health and Safety	Non-toxic, healthy indoor environments
Cultural Compatibility	Respecting local identity and aesthetics
Economic Empowerment	Job creation, local sourcing, inclusive supply chains
User Comfort	Thermal, visual, and acoustic well-being
Affordability	Access for low-income communities
Community Involvement	Participatory design, social cohesion
Ethical Labor Practices	Fair work conditions in production and sourcing

2.5 Social dimensions of sustainable building materials.

This is the reason for which the analysis of green building materials should have to go further than the analysis of how good they are technically, but should also consider the socio-economic importance of the materials in the life cycle, from extraction to manufacturing to application to end-of-life. Importantly, these social impacts impact occupant health, comfort, community cohesion, and the conservation of cultural values. Sustainability, and the social-building materials. From a social perspective it leads to benefits for occupants as it directly impacts their wellbeing, comfort, and quality of life. Low pollution building materials, indoor air quality materials serve as key ingredients for sustainable living to maintain thermal and acoustical comfort [36]. In such residential and educational buildings with continual exposure to indoor elements, these characteristics become critical for the mental and physical well-being. Responsible sourcing and the use of socially sustainable and responsibly made building materials also aid in socially fair labor practices and promote economic development at the local level. Hence, socially sustainable materials can serve a second role where they serve not just as a function and contribute to the environment but also play a social role as a means to strengthen the resilience of the community. Since the construction sector is a third pillar of sustainability, the social end of the social dimension allows construction practices to be inclusive, culturally responsive, and in the end human centred, rather than purely efficiency- or technology-centered [2].

2.5.1 Social dimension Building materials in Taif.

Construction material in Taif is not limited to environmental and technological parameters but include the social and cultural domains. The stone, adobe and lime plaster are the traditional material found here, already used for so long that has an inseparable relationship with the local identity and a vital element of its collective culture. The stability and ongoing utilization of these materials give community pride and a sense of community to the citizens as users, as well as support indigenous knowledge and artisan skills, traditional knowledge and the practice of traditional skills – vital elements of social sustainability [37]. Simultaneously, a growing reliance on modern industrial raw materials (concrete, steel, and glass) provide structural and functional benefits but, even if with some structural advantages, also result in social and cultural marginalization. Such materials are typically context inapplicable to, or are not well-suited to, local climate and cultural context, such as the local climate or local conditions. Due to the poor thermal adaptation of their thermal profile, the fact that occupants are less comfortable indoors, and therefore rely more on the mechanical cooling systems. This dependence not only affects energy efficiency, but also has severe, negative impacts on the health of inhabitants, which is very important [2].

2.5.2 Social Dimensions of Sustainable Construction Materials

The social sustainability of building materials encompasses a huge variety of human-centered issues, far beyond technical concerns. These include health, equity, cultural relevance, and community empowerment. The major social dimensions described in the literature are elaborated in the following subsections. Health and Safety. Materials used to build sustainable buildings must safeguard the health and safety of construction workers and building occupants. That involves limiting exposure to potentially harmful chemicals, like volatile organic compounds (VOCs) and asbestos, and ensuring safe working conditions for new and existing materials throughout the material life cycle, from extraction to installation[38] . Construction material choices, and their application, directly impact local communities positively (job creation to a certain degree) or disadvantageously (for instance, environmental destruction, noise and displacement). Thus, the voice of society in material choice decision is essential in the development of social legitimacy and participation[39].

2.5.3 Rights of Labour:

Ethical construction materials must comply with international labour standards, ensuring fair wages, safe working conditions, and the absence of exploitative practices such as child labour. Respecting workers' rights supports fair trade principles and strengthens social responsibility within construction supply chains [40]. Local sourcing of building materials contributes to economic empowerment by supporting local industries, developing skills, and enhancing regional resilience, while also reducing transportation-related emissions [37]. Culturally appropriate materials that reflect local values, traditions, and vernacular construction techniques promote social acceptance, reinforce cultural identity, and foster a sense of community belonging [2]. Affordability is essential to social equity, sustainable materials should be accessible to all social groups, particularly low-income communities, to support inclusive and dignified living environments [25]. Finally, material selection significantly influences thermal, acoustic, and visual comfort, directly affecting users' well-being, productivity, and quality of life, making it a key consideration in sustainable design [2].

2.5.4 Education and Awareness:

We must foster awareness among stakeholders including builders, users, and policymakers of the social benefits of sustainable materials. Educational campaigns can promote sustainable changes in behavior in the long term and encourage the move towards more socially responsible building [40]. This framework posits that building materials' social sustainability goes beyond their material characteristics to considerations of the impact on people's lives, work, identity, and dignity. Evaluation of sustainability of material should therefore include in future evaluation systems to consider these human-centered dimensions of material sustainability to create a comprehensive and equitable sustainable living and resilient built environment. Figure (1) displays integration of important environmental and social attributes of sustainable materials by defining resource efficiency, low carbon footprint, and recyclability as environmental aspects, along with user comfort, health and safety, and sustainability awareness as important social aspects. Cumulatively, these dimensions indicate that a multidimensional means of material sustainability is necessary for the attainment of material sustainability.

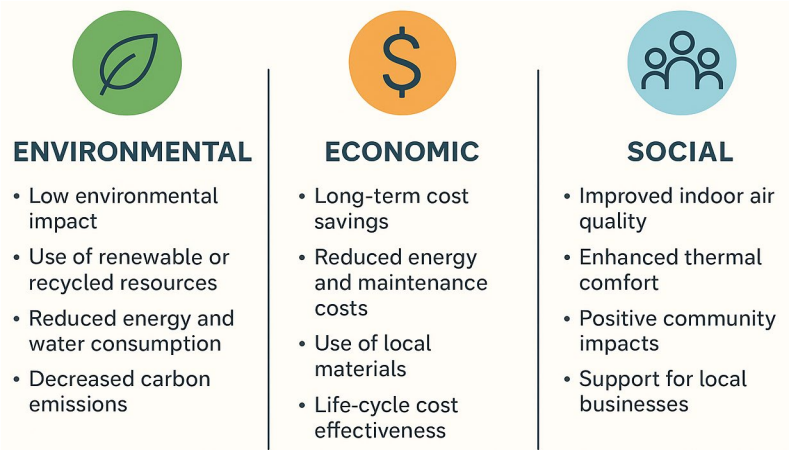


*Figure (*1*): shows the three pillars of sustainable building materials.*

We can also explain the characteristics of sustainable building materials across the three dimensions of sustainability through the Table (2) .

Table(2) *: Characteristics of Sustainable Building Materials Across the Three Dimensions of Sustainability*[2, 5,25 ,33, 31, 30 ,32, 35, 34,38] .

Sustainability Dimension	Key Characteristics	Description / Examples
Environmental	▪ Low embodied energy ▪ Recyclability and reusability ▪ Non-toxic composition ▪ Energy efficiency (thermal insulation) ▪ Reduced carbon footprint	Materials that minimize energy and emissions during production and use, promote natural ventilation and thermal comfort (e.g., rammed earth, bamboo, recycled steel).
Economic	▪ Cost-effectiveness over the life cycle ▪ Local availability ▪ Low maintenance and long durability ▪ Resource efficiency	Materials that lower operational and maintenance costs and support local supply chains (e.g., locally quarried stone, stabilized soil blocks).
Social	▪ Healthy indoor air quality ▪ User comfort and well-being ▪ Safety and adaptability ▪ Support for local employment and fair labor	Materials that improve health and comfort by avoiding VOCs and supporting community welfare (e.g., low-VOC paints, natural finishes, locally crafted materials).

3. Building Materials used in Taif:

A Review (Introduction to the Situation in Taif). Taif, on the high peaks of the Sarawat Mountains in western Saudi Arabia, has a temperate climate, which is characterized especially by summer compared to the rest of the Kingdom. This climatic advantage historically has characterized its architectural identity and mingled some traditional Hijazi elements with modern building practices. Material choices in Taif reflect environmental responsiveness, cultural heritage, and local resources.

3.1 Traditional Building Materials: Sustainability, Thermal Comfort, and Recycling:

Historically, Taif's architecture used locally available natural materials, including clay, stone, wood, and lime-based finishes. The materials were chosen for their climatic adaptability, cultural relevance, and sustainability potential. The next subsections discuss the important conventional substances with regards to environmental performance, thermal comfort, and recyclability.

3.1.1 Clay and Mud Bricks (Adobe)

Adobe is made from a mixture of clay, sand, water, and organic fibers (e.g., straw) and is sun-dried without energy-intensive firing, thus becoming very sustainable [41, 42]. Its high thermal mass contributes to thermo stability in indoor temperature control and proper insulation and humidity control which is beneficial to arid climates [43]. But adobe is moisture-sensitive and structurally restricted to internal partitions, and it cannot withstand heavy loads, thereby serving only for internal partitions and low-rise applications. If the material is properly stabilized, it is a suitable environmentally friendly material to which one can still hold cultural traditions.

3.1.2 For the Mountain (Al Shafa) and Al Hada, timber:

In traditional mountain homes in Al Shafa and Al Hada, wood used is known for its renewability, low thermal conductivity, and recyclability. Locally available wood also has a lower carbon footprint from transport emissions and captures carbon in the growing process, minimizing building footprints [2, 5]. The insulating properties of this material increase thermal comfort [13] in cooler climates. In addition, wood can be reworked or recycled into new construction elements, aiding the movement of circular material [44].

3.1.3 Marble:

It is one of the most widely used natural stones in construction for its beauty, smoothness, and durability. Its capacity to reflect light and appear lavish in appearance are why it is favoured by many interior finishes and building facades [5]. Marble also has a high thermal mass, which is important in natural temperature regulation and increased energy efficiency in buildings [45]. Nonetheless, marble extraction and processing consume energy, and the long-distance transportation of marble results in a large carbon footprint [2]. So local marble in Saudi Arabia will reduce its environmental footprint and promote its sustainable use, while minimizing transport emissions.



Figure (2) shows a picture of King Abdulaziz Hospital, whose facades were covered with natural marble.

3.1.4 Granite:

Granite is characterized by its high strength, durability, and weather resistance traits that make it an excellent candidate for heavy-duty building facades and flooring [5]. Granite also has low porosity preventing moisture from soaking into building components, thereby prolonging buildings' lifetime in regions where temperatures vary. Granite derives a high quality and long-lasting performance due to long durability, however, its extraction and cutting operations consume high energy and produce substantial dust and waste [21]. In countries like Saudi Arabia where granite deposits are relatively plentiful, the use of locally sourced granite supports sustainable building by lowering energy cost from imported granite, and encourages local industry to thrive.



Figure (3): A picture of King Faisal Hospital, whose facades were covered with natural granite.



Figure (4) An archaeological building in the city of Taif, constructed entirely of granite.

3.1.5 Hashmi Stone:

Because of their durability and beauty, along with their significant symbolism, the natural limestone that Saudi Arabia prefers and Hashemite stone that Jordan has chosen are popular materials used in regional architecture [46]. This local abundance also provides a distinct sustainability advantage with respect to reducing transportation energy and emissions while stimulating local economies [2, 47]. The stones both have high thermal mass and absorb and slowly radiate thermal energy, which can give good thermal comfort. This contributes to an indoor equilibrium, which minimizes the use of air conditioning systems [13]. While it is not strictly applied in the concrete industry at the time of construction, the waste produced in cutting and shaping can also be put to use in concrete or landscaping as aggregate, enhancing materials efficiency and enabling a circular economy in construction [48]. As quarrying has produced environmental impacts like land degradation and dust emissions [49], these changes can be counteracted with better quarrying management and waste reutilization strategies. Hence, the responsibility to use such stones locally improves environmental performance and keeps architectural identity, in accordance with the objectives of Saudi Vision 2030.

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Figure (5): *illustrates the cladding of facades with Hashemite stone.*

3.1.6 Basalt Stone:

Basalt is a volcanic stone with a high compressive strength, dark coloration, and durability under extreme thermal conditions. It is commonly employed in paving, structural blocks, and façade elements, mostly in terracing and infrastructure near volcanoes as was done in the Hijaz region [13]. The thermal mass of basalt enables passive temperature control, which is useful for reducing cooling loads in Saudi buildings. However, like all heavy natural stones, quarrying and cutting basalt is an energy-intensive activity [21]. Sustainable methods, such as the utilization of basalt aggregates from nearby quarries and the recycling of discarded stones, can both alleviate environmental impacts and maximize the effectiveness of green construction methods.

3.1.7 Lime Stone:

Limestone is one of the most common and historically utilized natural stones found in Saudi Arabia, mainly used in the western and central regions such as Taif and Makkah, where it has been commonly used in homes, religious, and civic buildings. The light hue, natural texture, and moderate compressive strength make it a suitable choice for its aesthetic, cladding, and ornamental aspects, giving it both strong aesthetic and structural significance [5]. Moreover, due to its porous texture, natural limestone walls promote thermal comfort by facilitating breathability of the wall while reducing heat transfer for passive cooling in the region's hot climate [13]. As for sustainability considerations, the embodied energy of limestone is quite low because of the very low mechanical processing demand for natural stones [2]. The wide local availability of the stone, particularly near Taif, means there is less need for long-distance transport, which reduces carbon emissions and leads towards local economic development [47]. Yet sustainable extraction is required to minimize environmental impacts including dust generation, land degradation, and visual impact on the environment [21]. Limestone is a natural material that is hardly ever recycled in architectural design but rather crushed and reused as aggregate in concrete applications or road base materials, and is considered to be part of circular construction. So, the responsible use of locally sourced limestone provides a very attractive combination of sustainability, thermal comfort, and recycling. It aligns with the environmental goals of Saudi Arabia's Vision 2030, while maintaining the cultural and architectural identity of its western cities.



Figure (6): illustrates a picture of the Taif University Mosque, whose facades were covered with limestone.

3.1.8 Mica Stone:

Mica is a naturally occurring silicate mineral. It is valued for optimal thermal and electrical insulation, robustness, and the way it appears overall mostly in wall finishes, coatings, and decorative panels [5]. From a sustainable development perspective, mica is a rich resource that takes far less energy to produce than other forms of synthetic media and has moderate embodied energy. However, unmonitored mining operation has environmental and social risks, especially where land degradation (and exploitation of labour) could occur [50]. The low thermal conductivity of the mica material, combined with its high heat resistance, makes it a reliable material for thermal insulation of building envelopes in terms of thermal comfort. This reduction minimizes heat transfer such that energy prices and climate adjustments take place in buildings [13]. Mica can be selectively reclaimed from industrial wastes and reused into composite materials or as a coating for surfaces. But it is impossible to conduct large-scale recycling here, for the processing takes place in fragmented units [51]. In the end, mica is the best source of recycled material for ecologically friendly building materials when responsibly collected. The good thermal characteristics, modest embodied energy and partial recyclability of the material now make it a component of use in green housing systems.

3.2 New Building Materials in Today's World:

The Sustainability, Thermal Comfort & Performance Issues Conventional concrete and steel used in construction of buildings and urbanisation has become a standard material since Taif construction experienced both a national trend with an overall trend in development phase. These are what the newest widely applied materials are:

3.2.1 Structural Applications: Reinforced concrete (RC)

Reinforced concrete (RC) in its highest compressive strength but also is known as the oldest and the most versatile building material, and is still one of the most common in construction materials nowadays. Reinforced concrete (RC) is a concrete (compression-strong) and steel (tensile force-resistant) combination with a range of structural members [52]. The use of RC on wall, slab floor and roof roofing systems of residential commercial and industrial buildings is widespread because, with an area having high resistance, there is no drop in structural integrity [53]. Its flexibility allows construction of intricate architectural shapes and structural designs; therefore, it is a good fit for modern architectural design [54]. Moreover, RC will not only withstand fire but also different environmental conditions. The sustainability of cement despite the energy consumption of cement production has been a challenge for many [55]. To resolve these difficulties, a variety of alternative practices were investigated such as SCM supplemented with recycled aggregates, and enhanced environmental aspects for RC structures are discussed, in relation to the SCMs and recycling aggregates [56]. While it has high structural advantages and efficiency in construction, RC has

long been known to have low thermal performance and cultural assimilation against the same materials as conventional constructions [57].



Figure (7): Depicts the application of reinforced concrete in the walls and ceilings of villas in Al-Ward City, Taif.

3.2.2 Concrete Blocks for Walls.

Concrete masonry units (CMUs), also known as concrete blocks, are used as wall building material because of their high compressive strength, durability, and convenience of installation [56]. Conventional concrete blocks from a sustainability point of view are a concern in terms of environmental impact, mainly because of the energy-intensive nature of cement production and its associated carbon dioxide (CO_2) emissions [55]. However, their longevity and low maintenance requirements play a positive role in the building lifecycle performance by decreasing repair frequency and waste materials [2]. Recent developments in green concrete block production involve the use of industrial by-products such as fly ash, slag, and recycled aggregates, contributing to minimizing embodied energy and carbon emissions [21]. The large thermal mass composition of concrete blocks helps in controlling the indoor temperature and consequently, avoids the need for mechanical heating and cooling, thus increasing efficient use of energy [13]. The structural performance, modularity, and sustainable value of concrete blocks is, therefore, an appealing construction option in the context of contemporary low- to mid-rise building typology.



Figure (8): Depicts A picture of a building in Taif made of concrete blocks.

3.2.3 Clay (Red) Bricks. Clay bricks:

known for their strength, durability, and thermal properties are among the oldest and most popular types of bricks among common materials that have attracted growing interest. These bricks are primarily made from natural clay, and are shaped and fired at high temperatures which have great compressive strength and weathering resistance for several structural and also non-structural applications to be made from them [56,55] argues that traditional firing processes are energy and CO_2 intensive, and because of this, are unsustainable from a sustainability perspective. In addition,

clay bricks possess high thermal mass which, in turn, could be utilised in buildings to enhance thermal comfort and energy conservation through reducing temperature range [13]. Red bricks also provide a compromise across efficiency, strength and environmental impact in a traditional and modern building use if produced responsibly and from in-country sources.

3.2.4 Aluminum, Glass, and Cladding – Facade Design

Numerous modern facades are covered with aluminum, glass and a multitude of other types of cladding since they also have aesthetic, structural and architectural functions. Aluminum is lighter and most recyclable, while recycled aluminum also significantly decreases energy consumption and greenhouse gas emissions compared with its primary production [58]. The use of glass helps in daylighting in addition to more energy-saving materials for double or triple glazing and low-emissivity coating, which prevents heat loss in winter, and leads to increased solar gain in summer [59]. The systems of cladding, comprising aluminum panels and composite materials (e.g., panels) give additional facade protection, improved appearance and thermal performance (however the impact of these factors on environmental performance varies from site to site) [5]. Nonetheless, properly constructed facades including aluminum, glass, and suitable cladding materials can increase daylight access, energy efficiency, solar radiation, energy usage and occupant comfort and energy usage efficiency respectively, to decrease glare, humidity, sunlight, and water consumption in the building, using minimal hours of cooling hours, and the energy used in heating. Conversely, in adverse scenarios, weak material selection can lead to overheating and/or energy requirements, highlighting the significance of facade construction in trade-off between ecological and thermal comfort as a necessary component for sustainability as well as energy and/or thermal comfort and thus should be one of the most essential considerations for facade material selection [60].



Figure (9): Depicts the building of the President of Taif University, with its facades clad in metal.

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*Figure (*10*): A picture of a building with a glass dome roof in the city of Taif.*

3.2.5 Curtain Wall Facades in Saudi Arabia:

Curtain wall facades are increasingly the trend in both commercial and high-rise buildings in the Kingdom of Saudi Arabia. Curtain wall systems (typically made from aluminum frames and glazed panels) have become very popular in construction and high-rise development in Saudi Arabia. They look very trendy and aero, lightweight, and are able to span large areas without stressing the main frame, so that they serve as an attractive visual architecture as well. The degree of transparency in a curtain wall will improve the penetration of sunlight on a daily basis, decreasing the need for artificial light. Furthermore, with the addition of high-performance technologies like double glazing, low-emissivity (low-E) coatings, and thermal breaks, the ability of curtain walls to improve thermal insulation increases and the overall energy efficiency is enhanced when properly engineered [61, 14]. Nevertheless, the hot arid climate of Saudi Arabia is particularly problematic when designing curtain walls. If shading devices are not implemented and selective glazing is not utilized, large glazed surfaces may induce excessive solar heat gain, resulting in substantial cooling demands and operational energy expenditure [62]. Further, due to the dust and extreme weather pattern in the region, there is a need to maintain these areas, including cleaning and sealant replacement, that if not properly detailed will affect performance in the long run. If curtain walls provide a facade with aesthetic elegance and design versatility, their environmental effects in Saudi Arabia are heavily reliant on strategies responsive towards climate. They include deep overhangs, external louvers, reflective or spectrally selective glazing, and hybrid façade systems combining opaque insulated panels with controlled glazing ratios, among others.

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*Figure (*11*): Depicts the Taif Chamber of Commerce building, with its facades covered with curtain wall.*

3.2.6 Wood Alternatives:

Conventional hardwood alternatives often include manufactured wood products, such as laminated veneer (LVL), cross-laminated timber (CLT) and recycled wood composites. Their eco-friendliness is clear when considering their manufacturing techniques, which are much less energy-intensive than traditional materials, such as steel and concrete. Moreover, usage of recycled materials minimizes their contribution to the overall environmental burden [5]. In addition to that, wood and the subsequent composites also have very good thermal insulation which is reducing the heat transfer, thus reducing energy consumption for indoor air conditioning [45]. Consequently, adopting more recycled, manufactured wood substitutes to find sustainable and thermal-efficient building materials is encouraging recycling and sustainable building.

4. Challenges Facing the Implementation of Sustainable Building Materials in Taif:

While Saudi Arabia's construction industry is making efforts to embed the principles of sustainability in its work, there are still several challenges to mainstreaming sustainable building materials in this industry. One major stumbling block is the relatively high cost of eco-friendly materials, largely due to limited domestic production and dependence on imported goods [11]. Another barrier is the lack of universally accepted criteria for the environmental performance of materials (especially in small- to medium-scale projects). Recycling and material reuse initiatives are underused on construction sites. In addition, the harsh climatic factors in the region, of which the mountainous Taif region is a typical example, make material selection a more challenging task, and the demand for locally adapted remedies must be made for overcoming special thermal and environmental challenges [63]. Nonetheless, government programs such as the Saudi Building Code Sustainability Requirements (2021) are aimed at promoting a transition to efficient and greener materials with regulations, financial incentives, and are aimed at supporting the Vision 2030 ambitions. Through research and institutional support, the construction industry in Saudi Arabia will transform for the better with future development.

5. Future Opportunities for Advancing a Sustainable Construction System in Taif:

A Proposal Next Steps to Optimize a Sustainable Construction System for Taif are further suggested. Taif possesses good promise of a sustainable construction environment which can be tailored to its unique environmental and climatic conditions and for the overall Vision 2030 objective of Saudi Arabia to facilitate sustainable construction activities. One huge opportunity lies in building buildings with greater thermal performance using local materials (stone, clay, wood, etc.), rather than relying on mechanical heating and cooling. This city's temperate mountainous context makes appropriate passive design features such as natural ventilation systems

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plus use of the optimal orientation to use of the building (to capture the sunlight and shading) possible [63]. Another opportunity is cultivating exploration and development of new sustainable building materials with local universities and research institutions. This is where sustainable materials that adapt to Taif's semi-arid zone conditions can be produced. In parallel, following the Saudi Building Code – Sustainability Requirements (2021) offers a guiding structure in terms of energy efficiency measures in new construction projects and the adoption of modern green concrete and intelligent thermal insulation as standards [11]. Through this, public–private partnerships can catalyze the movement towards more sustainable construction by providing funding and environmental standards for construction. These partnerships are able to address financing, capacity and execution gaps. In all, Taif's unique terrain and weather conditions present its own unique character as an important candidate to be considered a national benchmark of sustainability in construction. The use of the city's resources, adoption of green strategies from local producers, and inclusion of sustainability in urban design are two ways in which we can move in the direction of a safer built environment that will be both resilient and environmentally secure.

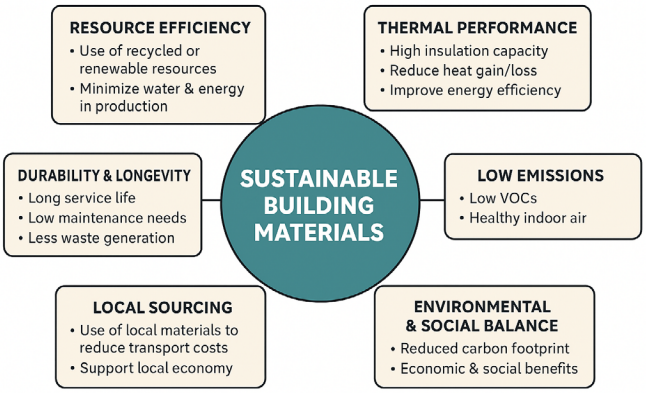


Figure (12): Illustrates the Key Sustainability Criteria for Building Materials in the Context of Taif's Construction Sector.

6. Commonly Used Building Materials in Taif and Their Sustainability Compliance

Construction Materials That are Used in Taif and Sustainability: Conformance. Conventional materials for Taif construction are mostly reinforced concrete, steel and cement blocks such as that used in other cities in Saudi Arabia. Selected building types and types of use, etc. are based on materials such as these for this purpose. Concrete possesses a high strength as a compressive material, and steel has been utilized to structure the design of commercial and multi-storey buildings[57, 63]. As sustainability starts to emerge in the construction industry, data on what kind of durable materials are going to be used (recycled aggregates, low-carbon concrete, lifecycle-based assessments…) is limited. The Saudi Green Initiative and municipal action indicate that consciousness of the environment is on the rise. The biggest one is expansion of green space to 8 million square meters in Taif and the planting of more than 600,000 trees and seedlings in Taif's center nursery for 2024 [64,65]. While the utilization of sustainable materials is still a work in progress but the projects as well as additional exploration/testing and experiments are evidence of a milestone shift towards the global deployment of sustainable building materials. However, new structures and development have to be a seamless blend of new low impact materials with sustainability – as a minimum value compromise of both structural quality as a matter of sustainability, and ecological behavior.

7. Trends in the Development of Sustainable Building Materials

The construction industry has focused on greener building materials to address environmental challenges and the rising energy demands required to keep buildings sustainable. The introduction of recycled industrial by-products (e.g., fly ash and blast furnace slag) into green concrete formulations, which substantially decrease the requirement of standard cement with high carbon emissions, has proven to be an ongoing trend [66]. Another important trend is the development of materials from locally sourced, low embodied energy raw materials (stone, clay, other resources) compatible with regional weather and transportation that reduce transportation emissions [2]. In Saudi Arabia, Vision 2030 has stimulated innovation in sustainable construction initiatives, which lead to the adoption of low-emission, high-performance concrete and sophisticated thermal insulation systems in line with the Saudi Building Code Sustainability Requirements [15]. Cities like Taif and Riyadh are gradually incorporating scholarly investigation and locally developed technologies into climate-responsive building solutions. The emerging changes reveal sustainable construction materials as strategic imperatives and are no longer "nice to have" for the industry but core business for improving resource efficiency and protecting the environment in the construction industry.

8. Comparative Assessment of Traditional and Sustainable Materials:

In Taif, it is therefore essential to investigate whether these traditional and sustainable building materials are more environmentally, economically, and climatically appropriate than the others. Conventional building materials like reinforced concrete, red bricks, and steel, the structural strength and availability of proven conventional materials make them widely used. But their production methods tend to consume energy and are a major contributor to carbon emissions. Green concrete, advanced thermal insulation, and recycled components as alternative options are considered eco-friendly alternatives that improve thermal performance and energy use efficiency [2, 11].

8.1 Eco-Performance:

Studies suggest that sustainable materials can greatly lower carbon emissions and conserve natural resources compared to traditional options. Green concrete and other materials, such as fly ash or slag, reduce the use of cement by 30–40%, thereby directly reducing CO_2 emissions, for instance. Furthermore, use of natural and wood-based insulation substances also enhances thermal regulation, minimizing the significance of mechanical heating and cooling systems [13].

8.2 Lifecycle Cost-Benefit

Although upfront costs of using sustainable materials may be higher, lifecycle analyses demonstrate long-term benefits that yield economic benefit. High-efficiency insulation systems, for example, yield 20–30% savings in annual energy consumption over the building's operational life. In addition, the option of using recycled materials reduces construction project costs for waste and environmental risks from these resources, increasing the financial sustainability of sustainable construction projects [66].

8.3 Climatic Suitability for Taif

Suitable for the climate of Taif. Taif has a mountainous terrain and a temperate climate—with daily and seasonal temperature variations requiring materials that will respond to thermal fluctuations well. Conventional materials, such as brick or dense concrete, are heat-retaining elements, which could result in a higher cooling burden. Even with minimal energy consumption, sustainable alternatives such as locally sourced wood with high-performance insulation achieve better thermal control and environmental protection from within. They demonstrate the qualities mentioned previously and are very appropriate in the Taif condition [63]. Table (3) provides the

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comparative results based on the materials for Taif (traditional and sustainable) and examines their sustainability, culture, and environmental performance.

Table (3): Comparison between Traditional and Modern Building Materials in Kingdom of Saudi Arabia[*13,* ,41 2*,* 21*, 30,* 9*, 34, 31, 33, 5,* 67*, 48,*32*, 13, 5*] :

Aspect	Traditional Materials (e.g., stone, adobe, lime plaster)	Modern Materials (e.g., concrete, steel, glass)
Climatic Suitability	High – Provides natural thermal insulation	Medium to low – Requires additional cooling systems
Environmental Impact	Low – Natural and locally sourced materials	High – Due to industrial production and transportation
Cultural & Architectural Identity	Reflects local heritage and aligns with urban fabric	Often lacks local character
Social Dimension	Supports traditional craftsmanship and the local community	Often depends on external supply chains
Cost	Low to medium (depending on availability)	Medium to high
Ease of Maintenance	Easy to maintain and replace	May require specialized maintenance techniques
Indoor Comfort (Thermal & Acoustic)	High – Natural insulation enhances comfort	Depends on additional processing (industrial insulation)
Long-Term Sustainability	High – Durable with strong environmental compatibility	Depends on ongoing maintenance and technological support

9. Discussion:

This section then provides discussion of results indicated in Tables (1) through (4), the multifactorial action of building materials in developing sustainable construction practices of Taif is accentuated. Table (1) presents the Social Dimensions (S) in Table (1). Table (1) indicates that building materials in Taif fulfill a social need to promote sustainable development. Non-toxic, locally sourced and culturally appropriate materials do not only help the health of the planet, but the health of the community. They are more safety promoting, they support local employment and they safeguard the architectural heritage. Sustainability in Taif requires an ecologically and human sustainable path between eco-mechanical activities and integration with environmental, social and cultural aspects so that built materials are conducive to community living. What we find in Table (2): The Sustainability Triple-Bottom Line. Table (2) reveals that climate-friendly construct materials offer environmental, economic and social dividends. But environmentally, this sort of thing decreases energy use and greenhouse gas emissions, and has some environmental benefits, as well: environmental benefits. They also benefit economically, not just with longevity opportunities (like life cycle savings) but in that they protect our local supply, making them a more cost-effective long-term model. From the societal perspective, they promote healthier living, more peaceful living conditions and sustainability in a natural way for consumers who are living inside in a more sustainable manner. By incorporating them, the three dimensions integrate to make selection of materials one that contributes towards holistic sustainability and enhancing overall performance on a building. Table comparison material performance — summary of points from Table (3). Table (3) A comparison of conventional and modern building materials used in Saudi Arabia. Classic materials — stone, clay, wood — are at their most climatically perfect, environmentally benign and culturally closer. In contrast, the modern materials–those whose performance is improved such as reinforced concrete and steel etc.—have structural and ecological performance advantages, but are often more costly environmentally and less culturally connected. Thus, this comparison reveals that a fusion of old and new practices in terms of environmental, social and technological sustainability is the way to reconcile sustainable practices in Taif. As we transition to Circular and Climate-Responsive Design – insights (Table (4)) Table (4) reiterates

that the maximise the sustainability benefits using locally sourced materials and design-for-disassembly design principles. Such green materials (e.g. materials having a high effect on the environment) can be obtained from local supply value chain processes, transported in a relatively rapid flow, and then assembled and manufactured for reuse or recycling, recyclability, and reusability. A review concluded that in terms of sustainability and thermal comfort, traditional materials derived from nature are more suited to circular economies and design-for-disassembly of climate action.

*Table (*4*): Comparison of materials sustainability, recycling, and thermal comfort*:

Material	Sustainability (summary)	Recycling / Reuse	Thermal comfort (effect)
Wood (local, sustainably sourced)	When sustainably harvested, high: renewable, low embodied energy, carbon-sequestering. Impacts rise if transported far or from unsustainable logging.	Excellent: components can be reused, remanufactured, or recycled into composites, biodegradable.	Good: low thermal conductivity, contributes to insulation and stable indoor temperatures, pleasant radiant surface.
Marble	Moderate–Low: natural, durable, long life, quarrying and transport are energy-intensive and cause landscape impact.	Moderate: large slabs are reusable in finish applications, off-cuts can be crushed for aggregate or landscaping.	High thermal mass: absorbs heat and slowly releases it good for diurnal temperature buffering but can feel cold to touch.
Granite	Moderate: reusable as facing material, crushed for aggregate or paving base.	Moderate–Low: very durable and long-lasting (reduces replacement), quarrying & transport energy are significant.	High thermal mass: effective for stabilizing indoor temperature swings, can retain cold/heat.
Basalt	Moderate: natural volcanic rock, durable with long service life, quarrying impacts similar to other stones.	Moderate: reused as crushed aggregate (high quality) or paving, architectural reuse less common.	High thermal mass: good for thermal storage and reducing peak loads.
Crushed stone (aggregates)	Depends: often a by-product of quarrying — useful in circular use if locally sourced, embodied impacts from extraction/transport.	Excellent: inherently recyclable as aggregate in new concrete, road bases, fill.	Low direct insulation: used in mass elements (contributes thermal mass when part of concrete), as loose material offers little insulation
Mica	Moderate: natural mineral with relatively low processing energy, but mining can cause social/environmental issues if unregulated.	Limited–Moderate: some reuse in composites/coatings, fine fragmentation limits direct large-scale reuse.	Good heat resistance and low thermal conductivity (as filler/insulation layer it can improve thermal performance), not typically used as primary insulating element.
Glass (façade glazing)	Variable: high embodied energy for production, but long life and benefits from daylighting/solar control when specified correctly. Recycled cullet lowers impacts.	Moderate: glass is recyclable (cullet) but architectural glass with coatings or laminated layers is harder to recycle.	Poor as a bare layer (single glazing): high heat loss/gain. Good if double/triple glazing with low-E coatings and thermally broken frames improves daylight while controlling heat transfer.

Cladding (aluminum panels, terracotta, fiber-cement, composites)	Variable by type: terracotta/ceramic and fiber-cement have moderate impacts, aluminum panels have high production energy but high recyclability, composites can be less sustainable.	Variable: metals (aluminum, steel) recycle well, terracotta can be reused, composite panels are harder to recycle.	Depends on system: ventilated façades, insulated rainscreens and cladding with cavity/insulation greatly improve thermal comfort and reduce heat transfer.
Cement bricks / Concrete blocks (CMU)	Low–Moderate: relatively high embodied CO_2 from cement, long life and low maintenance mitigate some impacts, using SCMs or recycled aggregate improves sustainability.	Moderate: masonry can be crushed and used as recycled aggregate, whole units are reusable with effort.	Moderate–High thermal mass: good for stabilizing temperatures but poor intrinsic insulation typically needs insulation layer for comfort in extreme climates.
Clay bricks (traditional fired clay)	Moderate: locally made sun-dried bricks have low impact, fired clay has energy demand for kilns but long life and local production can improve sustainability.	Good: bricks can be cleaned and reused; crushed bricks serve as fill/aggregate.	Good thermal mass and moderate insulation (depending on porosity and cavity design), provides comfortable indoor conditions when combined with ventilative design.

9.1 Proposed Framework:

9.1.1 A guideline or framework to adopt sustainable building materials:

A guideline or framework which will help guide the development of sustainable building materials will be of utmost essence to the construction industry in promotion of sustainable building materials. Policymakers, builders, and construction professionals can take a pragmatic, comprehensive view and develop guidelines for materials efficiency, environmental impact assessments, sustainability assessments, and/or practical suggestions for building new structures. This kind of framework provides clear guidelines for developers, contractors, and engineers to determine the environmental, thermal, and energy properties of the materials to be selected. This advice may include some key aspects, such as Life Cycle Assessment (LCA) that could assess a material's environmental impact throughout its life cycle, thermal efficiency and insulation regulations that would be implemented to minimize power consumption, and how closely a material aligns with the Saudi Building Code – Sustainability Requirements. The framework should also include a classification of materials between traditional and sustainable categories, and guidance to use low emission local sources, recycled materials, and high-performance thermal insulation material. Environmental Performance Indicators (EPIs) in order to measure materials' sustainable performance in a project can also be integrated so that the projects have data-based solutions that will ensure the sustainability of the project as per Vision 2030 objectives. Having a reference in this manner also increases stakeholder awareness and standardizes environmental and sustainable construction practices, in Taif projects on the local level, local experiences demonstrate the long-term effect of this step, as it saves energy and natural resources in the process.

9.1.2 Opportunities and Challenges in Implementing Sustainable Building Materials in Taif:

These are the opportunities and challenges on how to implement the sustainable building materials in Taif. Insights on the integration of the insights in Implementation Stages and Building Materials sector into the theoretical framework of research on the importance of implementation within Taif including opportunities and challenges to sustainable building materials in Taif can be represented in the following matrices underlining the correlation between key influencing factors and their

corresponding strategic policies or interventions. The Table No. (5) presents a holistic framework outlining structural, cultural, and organizational challenges of sustainable construction in Taif, which identifies that, in order to work through them, they must be addressed through multi-stakeholder collaboration and integration of policies, design, training, and awareness in order to meet the sustainability targets for Vision 2030 aspirations set out to achieve locally in terms of Vision 2030 in the region.

9.1.3 Guideline for the Adoption of Sustainable Building Materials

An ideal model for the practical usage of sustainable building materials is the first step towards promoting sustainability in the construction industry. This kind of framework sets concrete, actionable standards for what type of material to use — as per how it influences the environment, thermal performance, and energy efficiency. Underpinning the guideline can be at least the following:

- Life Cycle Assessment (LCA): Assessing the environmental impact of materials all the way from sourcing, manufacture and use until disposal.
- Thermal Efficiency Standards: Establish a standard for insulation and energy performance to reduce operational energy use.
- Regulatory Compliance: Complying with the Saudi Building Code – Sustainability Requirements to ensure alignment with national sustainability objectives.

In addition, the framework should classify materials into traditional and sustainable groups, promoting the use of locally sourced, low-emission materials, recycled content, and advanced insulation technologies. The use of Environmental Performance Indicators (EPIs) provides project teams data to evaluate material sustainability, enabling informed decision-making and linking the products and processes with Vision 2030 objectives. Recent evidence from local initiatives conducted in Taif showed that guidelines of this nature raise awareness among stakeholders, promote standardized sustainable practices, and contribute to long-term resource and energy savings.

9.1.4 Opportunities and Challenges in Taif's Sustainable Material Implementation:

This study draws on theoretical approaches as it is grounded in practical information received from the building materials sector, thereby mapping the opportunities and challenges of integrating sustainable construction practice in Taif. These are in Table (5) where the relationships of the major forces and strategic interventions are listed. The table reveals the major structural, cultural, and organizational constraints to sustainable construction in Taif that must be addressed. It underscores the importance of a coordinated group response from policymakers, designers, educators, and industry experts to address these issues. Key to success would be for sustainability to be incorporated within the design process, for technical training to be strengthened, for public and professional awareness of the subject to be raised, and for collaboration between sectors to be promoted. There are challenges to achieving sustainability in Taif's construction industry, and one of them is its need to take a local, multi-dimensional response informed by the unique environmental and cultural background of the city, and be in support of Vision 2030 in general.

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Table (5): Challenges Matrix for Sustainable Construction in Taif (Aligned with Vision 2030)

Challenge Area	Architectural / Environmental Implications	Policy / Strategic Response	Stakeholders
Hot and Dry Desert Climate	High temperatures, thermal expansion, material shrinkage, cracking, dust accumulation, reduced durability	Promote climate-responsive design: shading, high-performance insulation, natural ventilation	Architects, Engineers, Municipalities
High Initial Cost of Sustainable Materials	Greater upfront investment compared to conventional materials, delayed ROI	Implement financial incentives: subsidies, tax reductions, low-interest loans	Government, Economic Development Agencies, Developers
Limited Awareness and Technical Knowledge	Improper material selection and installation, suboptimal performance	Launch technical training, workshops, and certification programs	Contractors, Engineers, Developers, Training Institutes
Limited Local Material Availability & Supply Chain Gaps	Dependency on imports increases costs and carbon footprint, inconsistent material quality	Encourage local production, establish supply chains, and certify materials to recognized standards	Material Suppliers, Industry Associations, Local Manufacturers
Weak Regulations and Standards	Lack of enforcement and uniform criteria slows adoption of sustainable construction	Strengthen legislation, enforce SBC Sustainability Requirements, promote environmental certification systems	Government Regulators, Municipal Authorities
Shortage of Qualified Labor & Modern Technology Adoption	Specialized skills required for green construction, limited local experience	Develop capacity-building programs and provide access to advanced construction technologies	Contractors, Technical Institutes, Equipment Suppliers
Cultural Attitudes & Traditional Preferences	Preference for conventional aesthetics may resist sustainable design adoption	Promote awareness campaigns highlighting long-term benefits, market advantages, and social responsibility	Developers, Clients, Media, Industry Associations

The following strategic opportunities show on Table (6) which could help to uplift Taif's sustainable construction process. These resonate with national policies put into place at the country's level through the Vision 2030 framework, availability of locally sourced materials, increasing market demands and continuous technological improvements. And it's these components that are instrumental in promoting the environmental, economic and social aspects of the building process. They are the foundation for the sustainability standards being used and help establish Taif as a model of healthy resilient city development.

Table (6): Opportunity Matrix for Sustainable Construction in Taif (Aligned with Vision 2030)

Opportunity Area	**Strategic Potential**	**Architectural / Environmental Impact**	**Implementation Leverage**
Governmental Support & Vision 2030 Alignment	National policies encourage green construction	Facilitates regulatory adoption of sustainability standards across Taif	Apply SBC – Sustainability Requirements as mandatory baseline
Long-Term Economic Efficiency	Reduced operational costs through lower energy & water consumption	Improved thermal comfort decreases HVAC loads and extends building lifespan	Integrate passive cooling + efficient water reuse systems
Local Material Availability	Abundant stone, clay, and natural fibers	Enables production of vernacular-inspired low-carbon materials	Establish local manufacturing units / workshops
Growing Market Demand	Increasing consumer and developer interest in eco-friendly buildings	Enhances real estate value and public perception	Promote certification labels (e.g., "Green-Ready Building")
Technological Innovation	Adoption of smart shading, energy-efficient glazing, natural ventilation	Boosts building performance in hot-arid climates	Encourage hybrid systems integrating active + passive strategies
Emerging Sustainable Material Technologies	Low-carbon concrete, reflective coatings, green roofs, solar systems	Reduces heat gain and carbon footprint	Pilot projects and R&D partnerships in Taif
Economies of Scale Potential	Increasing demand will reduce sustainable material costs	Sustainable materials become cost-competitive	Aggregate purchasing programs among developers
Environmental & Social Benefits	Lower emissions, reduced heat and noise pollution	Enhances resident well-being and urban livability	Position Taif as "Healthy & Resilient City Model"

Conclusions:

A core conclusion is the main finding from the study over the overall questions and key investigations. Natural stone: the sustainable use of natural stone for Saudi architecture. The traditional stones [marble, granite, Hashmi stone, basalt, limestone] have played a leading role in shaping the character of the Saudi Arabian architectural project and in developing the concept of green building. Marble and granite add strength to style, basalt is used for thermal control and structural integrity, Hashmi stone is locally recognizable and weather-resistant, limestone strikes the right balance between aesthetic and environmental values. In cities such as Taif, having these local stones not only streamlines energy-saving transportation but also sustains the local economy and aligns with resource-efficient and life-cycle sustainability. Because they possess lower embodied energy and thermal mass, the buildings also can be designed with energy-efficient building envelopes that help to set up a facility in the hot arid climate of Saudi Arabia. Still, more effort has to be put into providing real sustainability and not without difficulties: the development of good quarrying techniques, proper waste management and recycling and reuse will all help to achieve it. These strategies, aligned with the goal of Saudi Vision 2030, are expected to boost environmental performance, keep a vibrant culture alive, and give a climate-responsive urban strategy based on local experience. How much can the implementation of building materials that are sustainable in Taif City benefit from the sustainability of the system? Environmental, economic and social components need to be integrated into sustainable building materials as building materials not only in terms of number of sustainable construction materials, the study suggests. Each dimension represents a characteristic that is related to (such as environmental, economic feasibility, community support, and sustainability) elements responsible for the choice and construction methods of sustainable materials. The data on the resources used as above, the

reduction of CO2 emissions, recycling rates highlight the environmental factors, The social factors refer to user comfort and health & safety of users, and sustainability. We find that deeper social conditions of cultural and ethical relevance, as well as cost, appear in the last chapter, as necessary prerequisites for a socially sustainable built environment. Traditional materials of different quality and usage as compared with more modern types show that what's most viable in Taif can be judged by their practical qualities: traditional materials (stone, brick, lime plaster, etc.) provide superior climatic efficacy, lower embodied energy, and integration with cultural heritage or quality management and artisanal skills. They are instrumental in achieving the sustainability environmental and social wise. On the other hand, modern materials with good structural properties, such as concrete and steel, are more energy-consuming, more industry-dependent, less culture-adaptable and heavily dependent on industry. Hybrid design techniques, such as recycled façade systems, high performance glazing and design-for-disassembly techniques, and the application of both material methods can further increase performance both environmentally and thermally.

What are the most commonly used building materials today in construction works like Taif and how environmentally and climatically suitable are they?

Taif is constructed with reinforced concrete, concrete blocks, red clay blocks, natural stone, steel, insulating and glass panels, gypsum/plaster finishes, and wood (used only infrequently) in the survey. Based on the framework provided in this study, the environmental and climatic fit of these materials to local applications is discussed and shown in Table (7).

Table (7): The most commonly used building materials in current construction projects in Taif and their environmental and climatic suitability for use.

Building Material	Environmental Assessment	Climatic / Thermal Assessment	Recommendation
Reinforced Concrete	Low to medium sustainability due to high carbon emissions	Offers good thermal mass but requires additional insulation	Use with cement substitutes and ensure proper thermal insulation
Clay Brick / Masonry Blocks	Environmentally favorable when locally produced	Excellent thermal balance	Recommended for external walls and double-layer roofing
Natural Stone	Environmentally sound, especially when locally sourced	Exceptional durability and thermal mass	Ideal for sun-exposed façades and exterior cladding
Steel	Moderate to high energy consumption in production, fully recyclable	Poor thermal performance	Best used as structural framing with adequate thermal cladding
Glass / Insulated Panels	Moderate sustainability, energy-intensive manufacturing	Ineffective without shading	Use as double-glazed units with shading devices or louvers
Gypsum / Plaster Finishes	Moderate environmental impact	Neutral thermal properties	Suitable for interior finishes, consider natural alternatives where feasible
Wood (Limited Use)	Environmentally beneficial—renewable and recyclable	Provides good natural insulation	Recommended for interior finishes and decorative applications only

What criteria are adopted when selecting building materials, and do they consider the material's life cycle and environmental impact?

What rules are followed in selecting building materials and do they take into account the life cycle of the material and the environmental footprint? Key criteria for selection of building materials have been identified following a theoretical review of the relevant literature and case studies aligned with the context of this study. These standards stress a need to consider products at every

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stage of their life cycle, with special attention to the extent to which they contribute to the environment. Table (8) provides a comparative assessment of conventional practices, lifecycle assessment-based sustainable approaches and proposed best practice for material selection in construction.

Table (8): Comparison of Conventional vs. Sustainable Material Selection Practices With Recommended Best Practice

Selection Criteria	Conventional Practice	Sustainable / LCA-Based Practice	Recommended Best Practice
Primary Decision Drivers	Based on initial cost, availability, and contractor preference	Focused on long-term durability, life cycle cost, and overall performance	Implement Life Cycle Costing (LCC) instead of relying solely on upfront pricing
Environmental Impact	Seldom measured or documented	Assessed using Life Cycle Assessment (LCA) tools (e.g., embodied carbon, pollution index)	Make LCA reporting mandatory for key materials prior to approval
Thermal / Energy Performance	Considered only when required by regulations	Integrated early in design to optimize building envelope and HVAC efficiency	Apply performance-based specifications aligned with thermal performance benchmarks
Durability & Maintenance	Often overlooked, future maintenance costs not prioritized	Materials chosen for extended lifespan and minimal upkeep	Require maintenance cost projections over a 20–30-year period before selection
Recyclability / End-of-Life	Typically disposed in landfills or reused without control	Preference for recyclable or reusable components	Establish material take-back programs and set targets for recycled content
Compliance & Certification	Limited to structural safety and fire regulations	Includes adherence to green standards (e.g., LEED, SBC Sustainability, ISO 14040)	Develop a local certification system for "Approved Sustainable Materials"
Supply Chain Considerations	Selection based on lowest bid	Emphasis on local sourcing and low-emission suppliers	Introduce a supplier sustainability rating system
Decision-Making Stakeholders	Decisions led by contractors or cost engineers	Collaborative input from architects, sustainability experts, and MEP engineers	Require multi-disciplinary review panels for material approval

Environmental and Economic Benefits of Adopting Sustainable Alternatives Compared to Conventional Materials

Benefits of using sustainable alternatives to other materials compared to conventional materials in environmental and economic terms. The results of the research confirm the fact that sustainable building material use is not merely a matter of policy choice but a strategic necessity of constructing an efficient, up-to-date building system in Taif, not a preference of Taif City environment. Well thought-out material selection plays a crucial role in the following:

- Reducing energy consumption.
- Cutting down carbon emissions.
- Improving indoor thermal comfort.

These advantages are especially important given the hot-arid climate in Taif. Through the implementation of such sustainable materials in local construction, we not only improve sustainability, but we also contribute significantly to building socio-cultural and economic resilience, thus promoting an eco-integrated city. The use of these materials is not, however, widely accepted in practice and confronts some limitations.

- High initial costs.
- Limited technical know-how in the industry.
- Lack of common guidelines for evaluating environmental performance.

Recommendations:

To enhance the transformation of Taif to sustainable construction, the following ways are suggested:

- Formulate Locally-based Recommendations for Sustainable Material Selection
- Setting transparent Life Cycle Assessment (LCA) and climate-sensitive considerations.
- Encourage LCC in Procurement Processes
- Transition from upfront cost-based selection to value and performance in the long term.
- Development and Training of Skills

Train architects, engineers, and builders in sustainable design and materials.

- Bring in Incentives for Sustainable Practices in place

Promote projects that focus on sustainable materials and methods for which financial or regulatory incentives may be used to award financial, social, or legal benefits.

- Develop a Local Certificates System.
- Establish a scheme for the certification of "Approved Sustainable Materials" with domestic and international standards as per the new framework.
- Promote Hybrid Design Approaches.
- Facilitate the convergence of traditional and modern materials for better environmental and cultural achievement.
- Promote Collaboration between Stakeholders.
- Require multi-disciplinary review panels that include sustainability experts, architects, and engineers to decide which materials to approve.

Policy Framework for Enabling Sustainable Construction in Taif:

Table (9) presents a strategic matrix of recommended policies designed to accelerate the adoption of sustainable construction practices in Taif. Each policy area outlines targeted actions, responsible stakeholders, policy instruments, and anticipated impacts.

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Table No. (9): Shows the matrix of recommended policies to enable sustainable construction in Taif.

Policy Area	Proposed Action	Responsible Stakeholders	Policy Instrument	Expected Impact
Regulation & Compliance	Integrate sustainability criteria into building permit approvals, aligned with the Saudi Building Code – Sustainability Requirements	Municipalities & Regulatory Authorities	Mandatory Guidelines / Permit Conditions	Ensures minimum environmental performance standards in all new construction projects
Economic Incentives	Offer subsidies, fee reductions, or tax benefits for projects using certified sustainable materials	Municipalities & Economic Development Agencies	Financial Incentives	Stimulates private sector investment and lowers financial barriers
Capacity Building	Launch professional training programs on sustainable material selection and life cycle assessment	Engineering Syndicates, Contractors' Unions & Training Centers	Technical Certification & Continuous Education	Improves technical expertise and feasibility of sustainable adoption
Research & Local Innovation	Support R&D initiatives for locally sourced or recycled materials suited to Taif's climate	Universities, Research Institutes & Private Sector	Research Grants & Public–Private Partnerships	Expands availability of affordable, climate-adapted building materials
Performance Monitoring	Develop a standardized framework for environmental assessment of construction materials	Government Agencies & Standards Organizations	Rating / Labeling System	Enables transparent evaluation and benchmarking across construction projects
Public Engagement	Conduct awareness campaigns on the health and economic benefits of sustainable buildings	Media, NGOs & Developers	Communication Campaigns & Public Outreach	Builds public demand and shifts consumer preferences toward sustainable solutions

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Adopting Sustainable Alternatives to Traditional Materials

Table (10) *outlines the anticipated environmental and economic benefits of using sustainable building materials compared to conventional options. The comparison highlights how sustainable alternatives contribute to improved performance across multiple dimensions, reinforcing their strategic value in future-oriented construction practices.*

Benefit Category	Conventional Materials	Sustainable Materials	Overall Advantage
Carbon Emissions	High embodied carbon due to energy-intensive manufacturing	Reduced embodied carbon through low-impact production and recycled content	Environmental
Operational Energy Use	Higher energy demand due to poor thermal performance	Lower energy consumption through enhanced insulation and compatibility with passive design	Environmental + Economic
Resource Consumption	Sourced from non-renewable or imported materials	Locally sourced or derived from renewable/recycled resources	Environmental + Local Economy
Waste Generation	Generates substantial construction and demolition waste	Engineered for recyclability or reuse, reducing landfill impact	Environmental
Maintenance Costs	Requires frequent repairs or replacements over time	Extended lifespan with minimal maintenance needs	Economic
Lifecycle Cost	Lower initial cost but higher long-term operational expenses	Higher upfront investment offset by long-term savings in energy and maintenance	Economic
Indoor Comfort & Health	Limited impact on indoor air quality	Use of low-VOC and breathable materials enhances occupant well-being	Environmental + Social
Market Value	Standard performance with limited differentiation	Increased asset value and market appeal due to sustainability credentials	Economic

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Occupant Satisfaction in Green vs. Conventional Buildings: A Systematic Literature Review

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Keywords: Sustainability, Green Building, Occupant Satisfaction, Rating Systems, Indoor Environmental Quality (IEQ), Post Occupancy Evaluation, Green Certification

Abstract. Through a systematic literature review, this paper investigates occupant satisfaction within green buildings compared to conventional buildings, focusing on how green certifications like LEED, BREEAM, and others impact occupant experiences across various attributes, including indoor environmental quality (IEQ) parameters such as thermal comfort, lighting, acoustics, and indoor air quality. The review is based on literature collected primarily from the Scopus and Web of Science databases, using defined search strings related to green buildings and occupant satisfaction. Through a comprehensive analysis of scholarly databases, examining 30 papers published between 2018 and 2025, this study reveals mixed findings on whether green certified buildings provide superior occupant satisfaction. The selection of studies followed a structured inclusion and exclusion process, focusing on peer-reviewed journal articles in English and excluding conference papers, book chapters, and unrelated studies after title, abstract, and full-text screening. Our review indicates that satisfaction levels are highly influenced by geographical and cultural contexts, suggesting that green building practices and their perceived benefits might be region-specific. Additionally, the research emphasizes the complexity of occupant satisfaction, highlighting discrepancies in satisfaction levels across different IEQ parameters. Despite some areas of inconsistency, the prevailing evidence points towards a general inclination for higher occupant satisfaction within green buildings, particularly in terms of lighting comfort and indoor air quality. However, the relationship between green certifications and occupant satisfaction remains ambiguous, necessitating further research to uncover the full extent of green buildings' impact on occupant well-being and satisfaction. This paper contributes to a more comprehensive understanding of the implications of green building certifications on occupant experiences, offering insights into future research directions and the development of green building practices globally.

Introduction

The pursuit of sustainability has transformed the landscape of building design and construction, leading to an increased focus on green buildings. These structures, characterized by their reduced environmental impact and enhanced efficiency, represent a significant shift towards more sustainable living and working environments. However, as the adoption of green building practices grows, so does the scrutiny regarding their actual benefits, particularly in terms of occupant satisfaction. Occupant satisfaction is a multifaceted concept encompassing IEQ parameters, Building Design (BD), and Facilities Management (FM) (Comfort of Furnishing, Space Layout, Maintenance, and Building Cleanliness) and overall well-being within the built environment. This paper seeks to investigate the satisfaction levels of occupants in green buildings, contrasting them with conventional buildings, to assess whether green certifications genuinely translate to improved occupant experiences.

Despite the rapid growth in green building certifications such as LEED, BREEAM, and Green Star, research presents mixed findings on whether these buildings offer superior indoor

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environmental quality (IEQ) and occupant satisfaction compared to their non-certified counterparts. For instance, Altomonte et al. (2019) highlight that LEED certification does not significantly impact occupant satisfaction regarding IEQ aspects, challenging the assumption that green certified buildings naturally offer better living and working conditions. Conversely, studies like that of Lee et al. (2019) suggest that occupants in Green Mark-certified buildings report higher satisfaction levels, indicating potential benefits in certain green certification schemes. However, existing studies are fragmented across different certification systems, geographical regions, and building types, and a comprehensive synthesis comparing certified and conventional buildings remains limited.

This paper aims to conduct a systematic literature review to identify patterns, trends, and gaps in the research on occupant satisfaction in green buildings. Through an extensive analysis of scholarly databases, this study will explore the complications of occupant experiences in certified sustainable and green buildings, contributing to a more comprehensive understanding of the real-world implications of green building certifications on occupant well-being and satisfaction.

Methodology

Through a systematic content analysis, this paper aims to identify patterns and trends regarding occupants' satisfaction with certified sustainable and green buildings. Thereby, scholarly databases, mainly Scopus and Web of Science, were systematically searched using two sets of search strings, which were combined using the Boolean operator AND in the database queries to identify original articles published on the topic, the time period of the study comprised the literature published between the years 2018 and 2025, the database research was formed including two search strings as follows:

Primary Search: "sustainable architecture" OR "sustainable building*" OR "green architecture" OR "green building*" OR "green certification" OR "green label*"

Secondary Search: "Occupant* Satisfaction" OR "Occupant* perception*" OR "user* Satisfaction" OR "user* perception*"

The initial database search retrieved 420 records (Scopus n=214; Web of Science n=206). In addition, four records were identified through snowballing from references of relevant studies (n=4), resulting in a total of 424 records before removing duplicates. After the removal of duplicates, 220 records remained. The screening process followed a three-stage approach:

- Eligibility assessment: Titles, keywords, and abstracts were screened to remove clearly unrelated articles, resulting in 68 records for further review.
- Screening: Full abstracts and available text were evaluated to apply inclusion/exclusion criteria, reducing the number of records to 43.
- Full-text assessment: The remaining articles were assessed for credibility and verification of claims regarding the building being green, either through certification evidence or mention of the assessment tool. After applying these criteria, 30 papers were included in the final analysis.

Inclusion criteria were limited to peer-reviewed journal articles published in English, while conference papers, book chapters, and other document types were excluded. Figure 1 illustrates the search and selection process.

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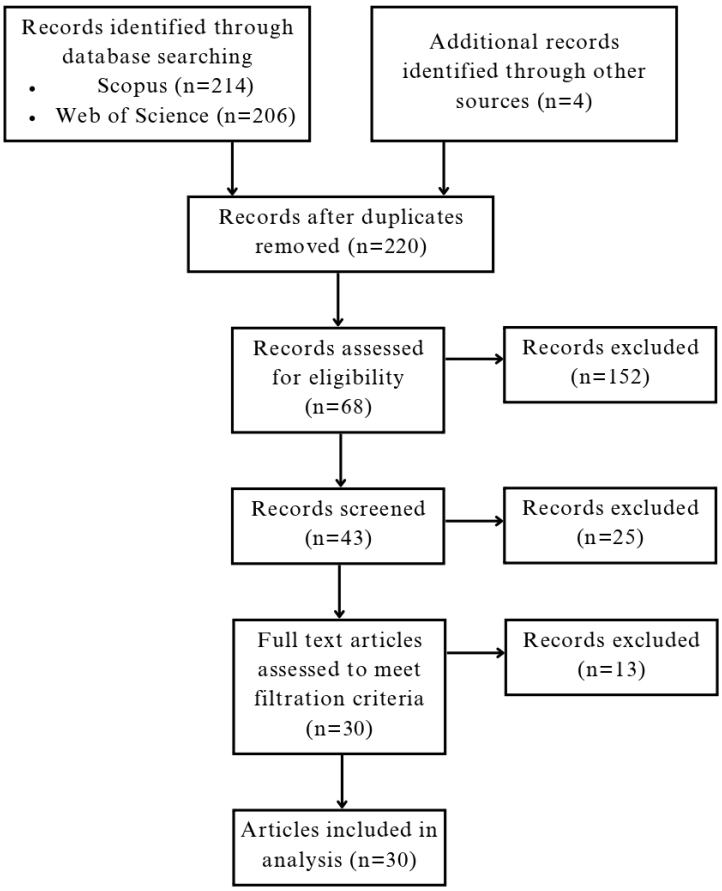


Figure 1 Search and selection process

Results and discussion

This section analyzes the literature taking into consideration many factors including trend of publications, their classifications based on (a) Research methods, (b) Assessment tool examined, (c) Building type, (d) Satisfaction with green building attributes.

Year of Publication. Research on the subject of occupant satisfaction in green buildings seems to be gaining momentum during the recent years as indicated by the upward trend shown in Figure 2, which also offers context on longer-term trends in the literature. This arises from the global emphasis on sustainability which led to increased adoption of green building practices, with a focus on understanding how features such as energy efficiency and improved indoor air quality impact occupants. The growing recognition of the influence of the built environment on occupant well-being and productivity, coupled with regulatory standards and financial incentives for green initiatives, has spurred interest in assessing the effectiveness of these strategies.

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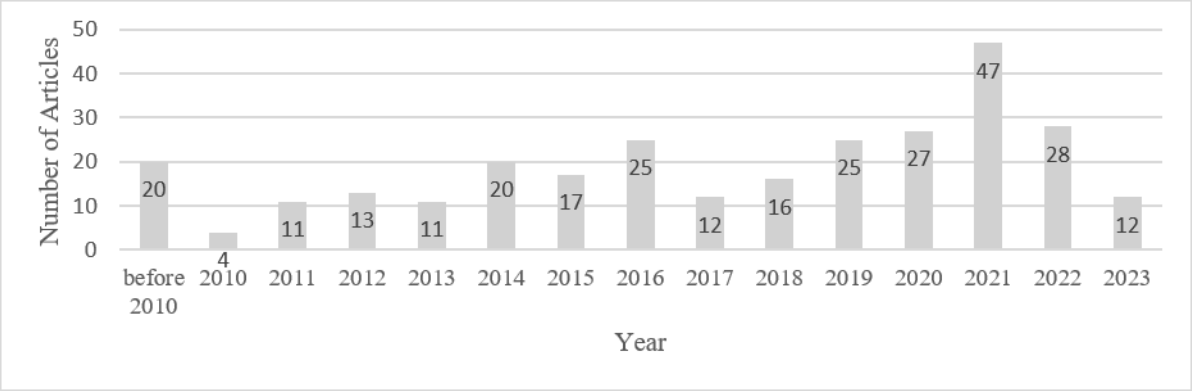


Figure 2 Literature distribution over years

Country of Publication. The comprehensive nature of the data compiled for the studies in this systematic literature review underscores its extensive geographical distribution, providing a truly global perspective. The diverse contributions originated from research conducted across various corners of the world, reflecting rich insights and perspectives.

Noteworthy is the recognition of top contributors to the field, with the United States, China, the United Kingdom, and Australia emerging as top contributors. These countries have significantly influenced the body of knowledge under scrutiny, showcasing their prominence in the global landscape of the subject. The inclusion of data from such varied sources enhances the robustness of the review, capturing a breadth of experiences and approaches that contribute to a more refined understanding of the topic.

Research Method. The systematic literature review reveals a diverse range of research methods employed across the selected papers, categorized by the level of investigation. Predominantly, 85% of the reviewed studies (n=28) adopt correlational research methods, elucidating relationships between variables influencing occupant satisfaction in green and non-green buildings. Explorative research methods are evident in 6% of the papers (n=2), contributing novel insights and generating hypotheses in the complex dynamics of sustainable building occupant contentment. Similarly, 6% of the literature (n=2) employs descriptive research methods, offering comprehensive overviews of the characteristics shaping occupants' perceptions. A smaller fraction, 3% (n=1), utilizes experimental approaches, manipulating variables to establish cause-and-effect relationships and providing controlled insights into the impact of interventions on occupant satisfaction. Some studies use mixed methods, combining two or more approaches in a single paper. This methodological diversity underscores the multifaceted strategies researchers employ to investigate the intricate relationship between green building practices and occupant well-being, enriching the depth and breadth of insights gained from the collective body of literature (Figure 3).

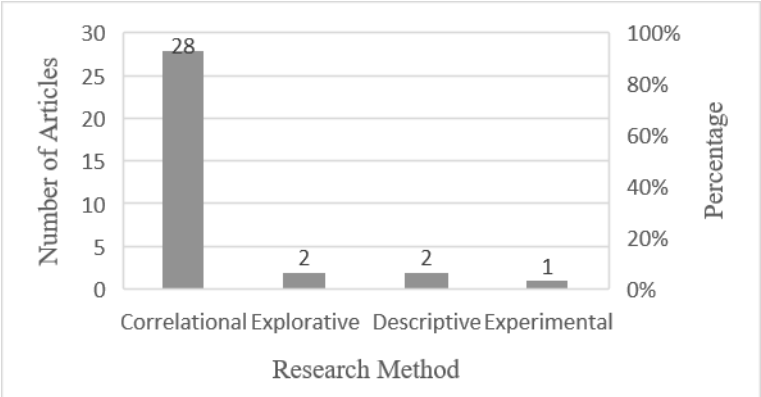


Figure 3 Literature distribution based on Research Method (Level of Investigation)

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Diverse research methods characterize the selected papers in the systematic literature review, particularly in the type of data collected. Notably, 83% of the studies (n=25) utilize quantitative approaches, providing statistical insights into occupant satisfaction trends in green and non-green buildings. A smaller but significant 7% (n=2) employ qualitative methods, capturing nuanced aspects of occupants' experiences. Additionally, 10% (n=3) of the literature adopts mixed-methods approaches, combining both quantitative and qualitative data for a more comprehensive understanding. This methodological diversity enhances the overall depth and richness of insights into the complex dynamics of occupant satisfaction within the built environment (Figure 4).

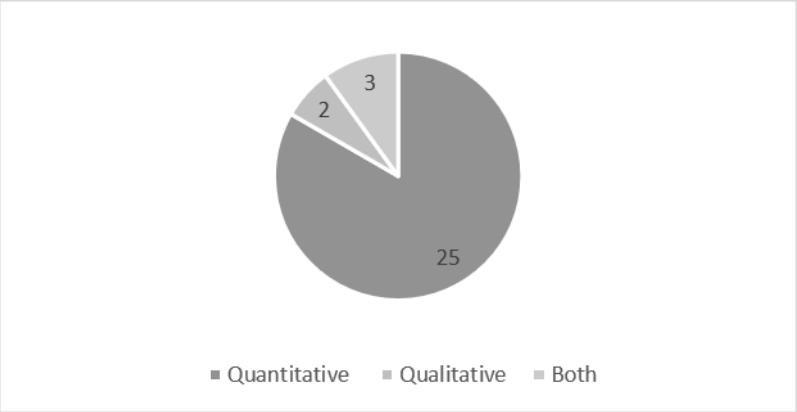


Figure 4 Literature distribution based on Research Method (Type of Data Collected)

Scope of Selected Papers. The systematic literature review encompasses a diverse array of studies that collectively contribute to a comprehensive understanding of occupant satisfaction within the context of green and non-green buildings. The selected papers are grouped into three dominant thematic emphases rather than strictly mutually exclusive categories, as some studies may address multiple aspects simultaneously. The themes shed light on different aspects of the relationship between sustainable building practices and occupant contentment.

Comparison of Occupant Satisfaction in Green vs. Non-Green Buildings (Conventional). A substantial portion of the reviewed literature (57%, n=17) is dedicated to studies that delve into the comparative analysis of occupant satisfaction between green and non-green buildings. These papers systematically assess and compare various factors influencing occupant well-being in both sustainable and conventional structures. Through rigorous methodologies, these studies contribute valuable insights into the tangible benefits and drawbacks associated with green building practices.

Examination of Individual Green Buildings. A significant subset of the selected papers (37%, n=11) focuses on the in-depth examination of individual green buildings. These studies go beyond the broad comparison and instead zoom in on specific structures, analyzing the nuanced relationships between sustainability rating tools and user satisfaction. By scrutinizing the performance of individual green buildings, these papers provide a granular understanding of the factors that contribute to or hinder occupant contentment within the realm of sustainable architecture.

Post-Occupancy Investigations for Policy Insights. A smaller yet valuable proportion of the literature (6%, n=2) concentrates on post-occupancy investigations conducted across multiple buildings. These studies aim to distill lessons learned and offer policy suggestions by examining the experiences of occupants in a variety of sustainable structures. By conducting thorough post-occupancy assessments, these papers contribute to the identification of best practices and potential areas for improvement in sustainable building design and policy implementation.

In summation, the selected papers collectively form a rich tapestry that captures the multifaceted nature of occupant satisfaction in the built environment. From comparative analyses to individual case studies and policy-oriented investigations, the literature reviewed herein offers

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a holistic perspective on the intricate interplay between green building practices and occupant well-being.

Assessment Tool Examined. This systematic literature review explores a diverse range of assessment tools employed to examine occupant satisfaction in green and non-green buildings. LEED (Leadership in Energy and Environmental Design) emerges as the predominant tool in 28% of the studies (n=12), followed by BREEAM (Building Research Establishment Environmental Assessment Method) at 9% (n=4) (Figure 5).

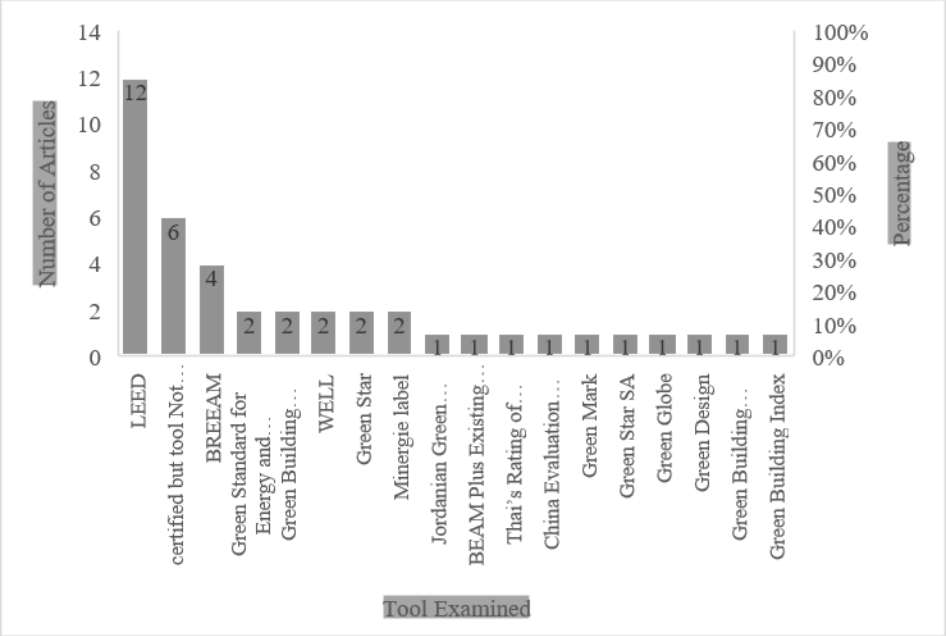


Figure 5 Literature distribution based on assessment tool examined

Additional tools include G-SEED, JGBG, BEAM Plus EB, GBL (Three-Star), TREES, CESGB, WELL, Green Mark, Green Star SA, Green Star, Green Globe, Green Design, Green Building Council of Australia, Minergie label, and Green Building Index. This comprehensive analysis reveals the varied landscape of sustainable building certifications, providing insights into how these tools contribute to understanding occupant satisfaction in the built environment.

Building Type. Within this systematic literature review, a diverse set of studies is examined, focusing on occupant satisfaction in various building types. Among the selected papers, 50% (n=16) delve into the realm of office buildings, reflecting a substantial emphasis on understanding occupant well-being in professional environments. Housing, including both apartment buildings and single-family houses, constitutes 28% of the studies (n=9), highlighting a significant interest in residential settings. Educational buildings are the focus in 13% of the literature (n=4), shedding light on the unique considerations for occupant satisfaction in educational spaces. Governmental buildings, including embassies and public structures, represent 6% of the studies (n=2), while a solitary paper, constituting 3% of the literature, examines retail and commercial buildings. This varied distribution underscores the importance of context-specific investigations, offering insights into the factors influencing occupant satisfaction across a spectrum of building types (Figure 6).

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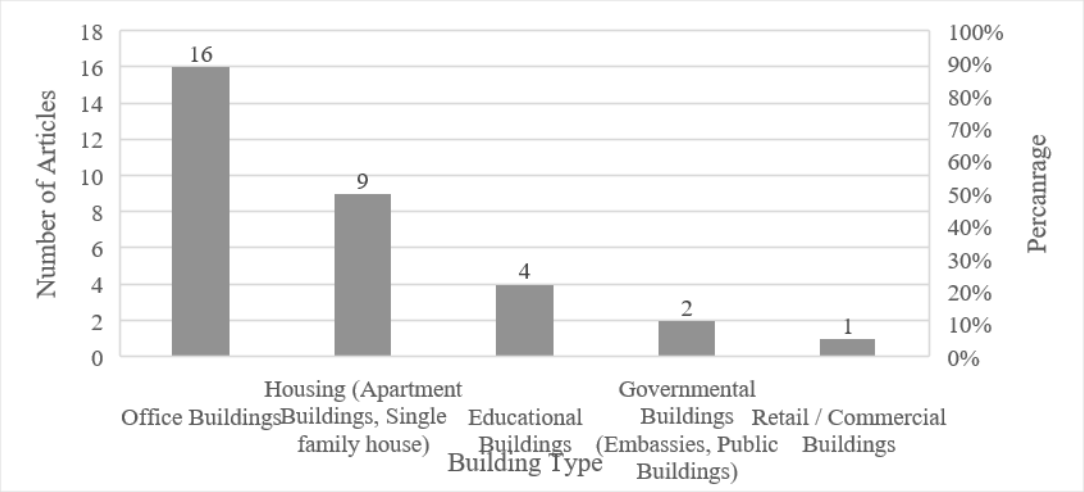


Figure 6 Literature distribution based on Building Type

Satisfaction with Green Building Attributes. A contradictory body of research was identified through a systematic literature review (Table 1). Despite this, the prevailing evidence suggests a greater inclination toward higher satisfaction with green buildings, particularly in terms of lighting comfort and indoor air quality (IAQ). Thermal comfort displayed greater inconsistency, with nearly 25% of the studies indicating no significant differences between green and non-green buildings. Regarding acoustic comfort, most studies reported comparable performances for both types of buildings, with no significant distinctions. In relation to other aspects of building design and facilities management, most papers pointed to superior performance in green buildings, especially in areas such as operation and maintenance, cleanliness, furniture, health, and productivity. Consequently, in light of the literature review and the conflicting outcomes, it is imperative for more studies to be conducted to unveil the true performance of green buildings.

The global comparison did not yield a definitive conclusion on occupant satisfaction in green buildings due to significant variance and inconsistency. However, this study noted some consistency in specific contexts with shared geographical and cultural similarities. Consequently, the study further segmented the comparative analysis based on these similarities into two parts: the Occident (western countries, such as the U.S. and the U.K.) and the Orient (eastern countries, such as China and South Korea). All studies were categorized into three groups: (1) higher satisfaction in green buildings, (2) no difference between green and non-green buildings, and (3) lower satisfaction in green buildings. A preliminary observation revealed that more studies from the Orient indicated higher satisfaction in green buildings, while studies from the Occident were distributed randomly across the three categories.

The reviewed studies utilized comparable survey items, encompassing indoor environmental quality, building design, and facilities management. These investigations employed a consistent Likert-scale, either ranging from 1 (very unsatisfied) to 7 (very satisfied), or from 1 (very unsatisfied) to 5 (very satisfied). Additionally, their methodologies were uniform, using non-green buildings as a reference for comparison to assess green buildings. For classification in the 7-point Likert scale, values were grouped as follows: (6-7) indicated higher satisfaction in green buildings, (4-5) suggested no significant differences, and (1-3) pointed to lower satisfaction. In the case of the 5-point Likert scale, (4-5) indicated higher satisfaction in green buildings, (3) indicated no significant differences, and (1-2) implied lower satisfaction. Although some studies did not explicitly outline numerical ratings, they conveyed the level of satisfaction through descriptive text.

Table 1 summary of key conclusions from literature reviews comparing satisfaction with green and conventional buildings

Parameters Addressed in Analysis (Satisfaction in:)	Higher Satisfaction in Green Buildings	No significant differences	Lower satisfaction in Green buildings
Thermal Comfort	[2, 3, 4, 5, 6, 7, 8, 9, 10]	[12, 13, 14]	[15, 16] [17, 18]
Lighting Comfort	[2, 4, 7, 8, 9, 10, 19, 20, 21] [13]	[12, 15,14]	[22]
Acoustics Comfort	[2, 3, 4, 7, 8, 9, 10, 19, 20]	[12, 13, 14, 23] [5]	[18] [22]
Visual Comfort	[2, 7, 8, 19]	[12]	[15]
Comfort of Furnishing	[10] [22]		
Indoor Air Quality	[2, 4, 6, 10, 20, 21] [13]	[14] [5]	[15, 16] [18]
Ventilation	[19, 21]		[3] [22]
Space Layout	[20]	[13]	
Maintenance	[19]		
Building Cleanliness	[10, 19] [22]		[15]
Overall Satisfaction	[14, 22, 24] [2, 4, 7, 8, 10, 19, 27, 28] [17]	[1, 12, 25, 26] [11]	
Legend	Orient	Occident	Other

Indoor Environmental Quality (Thermal Comfort, Lighting Comfort, Acoustics Comfort, Visual Comfort, Indoor Air Quality)

- LEED

A study conducts prior investigations into the impact of building design on occupant satisfaction. Utilizing archival data, including 11,243 responses from occupants of 93 office buildings certified under the Leadership in Energy and Environmental Design (LEED) program, an examination of the correlation between points achieved in the Indoor Environmental Quality (IEQ) category and the occupants' satisfaction levels has been done. The findings however indicate that acquiring specific IEQ credits does not significantly enhance occupant satisfaction with those IEQ aspects. Moreover, the level of LEED certification, as well as the specific product and version of the certification, appear to have no substantial influence on workplace satisfaction. This may be due to various factors, some of which are beyond the influence of the building's design and the rating system, which is predominantly focused on the design intent rather than occupant experience [1].

In another study investigating IEQ parameters in conventional buildings compared to "green" LEED-certified buildings, the findings indicate that occupants tend to be more satisfied with various IEQ aspects in conventional buildings than in LEED buildings. The only exception is noise levels, where LEED buildings seem to perform better. Furthermore, the report highlights that two major categories of IEQ – IAQ/ventilation and thermal comfort – are of significant importance to occupants, in contrast, lighting and noise are perceived as less critical [3]. Lee (2019) identified three key Indoor Environmental Quality (IEQ) factors needing improvement: air quality, temperature, and humidity. However, daylight, artificial lighting, and space size are satisfactory and meet expectations, and effort is needed for furnishings and acoustic quality.

These findings are critical as they challenge the general assumption that LEED-certified buildings, known for their green and sustainable features, would naturally offer better indoor environmental quality compared to conventional buildings. It suggests a need for further investigation and potential re-evaluation of what aspects of building design and operation contribute most significantly to occupant satisfaction, especially in the context of sustainable building standards.

- Green Star (Australia)

As shown in a number of studies, occupant satisfaction levels in green buildings certified by Green Star reveal weaknesses in regard to IEQ parameters, a study undertook a comparative analysis of a set of Green Star certified buildings against their non-certified counterparts, focusing on occupant satisfaction and perceptions of the indoor environment in office settings. Results indicated certain areas where Green Star buildings fell short, particularly in aspects like noise levels, air freshness, odors, and the quality of artificial lighting. [22]

- Green Building Index (Malaysia)

The correlation between occupant satisfaction and rating level, as explored by Esfandiari (2021), provides some critical insights, as it reports a statistically significant difference in occupant responses regarding the IEQ between two Platinum-certified buildings. While occupants generally reported comfort with the overall indoor environment, significant correlations were found among various variables that influenced their satisfaction. The primary factors causing dissatisfaction included overcooling at temperatures, high relative humidity, glare, and background noise.

- Jordanian Green Building Guide (JGBG)

The study by Elnaklah et al., (2021) reveal statistically significant improvements in thermal conditions that favor the green buildings, leading to enhanced occupant thermal comfort. Despite these positive changes, there is no notable improvement in occupant perceptions of air quality, visual comfort, and acoustic comfort after the move from a conventional building into a green one. Additionally, occupants in the green building report poor odors, mental concentration, and glare, which are associated with an increased prevalence of symptoms related to Sick Building Syndrome (SBS).

- Green Mark

Outcomes investigating Green Mark showed that people in certified buildings reported higher satisfaction with their indoor conditions and experienced fewer acute health symptoms compared to those in non-certified buildings. A Generalized Linear Mixed Model revealed a statistically significant increase in satisfaction regarding temperature, humidity, lighting, air quality, and overall indoor environment in green buildings. Additionally, there was a notable decrease in reports of headaches, unusual fatigue, and skin irritation among occupants of green buildings compared to those in non-green buildings [2].

Building Design (BD), and Facilities Management (FM) (Comfort of Furnishing, Space Layout, Maintenance, and Building Cleanliness)

- Green Star (Australia)

A research conducted a comparative evaluation between buildings accredited with the Green Star certification and others without it, results indicated a general preference for Green Star-certified buildings, especially in aspects related to Building Design & Facilities Management (BD&FM), including overall comfort, design, functionality, corporate image, cleanliness, availability of meeting spaces, storage solutions, and impacts on occupant health and productivity [22].

- LEED

Literature revealed that prioritizing action is essential for both cleanliness and the overall aesthetic appeal. While adequate attention is given to factors like space layout and visual privacy, aspects

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such as daylight, artificial lighting, and the size of the space are already meeting expectations and deemed satisfactory [15].

- Minergie Label

One study concluded that occupants in green buildings generally felt more satisfied compared to those in non-certified buildings. However, this increased satisfaction did not significantly extend to specific environmental and operational parameters, such as thermal comfort, lighting, noise, and air quality, where notable differences were observed in operational aspects like design, building needs, image, and cleaning, with green buildings performing better in these areas. While green buildings overall outperformed non-certified ones, the differences, particularly in environmental parameters, were minor. [14]

Overall Satisfaction

- Green Building Label (GBL) (Three-Star)

A study concluded that Three-Star certified buildings were found to be more satisfactory across all examined parameters compared to those in non-certified buildings, with the differences being significant in every aspect. In contrast, the impact of LEED or BREEAM certification on occupant satisfaction was not as pronounced as that observed with Three-Star certification. Additionally, the reviewed study highlighted that green buildings, in general, exhibited superior performance in conserving energy, water, materials, and land resources. They also demonstrated a significant enhancement in Indoor Environmental Quality (IEQ) and user satisfaction when compared to traditional buildings (Liu et al., 2018; Zhou et al., 2022).

- WELL

The findings present a contradictory picture regarding the impact of building certifications on occupant satisfaction. In one hand, the analysis done by Licina & Yildirim (2021) revealed that in 55% of the cases studied, there was no significant difference in satisfaction levels due to relocation to different buildings. While WELL certification showed a positive impact on aspects such as building cleanliness and furniture quality, it did not significantly affect satisfaction with noise and visual comfort. Moving from BREEAM to WELL-certified buildings had a minimal impact on Indoor Environmental Quality (IEQ) satisfaction, with air quality being the exception in one instance. Interestingly, regardless of the certification type, most buildings failed to meet the 80% standard satisfaction threshold. The satisfaction scores remained unchanged during the first year of occupation in WELL buildings, and the level of certification did not correspond with overall building satisfaction scores. In contrast, a study by Candido et al., (2021) report that the highest levels of overall satisfaction, workability, perceived productivity, and health were reported in WELL-rated premises. Offices that incorporated active design principles excelled in workability, satisfaction with work area, collaboration, reduction in unwanted interruptions, perceived productivity, and health. Activity-Based Working (ABW) environments surpassed traditional offices in terms of spatial comfort, thermal comfort, noise control, privacy, personal control, comfort of furnishings, adjustability of the work area, and collaborative space. Users of sit-stand workstations reported significantly reduced sitting time, and female workers were more likely to report pain over the past 12 months. The top-performing offices were those that implemented active and biophilic designs, prioritized overall ergonomics, and provided various spaces designed to support different work activities.

- Green Globe

A study revealed that occupants generally felt more content in green buildings compared to those in non-certified buildings. However, this higher satisfaction level did not significantly extend to various environmental and operational aspects such as thermal comfort, lighting, noise, and air quality. Noteworthy differences were observed in operational factors like building design, needs, image, and cleanliness. In both green and non-certified buildings, factors like air quality, design, and work requirements were key in shaping perceived comfort. Noise emerged as the most

influential factor affecting perceived productivity in both types of buildings. Despite green buildings showing overall better performance, the disparities in environmental parameters between green and non-certified buildings were minimal [14].

Conclusion

Many international studies investigating occupant satisfaction in green buildings have been conducted since the introduction of green building certifications. In order to determine if residents of green buildings are more satisfied than those of non-green buildings, this research does a thorough analysis of these investigations. However, several methodological limitations, including biases related to sample size, length of occupancy, and variations in green building features, should be noted as they affect the interpretation of results. The general conclusion that green buildings consistently outperform non-green buildings in terms of occupant satisfaction is not entirely confirmed by the data, as some research suggests that non-green building users are more satisfied.

An observed pattern across the reviewed studies indicates regional variation in satisfaction trends, though this should be interpreted cautiously given the small sample of studies and the diversity of building types and certifications. Incremental gains in satisfaction from green buildings appear modest in the Occident, where baseline satisfaction levels are already high. In contrast, improvements associated with green buildings are more noticeable in the Orient, where baseline satisfaction tends to be lower. This divergence may offer insights for the development of green buildings worldwide, highlighting potential benefits in regions where baseline occupant satisfaction is lower.

Due to these and other limitations, this review study should be interpreted cautiously even if it offers useful information about the socio-economic aspects influencing occupant satisfaction in green buildings. The small sample size, along with differences in survey procedures and statistical markers across studies, partly reflecting the varied disciplinary backgrounds of researchers, limits standardization and comparability. To facilitate more reliable comparisons, established survey procedures and statistical methods should be followed in future occupant satisfaction research.

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Adaptive Bio-PCM Envelopes for Smart City Thermal Regulation

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Abstract. Changing our urban settings into smart, resilient, and carbon-neutral ecosystems means that the building should no longer be considered a mere static barrier but must evolve into an adaptive-thermally active interface. In this paper, we propose a full framework for the application of Bio-Based Phase Change Materials (Bio-PCMs) to Adaptive Building Envelopes (ABEs) as a means of natural cooling in the smart city context. As urban heat island (UHI) effects become more severe, the necessity for phasing out petroleum-based paraffins and replacing them with bio-based ones derived from fatty acids and esters of the renewable feedstock is inevitable if cities are to be sustainable. This paper develops a qualitative approach for the choice of materials and their embedding in architectural design by combining the Analytic Hierarchy Process (AHP) with biomimetic mapping to ensure the thermophysical characteristics fit the specific weather conditions. The test results show that Bio-PCM installation has the potential to reduce the extent of temperature variations by around 28%, increase the thermal lag up to 3.4 hours, and cut down heating energy use in the temperate climate by 41%. Moreover, with the use of Bio-PCMs, the emission of CO_2-equivalent could be lowered by 40-60% compared to the traditional PCM systems. This paper offers solutions to the main issues of bio-based PCMs such as their packaging, durability over numerous cycles, as well as their commercial viability. Thus, serving as a guide for the introduction of energy-generating building exteriors or "living" skins which not only help in the demand-side management of smart energy grids but are also energy producers themselves.

Introduction

The contemporary urban landscape has been confronted with the challenge of rapid urbanization and climate change, which has made it imperative to rethink the design of buildings fundamentally. In the case of smart cities, which are predominantly driven by digital integration and energy efficiency, the building envelope still determines passive climate adaptation, but to a great extent, an untapped potential. The building facade has traditionally been considered as a static thermal barrier. And yet, as the instances of extreme heat are continually ramping up like the unprecedented 2023 heatwave, the performance deficit of inert building envelopes gradually becomes clearer. In fact, the UHI effect now contributes to a temperature rise of around 8°F in many major cities on average, which not only deteriorates public health but also leads to a greater cooling energy consumption [1]. Breaking this pattern of behavior requires the building envelope to become a dynamic interface that can autonomously regulate its thermal state. A revolutionary measure to this end is the embedding of Phase Change Materials (PCMs) that, among other things, bring the possibility of Latent Heat Storage (LHS).

During their phase change, PCMs take in and give out enormous amounts of energy at a nearly constant temperature, thus, handling a much larger energy storage than sensible heat. Building the fabric in synergy with this property, it becomes, in fact, a thermal battery that stores the surplus solar heat of the day and discharges it during the night. Although paraffins derived from petroleum have been the main source of the market, they also come with several environmental issues, such

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as the high embodied carbon and their flammability. The advent of Bio-PCMs has opened the door for the thermal management to be more in line with the principles of the circular economy. Bio-PCMs like fatty acids and esters obtained from vegetable oils, animal fats, and waste-derived lipids provide a sustainable, safe, and biodegradable option. These materials have the necessary thermodynamic properties such as high enthalpies of fusion and controlled melting points making them appropriate for human comfort ranges. This study focuses on the constitution of a holistic framework for the incorporation of Bio-PCM in smart cities.

This work presents a full, scale framework that connects the two fields of materials science and real, world urban planning of smart cities. At its core, it aims at finding key parameters in the building skin that can at the same time: reduce the UHI (Urban Heat Island) effect and control the indoor temperature. In order to help the architects with this, the research proposes a qualitative decision support tool based on the Analytic Hierarchy Process (AHP), which rationalizes the picking out of the most appropriate Bio, based Phase Change Materials (Bio, PCMs) with a preference to the local climate.

The concept of simply changing materials has been expanded in this research to the use of Bio, PCM thermal mass in conjunction with animal, inspired kinetic mechanisms. By replicating the plant motions such as elastic bending and hygroscopic changes, the system can actively regulate the PCM "charging" cycles. More importantly, the insulation paradox plight can be "insulation paradox" problem solved by this dynamic adjustment which occurs when very high static R, values prevent latent heat storage. Apart from that, the work increases the availability of green materials by testing discarded fatty acid esters and vegetable butters as potential replacements for paraffin.

Methodology: A Qualitative Framework for Bio-PCM Integration

Developing a framework for passive thermal regulation requires a shift from quantitative simulation to a qualitative methodology focused on material characterization, decision-support analysis, and biomimetic mapping.

Material characterization and selection criteria

The initial step consists of determining the characteristics of Bio-PCM candidates through a study of their thermophysical, chemical, social, economic, and environmental properties (Tab.1). The efficiency of a Bio-PCM is very dependent on its molecular structure. For instance, waste-derived lipids (like waste cooking oil) are getting increasingly used to not only sustain circular economy goals but also to achieve a high latent heat storage capability. In the case of fatty esters, the length of the carbon chain and the kind of alcohol that is used have a direct effect on the melting temperature and latent heat capacity, with the present studies aiming at a comfort temperature range of 22 °C to 28°C [2]. To make the best choice, the leading-edge methodologies utilize Multi-Objective Optimization (MOO) integrating building energy simulations (EnergyPlus) with genetic algorithms (NSGA-II) to determine the Pareto front between energy performance and life-cycle costs. Furthermore, decision-making models have reached a point where they incorporate typical "real-life" factors such as installation flexibility, initial cost, and durability of the materials over time.

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Table 1 Comprehensive Selection Criteria for Phase Change Materials (PCMs)

Criteria Category	Evaluation Factors	Significance
Thermophysical	Melting point, enthalpy, conductivity, specific heat	Determines energy storage and thermal response speed.
Physical/Chemical	Density, volume change, supercooling, stability	Influences encapsulation design and transition reliability.
Environmental	Biodegradability, toxicity, embodied carbon, origin	Ensures alignment with circular economy goals.
Economic	Raw material cost, availability, scalability	Determines feasibility for large-scale urban deployment.
Safety	Flammability, corrosivity, VOC emissions	Critical for indoor air quality and fire codes.

Biomimetic mapping for adaptive integration

The second phase of the project is the architectural integration that is achieved through a biomimetic mapping process. ABEs are the concept of being inspired by biological organisms that naturally have complex thermal regulation abilities. The developed framework applies an extended three step procedure in Bio-ABE systems:

- Setting boundary conditions and multi-level analysis: This is no longer just about recognizing solar gain or heat loss. Now in this step, the Bio-ABE systems are characterized at four levels: Scale (from the sub-component to the full-scale), Adaptability (mono vs. multifunctional), Biomimetics (morphological, physiological, or behavioral) and Performance targets (thermal/visual comfort) [3].
- Identifying and analyzing biological adaptations: Choosing to use spruce cones that have humidity, induced elastic bending or choosing the strelitzia reginae (bird-of-paradise) flower to show the system of "hingeless" louvering [4].
- System characterization and design generation: How to integrate into architectural design a biological multifunctionality? Most studies talk about "living" envelopes that besides being "filters" can also be "adaptive, " hence the plant, inspired kinetic responses are used to control heat and light, simultaneously [5].

Encapsulation and composite design

The last element concerns containment measures that can be used to prevent leakage and maintain stability. Recently, a series of powerful composite solutions have been introduced:

- Macro-encapsulation: Mainly used for Double-Skin Facades (DSF). Macro-encapsulated PCM blinds with a 30 or 60° tilt angle and a depth of cavity/width of blind ratio of 2.5 can lower the temperature in the cavity by as much as 2.9°C [6]. Innovative 3D-printed metallic reticular structures (copper/aluminum) fabricated through additive manufacturing have upgraded thermal storage/release capacity by 10% [7].
- Micro-encapsulation: Surrounding of PCMs particles (11000 μm) with bio-shells from renewable sources (chitosan, lignin) [8]. New "NRG-Foam" composites (15% Micro-PCM v/v) have achieved peak temperature reductions of 4.33°C and thermal delays of up to 440 minutes [9, 10].
- Shape-stabilization: Using porous matrices for Bio-PCMs impregnation. "NRG-WOOD" and SSPCM-OSB (oriented strand boards) embedded in high-density polyethylene (HDPE) not only physically contain the PCM but also help in keeping the material intact [11]. The use of Expanded Graphite (EG) as a filler has been evidenced to reduce melting times by as much as 52.9%. The presence of Cu-Gr nanoparticles in

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hybrid beeswax/coconut oil composites has resulted in conductivity enhancements of up to 604% of that of the base material.

Characterization of Bio-Based Phase Change Materials

Fatty acid esters and natural buffers

It is necessary to be well acquainted with the chemical properties of Bio-PCMs for local climate, specific customization. Fatty esters obtained via Fischer esterification provide a method for the precise adjustment of the phase transition temperatures at the molecular level. Study has proven that pentyl (C_5) esters always have a lower melting point than methyl (C_1) and decyl (C_{10}) esters that are obtained from the same carboxylic acid [2]. This is especially important for the adjustment of the 18 to 25°C range that is required for temperate urban environments [2]. An experiment using 4 agriculturally waste derived bio-based PCMs, including PureTemp 68 and Crodatherm 74, showed that these materials have 0% environmental impact [12]. Moreover, bio-composites with coconut oil infiltrated into the pomegranate peel biochar physically activated encapsulation efficiencies have reached 61.6%, thus giving a low-cost solution for turning agro-waste into building thermal mass [13]. The thermophysical data for specific fatty ester compounds evaluated in this study are detailed in Table 2.

Table 2 Thermophysical properties of selected fatty ester compounds [14, 15]

Fatty Ester Compound	Chain (Acid/Alcohol)	Melting Peak (∘C)	Latent Heat (ΔHm J/g)	Supercooling (∘C)
Methyl Arachidate	C_{20}/C_1	41.0	210	< 5.0
Pentyl Myristate	C_{14}/C_5	15.0	145	< 4.0
Pentyl Palmitate	C_{16}/C_5	22.0	160	< 3.0
Pentyl Stearate	C_{18}/C_5	28.0	185	< 4.0

Fatty acids like capric and lauric acid have better thermal stability than many traditional paraffins. An eutectic mixture especially a 9:1 mass ratio of capric to stearic acid, offers a steady melting point of 26.8°C and a latent heat of 96.4 J/g, which is perfectly suitable for human comfort applications [14]. The trend in the research has been towards vegetable butters (VBs) such as tucuma, murumuru, and cocoa butters, which have the right enthalpies for temperate climates and serve as a less chemically treated alternative to synthetic PCMs [15]. Generally, hybrid formulations using graphene, copper (Gr, Cu) nanoparticles in a beeswax/coconut oil base have broken the record for a thermal conductivity increase of 604% at 25°C to counter the low thermal conductivity (~0.2 W/m K) which is typical of organics [16].

Cyclic Stability

Long-term reliability is still the main technical challenge for the large-scale deployment of urban setting. Some of the most recent accelerated thermal cycling tests show the following performance benchmarks:

- Organic resilience: A study conducted by [17] have demonstrated that organic fatty acids can be thermally cycled 10,000 times at the molecular level without any changes in chemical bonds. However, a slight reduction in latent heat capacity may occur with time.
- Encapsulation sensitivity: After 700 thermal cycles, the experiment showed a decrease in latent heat by 23% for pure PCMs and up to 57% for PCM granules in cement mortar. Thus emphasizing the necessity for shell-matrix compatibility [18].
- Biodegradable durability: After 700 cycles the stability of the bio-based PCMs impregnated in thermally modified wood species (e.g., spruce or beech) is still very

good. Besides, these samples showed less discoloration from mold than the unmodified ones [19].

- System reliability: New bio-composites such as "NRG-WOOD" has a thermal energy storage capacity of more than 95% after 1,000 cycles. Thus it is a passive resilient cooling that is in line with the typical 25 year facade design life [19].

Adaptive Building Envelopes: Integration Strategies

Dynamic insulation and smart shading

Adaptive envelopes refer to dynamic insulation systems that switch their thermal resistance capability. Thus, a dynamic envelope might have a resistance of 2.30 m^2 K/W when sealed, which decreases to 0.38 m^2 K/W when open. Using Bio-PCM, the building envelope can be "charged" with cool night air through natural ventilation and then "closed" during the day. This can lead to a decline of annual heat gain anywhere from 3.5% up to 47.2% depending on the climate. The combination of Bio-PCMs with the glazing and shading systems helps to moderate the solar gains. To absorb direct solar radiation during the daytime, macro-encapsulated PCM blinds or shutters utilize aluminum shells. The experimental data on PCM shutters indicate a decrease in the maximum indoor temperature by as much as 8.7% and a rise in thermal lag by 1 hour [20].

Biomimetic "living" skins

The framework integrates sophisticated biomimetic ideas where the facade functions as "living skin". These types of systems generally continue to employ the use of natural materials to achieve kinetic movement free of mechanical actuators:

- Hygroscopic response: The HygroSkin pavilion is a great example of how spruce cones can be used to respond to humidity by the elastic bending of plywood.
- Elastic bending: The Flectofin system takes its cue from the Strelitzia reginae flower, a manipulative hingeless louver system that can bend when it is externally stressed.
- Thermal ventilation: The flower Crocus has served as a model for a series of samples using temperature, sensitive materials that open and close the passages in ventilation.

Experimental Evidence and Metrics

The feasibility of the Bio-PCMs as a sustainable solution to passive thermal regulation is basically confirmed by the large experimental data sets which indicate the effectiveness of these materials on different building components.

- Temperature regulation and comfort: In full-scale experiments on the 15m^2 office cubicle, uncovered Bio-PCM (range 18.523°C) was able to reduce the peak operative temperature by as much as 3.3°C [21]. On the other hand, when covered with aluminum plates and gypsum board, the temperature drop was only 0.7°C, thus demonstrating the role of thermal connectivity and air circulation in the wall cavities. Tests on adaptive glazing with a 28°C PCM showed outdoor temperature peaks reduced by 2.0°C during the daytime and indoor temperature raised by 1.5°C at night [22]. Thus, successfully providing stable temperature changes throughout 24 hours all year round.
- Energy savings and grid efficiency: Embedding Bio-PCM in residential walls resulted in an annual energy savings up to 5,476 kWh in Mediterranean climate, that is, it saved $1150/year and the carbon footprint was reduced to more than 2300 kg CO_2 eq [23]. In portable cabins, the carbon-PCM bio lowered the peak temperatures by 4.25°C, thus energy savings ranged between 25% and 45%, depending on the climate zone. The performance comparisons between paraffin and Bio-PCM systems are presented in Table 3.

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Table 3 Comparative performance analysis: paraffin-based vs. Bio-Based PCMs [12, 24]

Metric	Paraffin-Based PCM	Bio-Based PCM (2026)	Performance Benefit
Enthalpy Retention (1k cycles)	~90%	> 95%	Improved stability and reliability.
CO_2-Equivalent Emissions	Baseline (100%)	40–60% of baseline	Significant reduction in GWP.
Embodied Carbon	High (Petrochemical)	0.08 kg CO_2/kg	> 97% lower than conventional.
Electrical Efficiency (PVT)	Baseline	+2.9%	Hybrid cooling enhances electrical yield.
Peak Load Shifting	Limited	2–4 hours	Enhanced grid flexibility and resilience.

Implementation in the Smart City

Bio-PCMs offer a "passive battery" that can be included in the city's demand-response framework. By delaying peak cooling demand for 2-4 hours, buildings with Bio-PCM can get off grid electricity now of highest grid stress, which is a late afternoon situation. This feature is extremely important for smart cities targeting 100% renewable energy, where grid stability is frequently challenged due to the intermittency of solar and wind energy. Besides that, implementation in social housing enables "passive cooling resilience" during power cuts, thereby the risk of heat-related diseases of the vulnerable groups during the severe weather events is drastically lowered. Bio-PCM systems combined with smart building management systems (BMS) can be extremely effective. Bio-PCM mass "charging" can even be optimized by real-time weather forecasts and occupancy patterns using advanced algorithms such as Model Predictive Control (MPC) and Deep Reinforcement Learning (DRL). Such digital solutions have provided an increase in system efficiency between 20% and 35% in demonstration projects [25]. Digital twins of the building envelope have made it possible for the BMS to run simulations of the environmental responses and alter the ventilation paths even before human intervention, thus lowering the risk of operations and attaining the best use of energy. Notwithstanding the fact that the technology is technically feasible, the main barriers to the large-scale dissemination of latent heat storage systems in built facades are the higher upfront capital costs. BIPV-PCM facades costing 40%-60% more than conventional cladding and the absence of standardized building codes for latent heat storage [26]. Payback times differ widely; while Mediterranean regions experience paybacks in 47 years, cold climates may exceed 150 years. Therefore, government grants and "carbon credit" incentives will be needed to facilitate and encourage adoption.

Conclusions

The integration of Bio-PCMs) in adaptable building envelopes plays a critical role in the evolution of resilient and sustainable smart cities. The study has revealed that Bio-PCMs are a high-performance, environmentally friendly alternative to conventional thermal energy storage materials that can significantly lower the amplitude of indoor temperature fluctuations, help in reducing the urban heat island effect, and enable peak energy load shifts. The suggested framework outlines a qualitative-holistic method for material selection and architectural design. Materials molecular tuning of fatty esters, the 10,000-cycle stability of fatty acids, and the biomimetic skins like the "Solar Gate" that respond autonomously at the kinetic level are the elements that architects and urban planners can combine to make building envelopes not only functionally efficient but also environmentally friendly. Even though there are still economic and regulatory constraints, the potential of environmental benefits seen through a 40- 60% decrease in CO_2 emissions and an embodied carbon footprint 97% lower than that of paraffins justifies making Bio-PCM integration a key tactic for urban decarbonization. Ultimately, we need to think of the building envelope as a living interface. The combination of bio-based material science, AI-driven adaptive control, and

smart city infrastructure will give the urban built environment the change from a passive consumer of energy to an active participant in global climate resilience. This framework is a guide for this change, making sure that the future smart cities are technologically advanced, thermally resilient, and socially equitable.

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Exploring the Integration of Building Integrated Photovoltaics (BIPV) in School Buildings in Saudi Arabia

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Abstract. Building-integrated photovoltaics (BIPV) can improve building energy performance while contributing to architectural expression. This study evaluates the potential of BIPV integration in Saudi school buildings through energy simulation of a prototype three-storey school in Dhahran. Two scenarios were analysed using DesignBuilder/EnergyPlus: a baseline model without BIPV and a second model with BIPV integrated into the south, east, and west façades and the courtyard skylight. The results show that BIPV improves performance through two mechanisms. First, the integrated PV surfaces reduce solar heat gains and lower annual cooling electricity use by about 15%. Second, the system generates approximately 347,610 kWh/year of on-site electricity, meeting about 58% of the annual demand in the BIPV scenario. Overall, net grid electricity use falls by about 60% compared with the baseline case. These findings indicate that BIPV can be an effective retrofit and design strategy for Saudi schools, supporting energy-efficiency goals, renewable-energy deployment, and sustainability education in line with Saudi Vision 2030.

Introduction

Rapid population growth and continued expansion of the building sector in Saudi Arabia have increased national electricity demand, with cooling representing a major share of consumption in hot climates. In this context, renewable-energy integration and improved envelope performance are key strategies for reducing operational energy use in public buildings such as schools. Building-integrated photovoltaics (BIPV) incorporate photovoltaic modules into envelope elements such as roofs, façades, glazing, and shading devices, enabling on-site electricity generation while also reducing solar heat gains through shading [1–3]. In Saudi school buildings, where façade design and glazing quality strongly influence cooling demand, BIPV can operate as both an energy system and a climate-responsive architectural element [4]. Green schools seek to reduce resource consumption, improve indoor environmental quality, and support sustainability education [5,16,17]. Previous studies have shown that energy-efficient school design can reduce operating costs and emissions while allowing the building itself to serve as a teaching tool for sustainability [17,18].

In Saudi Arabia, renewable-energy policies and grid considerations affect PV deployment. Distributed PV capacity is often discussed in relation to transformer limits, and previous work has suggested that about 150 kW may be a practical upper bound for typical school rooftop systems [6]. These ambitions align with Saudi Vision 2030, which promotes wider renewable-energy adoption and reduced environmental impact across sectors, including education [8,19]. Against this background, the present study evaluates the integration of BIPV in Saudi school buildings

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through simulation. Two scenarios are compared: a baseline school without BIPV (Scenario A) and the same school with BIPV integrated into selected envelope surfaces (Scenario B). The study hypothesises that BIPV can substantially reduce net grid electricity demand through the combined effects of on-site solar generation and reduced cooling loads due to façade shading.

Although research on photovoltaic systems, sustainable schools, and energy-efficient design in hot climates has expanded, relatively few studies have examined BIPV specifically in school buildings in Saudi Arabia or the wider Gulf region. Most existing studies focus on rooftop PV systems, general efficiency measures, or envelope performance in isolation, with less attention to BIPV as a dual-function strategy that both generates electricity and improves envelope performance. This gap is particularly important in Saudi Arabia, where school buildings have high cooling demand and where façade design, shading, and solar exposure strongly influence energy use. This study therefore contributes to the literature by evaluating BIPV integration in a prototype school building in Dhahran and by assessing its value not only as a renewable-energy technology but also as a climate-responsive architectural intervention.

Literature Review

Saudi Arabia has high solar irradiance, which makes solar power a practical and increasingly cost-effective renewable-energy option [7]. Vision 2030 emphasises both reduced building energy consumption and a higher share of renewables in the national energy mix [8]. Earlier national targets referred to approximately 54 GW of renewable capacity by 2030, with a large proportion expected from solar technologies [6]. Parallel efforts have also focused on energy-efficient design strategies and grid upgrades to support additional distributed generation [3]. Daylighting is a well-established passive strategy that can reduce artificial lighting demand while improving indoor environmental quality, particularly in schools [9–11]. Its performance depends on envelope and design variables such as glazing type, shading, and window-to-wall ratio; poor glazing design can increase solar heat gain and cooling demand [4]. BIPV extends this logic by integrating photovoltaic modules into façades, roofs, glazing, and shading devices so that the same element functions as both a building component and an electricity generator [1,12,13].

Grid-connected BIPV is particularly attractive because it avoids storage losses and can support both on-site consumption and electricity export, thereby benefiting both building owners and the grid through demand reduction and cleaner generation [3]. Successful BIPV implementation depends on early design-stage integration to balance energy yield, architectural quality, and user acceptance [2,13]. Key design considerations include building load profiles, climate, PV technology, and integration method, as well as essential electrical and safety components such as inverters and disconnects [1,3]. Simulation-based research in Saudi Arabia has shown that BIPV can contribute to substantial reductions in energy use and emissions when combined with envelope improvements and efficient HVAC systems. In hot climates, cooling is typically the dominant end use, often exceeding 70% of total demand, while lighting commonly accounts for a much smaller share [14]. Adjusting HVAC setpoints and integrating PV can therefore reduce energy bills with reasonable payback periods [14].

Schools are critical public facilities, and their design strongly influences both energy performance and the quality of the learning environment. In Saudi Arabia, a growing youth population has intensified the need for new school buildings [6]. To achieve high-performance schools with contemporary infrastructure, core design decisions need to be addressed from the earliest project stages [8]. Previous research has shown that many Saudi schools still rely on single-pane glazing, resulting in poor thermal performance and substantial heat gains [4]. This condition directly increases cooling demand and overall electricity use.

School design must also respond to the local microclimate. In hot regions, natural ventilation can improve comfort and reduce dependence on air conditioning when outdoor conditions permit. In milder periods, cross-ventilation can help maintain acceptable thermal conditions with less

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mechanical cooling [6]. Studies have shown that relatively straightforward design improvements, such as enhanced insulation, better orientation, and effective shading, can reduce a school's electricity use by up to about 35% and improve HVAC efficiency by roughly 31% [6]. Such measures can translate into meaningful reductions in operating costs.

Several Saudi case studies illustrate the influence of school design on environmental performance. Al-Mahad High School, for example, is a large public secondary school consisting of two separate three-storey buildings with classrooms, laboratories, offices, clubs, computer labs, a theatre, a mosque, and a multi-purpose sports hall [15]. In Jeddah, Gadi and Alwetaishi [4] examined school buildings such as Al-Noor School, where classrooms are arranged around a central courtyard that supports daylight and ventilation. They also identified two external wall types, including EW1 at Bader School, which used a single 250 mm clay-brick layer, and EW2, used in Al-Ameer and Al-Noor schools, underscoring the thermal importance of envelope construction [4]. In Arar City, Alfaraidy and Sulieman [6] analysed a three-storey intermediate school with a roof skylight and reported representative electricity-consumption values for different Saudi school types, providing useful context for solar-energy applications in educational buildings.

Typical Saudi school layouts often centre on a courtyard, which can support daylighting and ventilation when used effectively. However, many existing schools still require improvements in insulation, glazing, and environmental control to become genuinely green schools. Common strategies include high-performance envelopes, efficient HVAC systems, improved daylight and ventilation design, reduced water use, and the integration of renewable energy technologies [5,17]. Many green-school frameworks also treat the building itself as a hands-on teaching tool for sustainability [11,16]. Although initial costs may be higher, lifecycle studies suggest that the combined benefits of lower energy use, improved health, and better productivity can outweigh the additional investment [18]. In Saudi Arabia, where cooling dominates energy demand, priorities should include passive cooling, effective shading, high-performance envelopes, efficient cooling systems, and on-site renewable generation. BIPV is well suited to this context because it produces clean electricity without requiring additional land and becomes even more effective when combined with measures that reduce demand.

Materials and Methods

This study employed whole-building energy simulation using DesignBuilder with the EnergyPlus engine to evaluate a prototype school building under Dhahran climate conditions. Two scenarios were analysed: Scenario A, a baseline school without BIPV, and Scenario B, the same school with BIPV integrated into selected envelope components. Annual and monthly electricity consumption by end use were extracted for both scenarios, while PV generation was also recorded for Scenario B. The comparison was used to assess the effect of BIPV on overall electricity demand, cooling-related energy use, and net grid electricity after on-site generation was considered.

The prototype school was developed as a conceptual reference model rather than a replica of a specific existing building. It was intended to represent spatial and architectural features commonly found in Saudi school buildings, including a compact plan, a central courtyard, a multi-storey configuration, and insulated construction. This assumption-based prototype provides a simplified but representative basis for comparing the baseline and BIPV cases under controlled design and climate conditions. Accordingly, the model should be understood as a conceptual Saudi school reference case rather than a surveyed real-world school.

The assumed school has a square footprint of approximately 50 m × 50 m (2,500 m² gross area) arranged around a central courtyard measuring about 20 m × 20 m (400 m²), as shown in Figure 1. The courtyard provides daylight to the surrounding corridors and classrooms and also functions as a shaded outdoor gathering space. In the prototype, the courtyard is covered by a skylight or tensile shading element that admits daylight while limiting direct solar heat gain during summer. The building is three storeys high, with an approximate floor-to-floor height of 3.5 m and an overall

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height of about 10.5 m. The longer façades face north and south to reduce low-angle morning and afternoon solar exposure on the east and west elevations, which helps limit unwanted heat gain and glare.

The simulation model was created in DesignBuilder using an updated EPW weather file for Dhahran. The building geometry followed a courtyard-based school layout appropriate to the Saudi context. The longer façades were oriented north-south to reduce direct solar exposure on the east and west façades and thereby lower cooling demand. This geometry and orientation were selected to provide a realistic test case for evaluating the interaction between envelope design, solar exposure, and BIPV integration.

The envelope construction was defined using insulated assemblies representative of locally relevant school construction with improved thermal performance. The external wall assembly consisted of 3 cm external plaster, 14 cm concrete, 5 cm lightweight polystyrene insulation, 14 cm concrete block, and 2 cm internal plaster, resulting in a wall U-value of approximately 0.32 $W/m^2 \cdot K$ and an R-value of about 3.05 $m^2 \cdot K/W$. The flat roof assembly comprised 2.5 cm clay tile, 2.5 cm cement screed, 5 cm polystyrene insulation, 1 cm moisture barrier, and 30 cm concrete, with a roof U-value of approximately 1.68 $W/m^2 \cdot K$. The courtyard cover was modelled as a skylight or tensile shading structure that admits daylight while reducing excessive solar gains.

Operational schedules were based on a typical school timetable. The building was assumed to operate on weekdays from 07:00 to 16:00, during which classrooms and support spaces were occupied and the cooling system was active. Occupancy density represented typical classroom use, with approximately 20-30 students per classroom and standard staff occupancy in administrative spaces. Internal gains from lighting and equipment were included using typical school-building assumptions in DesignBuilder. The HVAC system was modelled as a conventional mechanically cooled system operating during school hours with an indoor cooling setpoint of 24-25°C, which reflects common comfort conditions in Saudi school buildings.

The total conditioned floor area, excluding the courtyard, was approximately 2,100 m^2 per floor, or about 6,300 m^2 in total. Lighting schedules followed occupied hours, while equipment loads were assigned primarily to classrooms, offices, and computer-related spaces. Although the building benefits from daylight access, the simulations assumed that electric lighting was used as needed to maintain acceptable indoor illuminance. To observe seasonal variation during the academic year, the results were also interpreted across three school terms: Term I (August-November), Term II (December-February), and Term III (March-June).

In Scenario B, BIPV elements were integrated into envelope surfaces with the highest solar exposure and the greatest architectural suitability. Photovoltaic panels were applied to the south, east, and west façades, while the north façade was excluded because of its relatively limited solar potential. In addition, semi-transparent photovoltaic panels were integrated into the courtyard skylight so that the element could admit daylight while also generating electricity. For the simulation, the BIPV system was assumed to cover the available opaque or semi-transparent portions of these surfaces, allowing the façade-mounted panels to function both as electricity-generating components and as external shading devices.

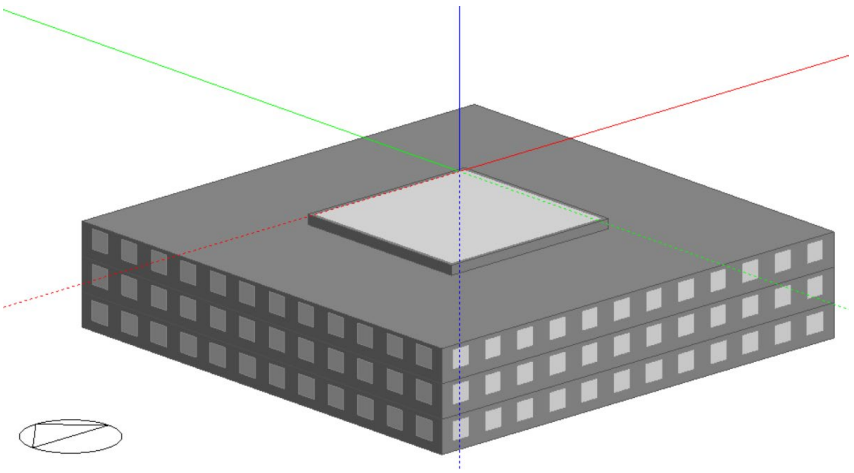


Figure 1. Baseline case-study model.

Results and Discussion

Scenario A: Baseline case

Key results for Scenario A, the case without BIPV, are summarised in Figure 2, which shows the breakdown of annual electricity use by end use. Total annual electricity consumption for this scenario was approximately 633,293 kWh. Cooling was the dominant component, with annual cooling electricity use of about 396,723 kWh, or roughly 63% of total consumption. Cooling demand was highest during Term I (August-November), when outdoor temperatures are greatest. Lighting consumed about 213,639 kWh/year, representing approximately 34% of total electricity use. The remaining share was associated with other electrical uses, including domestic hot water and miscellaneous equipment.

These results highlight the baseline challenge for school buildings in Saudi Arabia: cooling and lighting are major electricity consumers, with cooling dominating overall demand. Without on-site generation, the full annual load of more than 633,000 kWh must be supplied by the grid, together with the associated operating costs and environmental impacts.

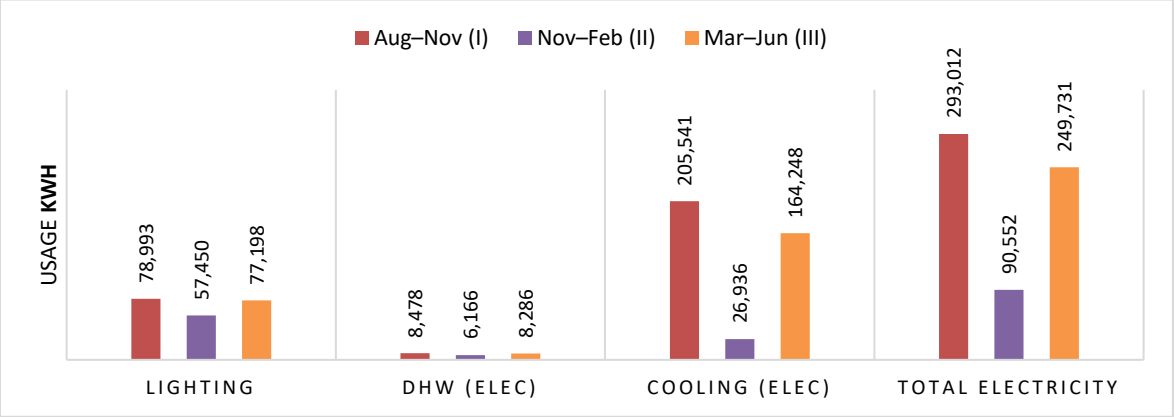


Figure 2. Electricity-use breakdown for Scenario A.

Scenario B: School with BIPV integration

In Scenario B, BIPV was incorporated into the school model, as shown in Figure 3. Photovoltaic modules were integrated into the south, east, and west façades and into the skylight above the courtyard. The north façade was excluded to prioritise sun-exposed elevations with higher energy yield. The system size and coverage were selected to provide a substantial but still architecturally plausible offset of the building's electricity demand within the available surface area.



Figure 3. Assumed case-study model with BIPV.

The Scenario B simulation produced both building electricity-consumption data and electricity generation from the BIPV system. Figure 4 presents the monthly breakdown of consumption and generation. The annual results indicate several important effects of BIPV integration.

- Lighting electricity use remained broadly comparable to Scenario A at approximately 215,436 kWh/year. The small difference is not significant in practical terms and mainly reflects minor modelling variation.
- Cooling electricity use decreased to approximately 336,118 kWh/year, which is about 15% lower than in Scenario A. This reduction can be attributed to the façade-integrated BIPV elements acting as an additional shading layer and reducing solar heat gains through the envelope.
- Total annual electricity consumption before accounting for PV generation was approximately 600,958 kWh/year. This reduction relative to the baseline case reflects the passive energy benefit provided by the BIPV-shaded envelope.
- Annual PV generation from the BIPV system reached approximately 347,610 kWh/year, representing a major on-site electricity contribution.

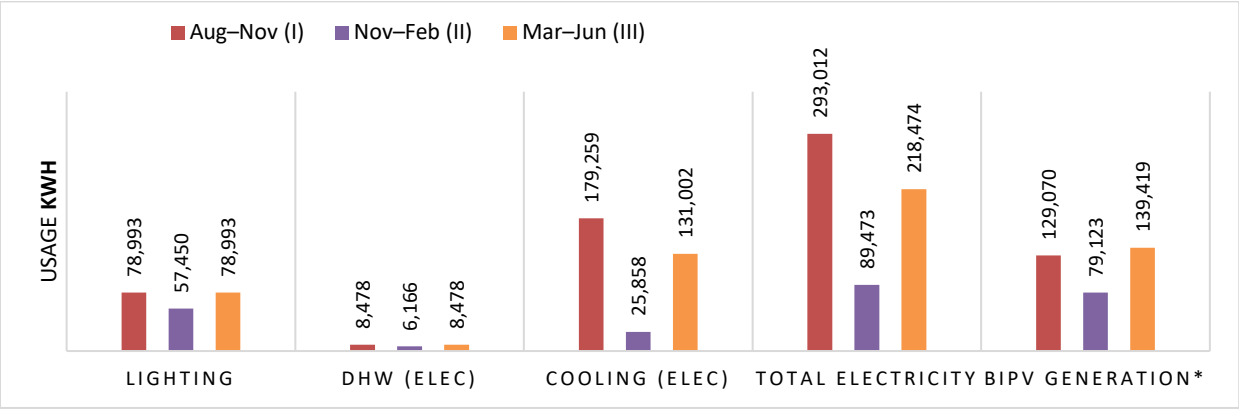


Figure 4. Electricity-use breakdown for Scenario B.

When PV generation is compared with annual consumption, the BIPV system supplies a substantial share of the building's electricity demand. Specifically, 347,610 kWh generated against 600,958 kWh consumed indicates that approximately 58% of annual electricity demand in Scenario B could be met by BIPV generation. A significant share of this electricity would likely be consumed directly during daytime school operation, while any surplus could be exported to the grid or stored if battery systems were available.

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Expressed as net grid demand, Scenario B required approximately 253,348 kWh/year (600,958 - 347,610). Compared with Scenario A, this represents an approximately 60% reduction in grid electricity use. For clarity, three distinct performance indicators are reported in this study: an approximately 15% reduction in cooling electricity demand, approximately 58% of annual demand in Scenario B met by BIPV generation, and an approximately 60% reduction in net grid electricity use relative to the baseline case.

At the monthly scale, PV generation was highest during the sunnier months. During Term I, generation covered a large share of the combined lighting and cooling load. In winter, PV output declined somewhat because of lower solar availability, but total electricity demand also decreased, primarily because cooling loads were lower.

Comparison between Scenarios A and B

The comparison between the two scenarios clearly demonstrates the value of BIPV integration. Scenario A consumed approximately 633,293 kWh/year, whereas Scenario B reduced gross annual electricity use to about 600,958 kWh/year and generated approximately 347,610 kWh/year on site. As a result, net electricity drawn from the grid fell from approximately 633,293 kWh/year in the baseline case to about 253,348 kWh/year in the BIPV case, equivalent to an approximately 60% reduction.

The reduction in cooling electricity demand is primarily associated with the shading effect of the BIPV-integrated envelope rather than with electricity generation itself. By covering the south, east, and west fades, the PV elements act as a protective outer layer that intercepts solar radiation before it reaches the walls and glazes. This effect is especially important in Dhahran, where cooling is the dominant end use. The semi-transparent photovoltaic skylight performs a similar role by moderating solar penetration into the courtyard while still admitting daylight.

It is important to distinguish between the two contributions of BIPV observed in this study. First, the passive envelope effect reduced annual cooling electricity use from approximately 396,723 kWh/year in Scenario A to 336,118 kWh/year in Scenario B, or about 15%. Second, the active electricity-generation function produced approximately 347,610 kWh/year of renewable electricity. The larger reduction in net grid demand therefore came from on-site generation, while the reduction in building energy demand itself resulted mainly from shading and thermal buffering provided by the integrated PV surfaces.

Table 1. Summary comparison between Scenario A and Scenario B

Metric	Scenario A	Scenario B	Interpretation
Gross annual electricity demand (kWh/year)	633,293	600,958	5.1% lower due to passive shading
Cooling electricity (kWh/year)	396,723	336,118	15.3% reduction
Annual PV generation (kWh/year)	0	347,610	Supplies 57.8% of Scenario B demand
Net grid electricity (kWh/year)	633,293	253,348	60.0% reduction vs Scenario A

The school's daytime operating schedule aligns well with photovoltaic generation. During occupied hours, PV electricity can directly support lighting and cooling loads and reduce peak demand. This makes school buildings particularly suitable for solar integration. From an environmental perspective, the resulting reduction in grid electricity demand also implies a lower operational carbon footprint, especially in a national electricity system still strongly influenced by fossil-fuel-based generation.

Where net-metering or similar grid-export mechanisms are available, surplus electricity generated during weekends or school holidays could further improve the value of the system. More broadly, the results show that BIPV improves school-building performance through two complementary mechanisms: it reduces thermal gains through shading, and it supplies a large share of the remaining electricity demand through on-site renewable generation.

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Although BIPV requires additional upfront investment, the combined benefit of cooling-energy savings and on-site electricity generation can yield meaningful long-term cost savings. The reduction of roughly 380,000 kWh/year in grid electricity use suggests a substantial decrease in operating expenditure, depending on the tariff applied to educational buildings. Over a 20-year service life, this corresponds to about 7.6 million kWh of avoided grid electricity purchases. Beyond economics, visible solar installations can support sustainability education by allowing students to engage with real-time generation data and by turning the building itself into a demonstrative learning environment.

School buildings are particularly strong candidates for BIPV integration for several reasons. Their operating hours coincide with daylight hours, many are publicly funded and suitable for long-term investment strategies, and the visibility of renewable-energy systems adds educational and social value. Because schools are community-oriented institutions, visible sustainability measures such as BIPV can also strengthen public awareness of environmental responsibility and encourage broader adoption of green-building practices.

In summary, the comparison between Scenarios A and B as shown in table 1indicated that BIPV integration in Saudi school buildings can reduce cooling electricity demand by about 15%, meet approximately 58% of annual electricity demand in the BIPV scenario, and lower net grid electricity use by about 60% relative to the baseline case. These findings are consistent with previous international reviews showing that BIPV systems can supply a substantial share of building energy demand under favourable conditions [3]. Given Saudi Arabia's strong solar resource, the results support broader deployment of BIPV in school buildings as part of national energy-efficiency and renewable-energy objectives.

The results should be interpreted in light of the modelling assumptions used in the study. Because the analysis is based on a conceptual prototype school in Dhahran, the magnitude of the reported savings depends on the assumed geometry, façade exposure, operating schedule, HVAC settings, envelope properties, and extent of BIPV coverage. In particular, the cooling-load reduction is closely linked to the amount and orientation of the shaded façade area, while PV generation depends on the assumed integration area and the local weather data. The results should therefore be understood as indicative of BIPV performance potential in a representative Saudi school model rather than as universally transferable values for all schools.

Limitations

This study is based on simulation of a conceptual reference school and should therefore be interpreted as an assessment of performance potential rather than measured in-use performance. The model was not calibrated against monitored data from an existing school, and the results remain sensitive to assumptions related to geometry, schedules, envelope properties, HVAC operation, and BIPV coverage. In addition, the analysis did not explicitly account for maintenance-related factors that can affect photovoltaic performance in Saudi conditions, including dust accumulation, surface soiling, cleaning frequency, and long-term degradation. Future work should therefore include monitored case studies, field measurements, and calibrated simulation to validate the results under real operating conditions.

Conclusion

This study demonstrates the feasibility and value of using building-integrated photovoltaics in Saudi school buildings. The simulation results show that BIPV improves energy performance through both passive and active mechanisms: it reduces solar heat gains and cooling demand through façade and skylight shading, and it generates a substantial amount of on-site renewable electricity. In the present case, BIPV reduced net grid electricity use by approximately 60% relative to the baseline case, lowered cooling electricity demand by about 15%, and supplied roughly 58%

of annual electricity demand in the BIPV scenario. These outcomes support Saudi Vision 2030 and broader national sustainability objectives.

Beyond energy and financial benefits, BIPV is particularly suitable for school buildings because school operating hours align with daytime solar production, many schools are publicly managed and therefore well suited to long-term sustainability investment, and visible renewable-energy systems can strengthen environmental awareness among students and the wider community. The study therefore supports pilot BIPV projects in both new and existing schools and recommends further work based on field measurements to assess practical issues such as maintenance, dust accumulation, and long-term performance. From a design perspective, BIPV should be considered early in the design of new schools, while retrofit strategies such as PV-integrated shading devices and rooftop systems can be explored for existing buildings. At the policy level, clear guidelines, incentives, certification credits, and streamlined grid-connection procedures would help accelerate BIPV adoption in the education sector.

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Evaluating The Effectiveness of HDPE Shading Devices in Madinah

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Keywords: High-Density Polyethylene (HDPE), Tensile Shading, Microclimate Measurement, Thermal Comfort, Urban Heat Island (UHI), Solar Radiation Mitigation, Infrared Thermography, Mean Radiant Temperature (MRT), Physiological Equivalent Temperature (PET)

Abstract. As part of the Vision 2030 initiative, the "humanization" of Saudi cities aims to transition toward pedestrian-centric urban environments to enhance public health and environmental sustainability. In Madinah, this objective faces significant challenges due to an arid climate where summer temperatures frequently exceed 45°C, rendering outdoor plazas and walkways underutilized heat islands. This study evaluates the effectiveness of High-Density Polyethylene (HDPE) tensile shading devices as a localized heat mitigation strategy. Utilizing infrared thermography and illuminance (lux) monitoring during peak solar intensity, field measurements were conducted to quantify surface temperature differentials and solar radiation filtration. The results indicate significant thermal variance, with shaded asphalt recording temperatures 31.7°C lower than exposed surfaces, which peaked at 75.7°C. Optical analysis confirmed that HDPE structures filter an average of 76.1% of incident solar radiation. These interventions effectively lower the Mean Radiant Temperature, translating to an estimated reduction in perceived pedestrian heat stress of 9.5°C to 12.5°C. The findings suggest that permeable tensile structures provide a scalable method for moderating microclimate temperatures. Such strategies are foundational for accommodating for supporting Madinah's projected growth to 30 million annual visitors, ensuring that urban infrastructure remains physically viable and supports the city's long-term sustainability and walkability goals.

Introduction

The Kingdom of Saudi Arabia's Vision 2030 framework emphasizes environmental sustainability and public health by prioritizing the "humanization" of cities. This shift toward pedestrian-centric urban environments is particularly vital in Madinah, a city managing 1.5 million permanent residents and a transient visitor population expected to reach 30 million annually by 2030 [1,2]. This projected increase in footfall necessitates robust pedestrian infrastructure; however, the utility of these spaces is severely limited by Madinah's extreme climatic conditions, where summer temperatures frequently exceed 45°C [3,4].

Pedestrian thermal comfort is the primary determinant of whether these urban interventions achieve their sustainability goals or remain underutilized heat islands [5]. While High-Density Polyethylene (HDPE) tensile shading devices have been widely deployed to mitigate heat, their specific impact on Madinah's microclimate remains under-researched. Unlike solid structures, HDPE's "breathable" knitted construction allows trapped hot air to escape while providing significant UV radiation blockage [6,7]. Despite their prevalence, there is a distinct lack of localized empirical data evaluating their performance. This paper addresses this research gap by quantifying the effectiveness of HDPE shading in enhancing the thermal comfort of residents and visitors within Madinah's unique urban fabric.

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Methodology

Field measurements were conducted to evaluate the effectiveness of HDPE tensile shading structures in reducing surface temperature and solar radiation exposure under peak summer conditions in Madinah. The validation of the results was performed through repeated measurements, comparative analysis between shaded and unshaded surfaces, and statistical evaluation of the recorded data.

All measurements were taken under clear-sky conditions between 12:00 PM and 1:00 PM, representing the period of maximum solar intensity (see Fig .1). To ensure consistency, measurements were performed at the same location, using identical surface materials (asphalt), and at a fixed sensor height of 1.2 m meters (approximating the average waist-height of a pedestrian) to accurately reflect the visual and thermal experience of users within the urban space. Each measurement cycle was repeated three times, and the results are presented as mean values with observed variation.

The thermal data were collected using a Fluke TiS55+ infrared thermal imager (MyFlukeStore, Wilmington, California, United States) with an accuracy of ±2 °C, while illuminance levels were measured using a Bside digital lux meter (Bside, Shenzhen, Guangdong, China) with an accuracy of ±3%. These accuracy ranges were considered during the interpretation of results to ensure that the observed differences significantly exceed instrument uncertainty.



Fig. 1. *On-site thermal data collection setup. (Left) The TiS55+ Thermal Imager (Fluke Corporation, Everett, WA, USA) used for measuring surface temperature differentials. (Right-top) Visual context of the shaded pedestrian/parking corridor. (Right-bottom) Corresponding thermogram displaying surface temperatures*

The inferred thermal imagery was taken using a comparative sampling technique, capturing both unshaded and shaded environments within a single frame. This approach allows for a synchronized analysis of surface temperature differentials, effectively isolating the cooling performance of the intervention from fluctuating ambient conditions [8].

To quantify the solar radiation mitigation provided by the HDPE structures, illuminance levels were recorded. Although illuminance specifically measures the visible spectrum of light, it serves as a reliable proxy for total solar irradiance in high-exposure environments, as changes in visible light intensity strongly correlate with variations in the broader electromagnetic spectrum responsible for thermal gain [9]

Results and Discussion

Surface Temperature Reduction

Infrared thermography (See Fig. 2) revealed a substantial difference in surface temperature between exposed asphalt and areas shaded by the HDPE structure.). Using data recorded by the TiS55+ Thermal Imager, Mean Radiant Temperature (MRT) was estimated using surface temperature measurements following ISO 7726 guidelines. The maximum recorded temperature of the unshaded asphalt reached 75.7 °C, while the shaded surface recorded a minimum temperature of 44.0 °C.

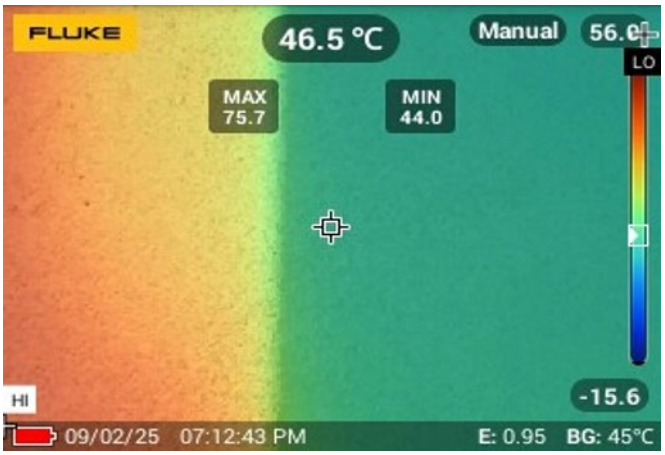


Fig. 2. *Infrared thermogram capturing the sharp thermal gradient at the boundary of a shaded urban space. The exposed asphalt (left) reached a maximum surface temperature of 75.7°C, while the adjacent shaded surface (right) recorded a minimum of 44.0°C. The center-point temperature of 46.5°C demonstrates a significant 29.2°C reduction in surface heat absorption due to the overhead HDPE shading intervention.*

Table 1. *Repeated measurements used to validate the temperature reduction.*

Trial	Unshaded Surface (°C)	Shaded Surface (°C)	Temperature Reduction (°C)
1	75.7	44.0	31.7
2	73.9	45.2	28.7
3	76.3	46.1	30.2

Mean reduction = 30.2 °C
Standard deviation ≈ 1.5 °C

The results indicate a consistent reduction of approximately 30 °C in surface temperature due to the shading intervention. The variation between trials remains small relative to the magnitude of the reduction, confirming the reliability of the measurements.

The observed temperature difference is significantly larger than the thermal imager uncertainty (±2 °C), indicating that the cooling effect of the shading structure is statistically meaningful.

Such reductions are critical in hot-arid environments, where exposed asphalt surfaces may exceed safe contact limits. Previous studies report that skin contact with surfaces above 50–60 °C may cause thermal injury [10], confirming that unshaded urban materials in Madinah may become physically hazardous during peak summer conditions.

The shading structure interrupts direct solar gain and reduces long-wave heat re-radiation, which is the primary driver of the Urban Heat Island (UHI) effect at the pedestrian level.

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Solar Radiation and Illuminance Reduction

Illuminance measurements were used as a proxy for solar radiation intensity to quantify the ability of the HDPE fabric to filter incoming solar energy. While thermal imaging captures the long-wave heat re-emitted by surfaces, lux levels quantify the immediate intensity of the sun's rays at the pedestrian level.

The lux data was processed to determine the Transmission Percentage (T) using Eq .1, which represents the fraction of solar illuminance that penetrates the fabric weave. The relationship is defined by the following equation:

$$T = (\frac{E_{shaded}}{E_{unshaded}}). \quad (1)$$

Where E_{shaded} is the illuminance level measured directly beneath shading device, and $E_{unshaded}$ is the baseline illuminance measured on the open asphalt.

The inverse of this value provides the Reduction Percentage, signifying the total amount of short-wave radiation successfully blocked by the intervention.

$$R = 100 - T \quad (2)$$

The results of the three experimental trials and their corresponding calculations are summarized in Table 1.

Table 2. *Illuminance Reduction and Transmission Analysis of HDPE Shading*

Trial	Unshaded [Lux]	Shaded [Lux]	Calculations	Transmission (%)	Reduction (%)
1	15,850	4,280	4280 / 15850) * 100	27.0%	73.0%
2	14,970	2,680	(2680 / 14970) * 100	17.9%	82.1%
3	9,990	2,680	(2680 / 9990) * 100	26.8%	73.2%

Mean reduction = 76.1 %
Standard deviation ≈ 4.7 %

The results demonstrate that the HDPE shading structure blocks more than three-quarters of the incoming solar radiation. Figure 3 presents an Isolux diagram, illustrating the gradient of illuminance levels as they transition from the unshaded asphalt into the core shaded zone of the HDPE structure. The variation between trials is attributed to minor changes in solar angle, atmospheric conditions, and fabric orientation, but the overall performance remains consistent.

The measured reduction values exceed the lux meter uncertainty (±3%), confirming the validity of the results.

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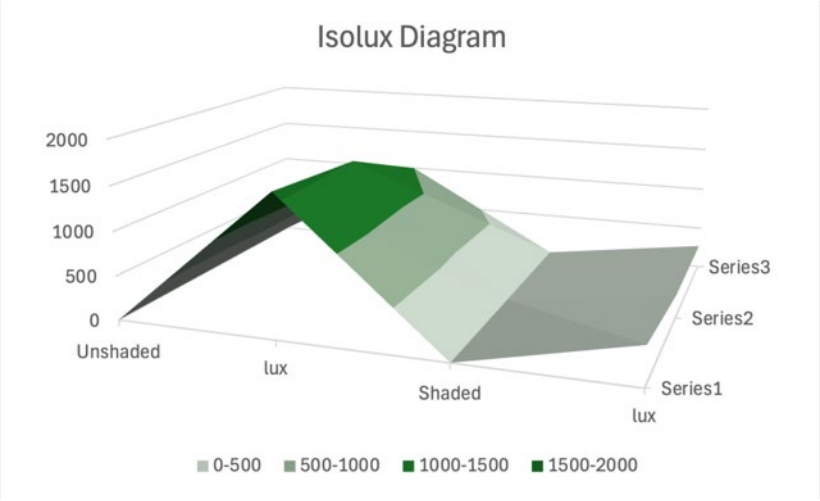


Fig. 3. *Isolux Diagram of HDPE Shading Intervention. The 3D surface plot visualizes the sharp gradient between unshaded and shaded zones, illustrating the material's capacity to significantly dampen solar intensity and enhance the local microclimate.*

Implications for Mean Radiant Temperature and Thermal Comfort

Surface temperature reduction directly influences Mean Radiant Temperature (MRT), which is the dominant factor affecting outdoor thermal comfort in hot climates. Lower surface temperatures reduce long-wave radiation emitted toward pedestrians, thereby decreasing perceived heat stress.

Based on commonly reported outdoor comfort relationships, a reduction of approximately 10 °C in surface temperature may correspond to a decrease of 3–4 °C in Physiological Equivalent Temperature (PET). Applying this relationship to the measured average surface reduction of 30.2 °C suggests an estimated PET reduction of approximately 9.5–12.5 °C.

This shift represents a transition from extreme heat stress conditions to more tolerable thermal environments, significantly improving the usability of outdoor spaces during peak hours.

Similar reductions have been reported in previous studies investigating tensile shading systems in hot-arid climates, where temperature decreases between 20 °C and 35 °C were observed, supporting the validity of the present results [11,12].

To improve the validity of the study, measurements were repeated under consistent environmental conditions and using calibrated instruments. The recorded temperature differences are substantially larger than the instrument uncertainty, indicating that the observed cooling effect is not due to measurement error.

However, several limitations should be acknowledged. The measurements were conducted at a single site and during a limited time period, and additional variables such as wind speed, relative humidity, and long-term climatic variation were not included. These factors may influence outdoor thermal comfort and should be considered in future research.

Despite these limitations, the consistency of repeated measurements and agreement with previously published studies confirm that HDPE tensile shading structures provide a reliable and effective strategy for mitigating extreme heat in arid urban environments.

Conclusion

The empirical findings of this study demonstrate that High-Density Polyethylene (HDPE) shading structures are an effective intervention for mitigating extreme heat in arid urban environments. Thermal profile analysis revealed a 31.7°C reduction in surface temperatures, preventing unshaded asphalt from reaching a peak of 75.7°C, a value that exceeds safety thresholds for human contact. Optical data confirmed that these structures attenuate an average of 76.1% of incident solar radiation, effectively lowering the Mean Radiant Temperature (MRT).

These interventions result in an estimated reduction in perceived pedestrian heat stress of 9.5°C to 12.5°C, shifting the microclimate from "Extreme Heat Stress" to more manageable thermal categories. Such measurable improvements are essential for the physical viability of pedestrian infrastructure in Madinah, particularly as the city scales to accommodate 30 million annual visitors. By providing a breathable, high-blockage barrier to solar gain, HDPE tensile structures offer a scalable and evidence-based solution for fostering walkability and reducing the Urban Heat Island (UHI) effect in warming metropolitan regions.

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Design and Performance Validation of a Sustainable Housing Prototype in the Kingdom of Bahrain Using Green Building Concepts and Smart Technologies

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Keywords: Sustainable Housing, Green Concrete, Smart Glazing, Occupancy Sensors, Photovoltaic Systems, ETABS, LEED Certification, Climate-Responsive Design, Bahrain Vision 2030

Abstract. Rapid population growth in the Kingdom of Bahrain has intensified demand for residential housing while increasing environmental impacts associated with conventional construction practices. This study presents the design, structural validation, and performance evaluation of a sustainable housing unit based on the Ministry of Housing T8 model, integrating green building materials, renewable energy systems, and smart technologies. The proposed design incorporates green concrete with 50% cement replacement by fly ash, recycled steel reinforcement, smart glass façade systems, occupancy-based LED lighting sensors, photovoltaic panels, high-performance wall and roof insulation, and water reuse through rooftop hydroponic cultivation. Structural analysis was conducted using ETABS software in accordance with BS 8110 and BS 6399 standards. Results indicate that green concrete achieved a 28-day compressive strength of 20.22 N/mm² compared to 21.34 N/mm² for conventional concrete, demonstrating negligible structural performance reduction. Material cost analysis revealed a reduction from 22.82 BHD to 20.33 BHD per mix batch, while recycled steel reduced reinforcement costs by approximately 60%. Energy-efficient systems significantly lowered projected electricity consumption, particularly through solar integration and occupancy-controlled lighting, which reduced monthly lighting costs from 43.77 BHD to 8.75 BHD. The findings confirm that sustainable residential construction in Bahrain is technically feasible, structurally reliable, economically advantageous, and environmentally responsible, offering a scalable prototype aligned with Bahrain Vision 2030 and global Sustainable Development Goals.

1 Introduction

The housing sector is one of the largest sectors of energy consumption and a major contributor to global greenhouse gas emissions. There is therefore an urgency to develop sustainable residential developments that are in line with both the present agenda of public policy and present research in academia. Recent systematic reviews have identified that building energy efficiency may be achieved by implementing a comprehensive strategy that utilizes enhanced insulation, renewable energy systems and smart building technology to reduce energy consumption and the environmental impacts from buildings throughout the full life cycle of the buildings [1-2]. Sustainable housing is being defined by its ability to not only operate in an efficient manner (in terms of operational energy), but to also produce lower amounts of embodied carbon and to create long-term economic benefits to society [2-4, 17]. The literature indicates that, by using green

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materials (e.g., recycled aggregate and alternative low carbon concrete), the amount of greenhouse gas emissions associated with construction activities may be reduced without loss of structural integrity [2-5, 14]. Additionally, frameworks for zero-carbon housing are being developed to combine a variety of passive design strategies with renewable energy generation and/or advanced building management systems to significantly lower the total energy needs of the house [6-7, 15].

It has been shown through various research studies that model based engineering techniques, along with digital technologies, can enhance sustainability performance within the housing system[5, 8-10]. Model based engineering and digital technology methods are most effective for improving sustainability performance in housing systems when they are aligned with national development strategies such as Vision 2030 [8-10]. The application of smart building technologies, including adaptive façades, photovoltaic (PV) integration and occupancy-based lighting control, have also provided significant improvements in energy efficiency and a reduction in reliance on grid supplied electricity [6, 11, 17]. In addition to this, studies regarding housing sustainability have emphasized the need for several measures; including development of environmental performance indicators, adoption of energy efficiency standards and development of policy to enable sustainable housing to be achieved over time [12-15]. All of which show clearly that a holistic approach to sustainability using new materials, renewable energy systems, smart technologies and compliance with regulations will be required to achieve sustainability within housing.

In the Gulf Area, particularly in Bahrain, the sustainability challenge for housing must be analyzed considering the unique climate of Bahrain that is characterized by high requirements for cooling, extreme levels of solar irradiation and limited availability of water. Sustainability is one of the key themes of the national development strategy of Bahrain "Bahrain Vision 2030". In Bahrain, like in the rest of the Gulf Region, however, local building practices are still based on high carbon materials and energy-consuming technologies.

The sustainable housing prototype presented in this study provides an answer to the sustainability challenges at the global and local levels for the country of Bahrain. This prototype meets both the climate requirements and the legal requirements of Bahrain through a combination of green concrete, recycled reinforcing bars, smart glass windows, photovoltaic (PV) systems, advanced insulation materials, and adaptive energy management systems. In addition to providing a sustainable housing option on a large scale and meeting the national and international sustainability goals, the main goal of this research is to provide additional data to help inform the discussion surrounding sustainable housing options as well as to validate the structural properties and assess the environmental performance of the sustainable housing prototype.

Despite the growing body of research on sustainable construction materials and energy-efficient building systems, there remains a lack of integrated and validated housing prototypes tailored to Bahrain's climatic and regulatory context. In particular, limited studies have combined low-carbon materials, renewable energy systems, and smart technologies within standardized housing models such as the Ministry of Housing T8 prototype, while also verifying structural performance using established design codes. This gap highlights the need for a holistic, climate-responsive, and structurally validated housing solution that aligns with Bahrain Vision 2030 and can be replicated at scale [16, 19].

2 Methodology

This investigation adopted an analytically based/structured design methodology for developing an environmentally friendly housing prototype that can be utilized in the climatic, structural, and regulatory environment of the Kingdom of Bahrain. The study's research methodology is presented as a sequence (See Figure 1); this shows how literature review and problem definition occur in succession with architectural development, selection of sustainable materials, integration of renewable energy systems, structural modeling, environmental assessment of performance, and

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feasibility assessment. The methodology presents a systematic process by which sustainability-based interventions are incorporated into the technical framework.

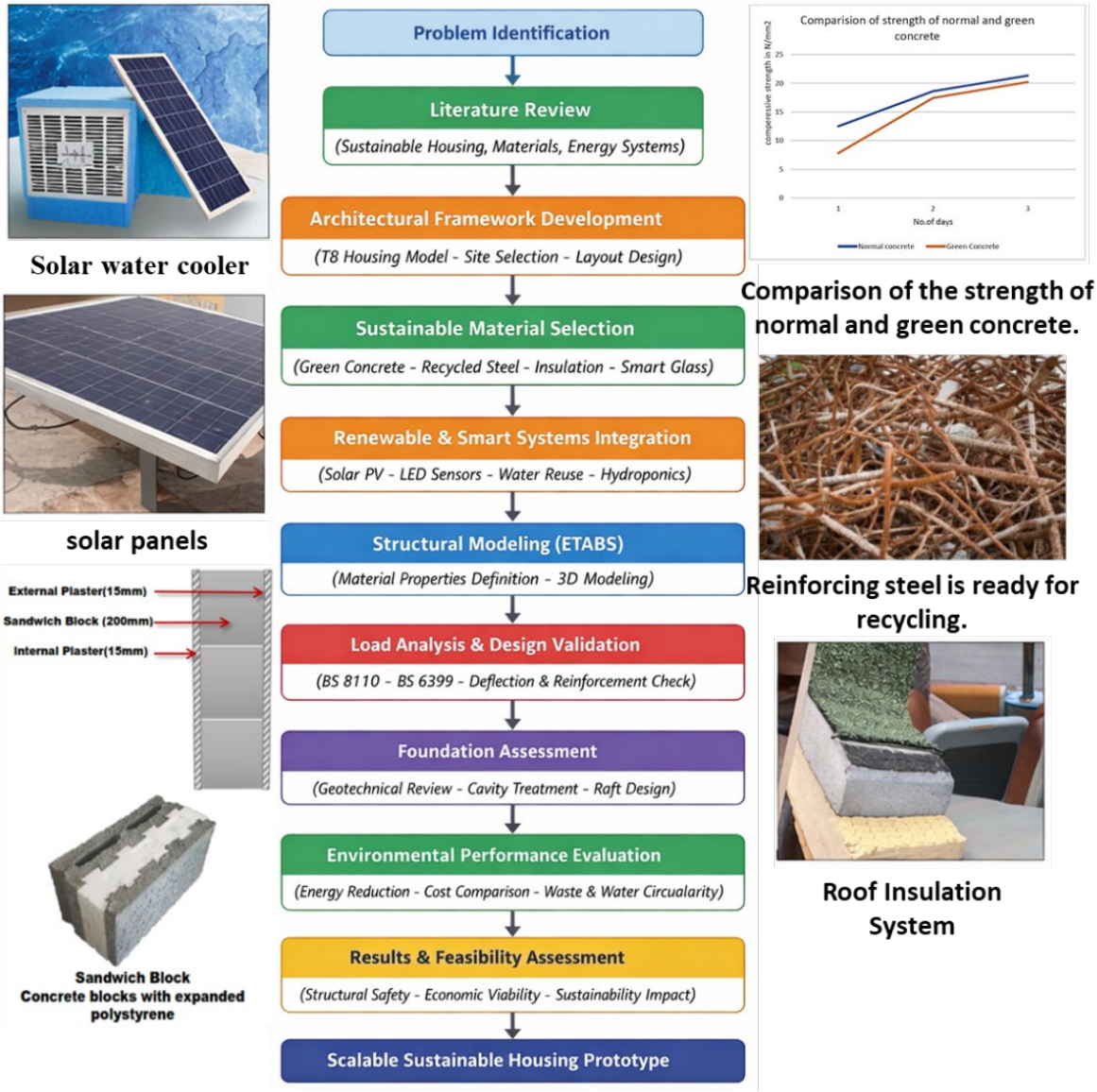


Figure 1 Integrated Research Framework and Sustainable Systems for the Housing Prototype

In addition to the methodology shown in Figure 1, the architectural development phase used the Ministry of Housing T8 residential model. The T8 residential model allowed the proposed housing unit to meet national housing standards and served as a practical example of how the proposed housing unit would be constructed. The proposed housing unit is a two-story detached villa that includes an attached garage. The ground floor will have approximately 113.7 m² of space and include: a Majlis (a guest reception area) family hall, kitchen, storage room, bathroom, one bedroom, lobby and porch. The first floor will have approximately 95.2 m² of space and include a master bedroom, two other bedrooms, bathrooms, and a central circulation hallway. The garage is located adjacent to the main entrance and has an area of 23.8m². The total area of the unit is approximately 232.7m². The layout of the unit provides a separation of public and private areas while also providing efficient circulation and structural grid regularity. The architectural layouts are displayed in Figure 2a, while the front, rear, and side elevations are displayed in Figure 2b.

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A compact rectangular configuration was selected for the villa to provide structural stability and minimize the amount of exposed façade surface area thus enhancing thermal performance due to Bahrain's high solar radiation. Sustainable materials were selected at the design stage. Green concrete with partial cement replacement was selected to reduce the amount of embodied carbon produced by the structure while still being compatible structurally [14]. Recycled reinforcing steel was selected to minimize raw material extraction and lifecycle environmental impact. The building envelope features sandwich block wall construction with expanded polystyrene insulation and a multi-layer roof insulation system to reduce the amount of heat transferred between the inside and outside of the building. Smart glazing was selected for the solar-exposed façades to reduce heat gain and enhance occupant comfort.

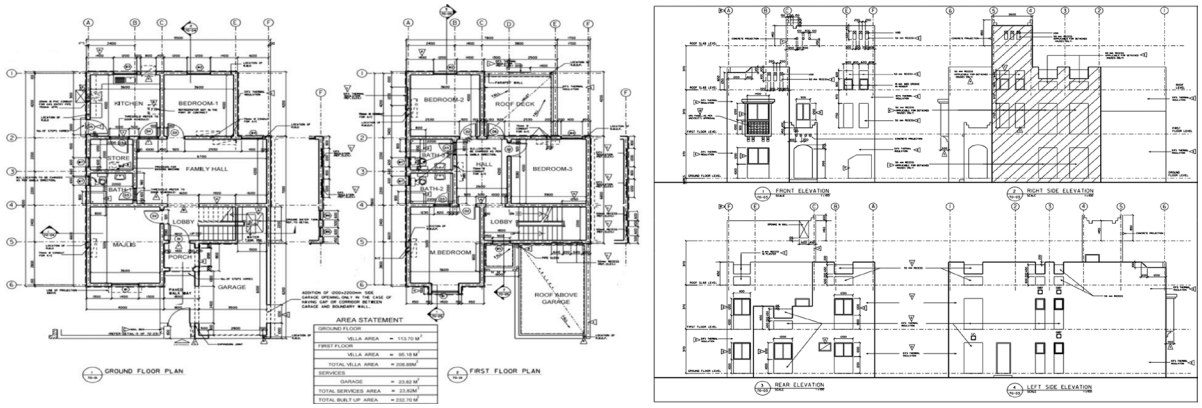


Figure 2 (a). Ground and first floor architectural plans (b). Front, rear, and side elevations of the proposed housing unit.

Renewable and smart technologies have been combined to improve operational sustainability. The integration of on-site renewable electricity generation using rooftop PV panels enabled a portion of the electrical energy for the facility to be generated on-site. A solar powered water-cooling system was also added to help mitigate the peak electrical load in the hot summer months [16, 18]. Sensors that utilize occupancy-based light levels will provide additional lighting efficiencies as well as condensate water recovery systems are being proposed to support irrigation of plants grown in a rooftop hydroponic cultivation system.

To perform a structural analysis, ETABS version 18 was used. An analytical three-dimensional model representing the structural layout of the building (slab systems; beams; columns; etc.) was developed. Material characteristics typical of green concrete and recycled reinforcement steel were established in this modeling environment. Load case assignments were made to the model according to British Standard 8110 and British Standard 6399. The three-dimensional model is shown in Figure 3 and illustrates the spatial structural framework which was evaluated analytically. The use of ETABS permitted an assessment of the global structural behavior, load distribution patterns and serviceability conditions of the structure, and verified that the use of sustainable materials did not compromise the structural integrity of the structure. As a whole, the methodology integrates detailed architectural planning, sustainable materials, renewable energy systems, and structural validation into a comprehensive and scalable sustainable housing model designed to meet the environmental and regulatory requirements of the Kingdom of Bahrain.

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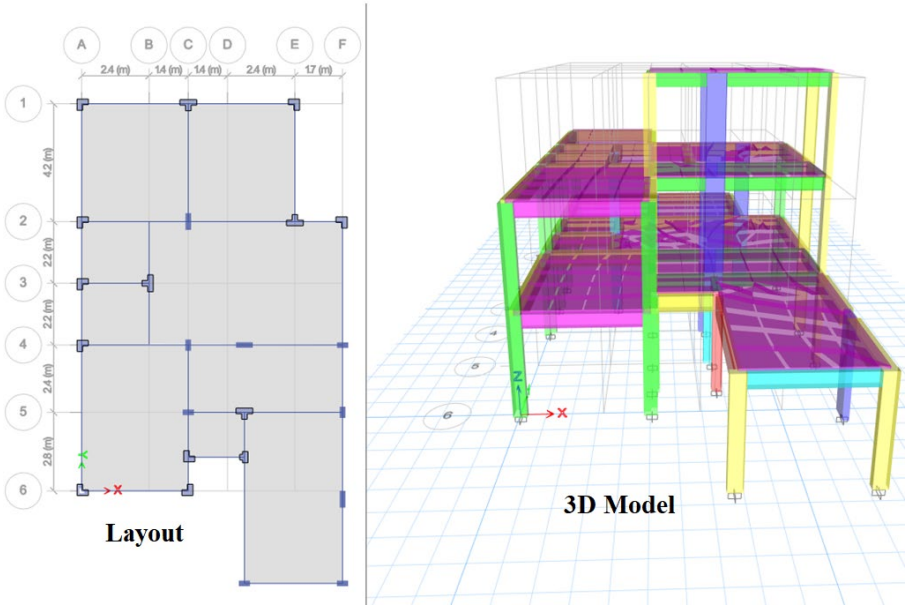


Figure 3 Three-dimensional ETABS structural model of the proposed housing unit.

The green concrete mix was designed with a **50% replacement of ordinary Portland cement by fly ash**, with an approximate water-to-binder ratio of **0.45**. Natural coarse and fine aggregates were used in accordance with standard grading requirements, and a superplasticizer was incorporated to maintain workability. Specimens were cast and cured under controlled laboratory conditions using water curing for 28 days. A total of **three cube specimens** were tested in accordance with British Standard 12390 to determine compressive strength.

4 Results and Discussion

The results of this research show that by using sustainable materials; incorporating renewable energy sources and smart technologies into a new home design will result in demonstrable improvements in structure, environment, and economics. Most current residential structures use separate approaches for sustainability and do not address all areas of sustainability (structure, energy, life cycle cost, resource) with one system or housing model.

4.1 Structural Performance Validation

The structural integrity of a building was evaluated through a structural validation process using ETABS; it demonstrated that replacement of conventional concrete with green concrete, along with replacement of recycled steel reinforcement, does not significantly affect the structural integrity of a building. Although the 28-day compressive strength of green concrete (20.22 N/mm²) was approximately 5% less than that of traditional reinforced concrete (21.34 N/mm²), this slight decrease in compressive strength was still within acceptable limits based upon the design criteria as defined in BS 8110, and it had no adverse effect upon the load-bearing capacity or detailing of the reinforcing steel.

Structural validation also supported that the structural behavior of the building meets the required standards. The calculated slab service and ultimate loads were 6.155 kN/m² and 9.517 kN/m² respectively, and the calculated beam service and ultimate loads were 18.587 kN/m and 34.022 kN/m respectively. In addition, deflections were found to be well within permissible limits, indicating that the stiffness and serviceability performance of the structure have been maintained. The maximum calculated deflection values were within acceptable serviceability limits, not exceeding span/250, as prescribed by BS 8110. For example, the maximum slab deflection was

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approximately 8.5 mm, which is significantly lower than the allowable limit, confirming adequate stiffness performance. Comparative data regarding structural parameters are shown in Table 1.

Table 1 Structural Performance Comparison

Parameter	Normal Concrete	Green Concrete	Variation
28-day Compressive Strength (N/mm²)	21.34	20.22	−5%
Slab Service Load (kN/m²)	6.155	6.155	No Change
Slab Ultimate Load (kN/m²)	9.517	9.517	No Change
Beam Service Load (kN/m)	18.587	18.587	No Change
Beam Ultimate Load (kN/m)	34.022	34.022	No Change

As shown in Table 1, the negligible variation demonstrates that green concrete can effectively replace conventional concrete in low-rise residential applications without compromising safety [14].

4.3 Energy and Thermal Performance

Thermal performance improvements substantially reduced cooling loads in the hot maritime climate of Bahrain. A U-value of 0.548 W/m²K was obtained for the sandwich block wall system, and the roof insulation system achieved a U-value below 0.3 W/m²K. The solar-powered water-cooling system demonstrated temperature reductions from 62°C to approximately 28–30°C thus providing improved occupant comfort while reducing electricity consumption. The key performance indicators are listed in Table 2.

Table 2 Thermal and Energy Performance Indicators

Indicator	Value Achieved
Wall U-value	0.548 W/m²K
Roof U-value	< 0.3 W/m²K
Solar Water-Cooling Temperature Reduction	62°C → 28–30°C
Lighting Cost Reduction	~80%

As shown in Table 2, envelope optimization combined with renewable integration plays a critical role in operational energy reduction under extreme climatic conditions.

4.4 Environmental and Resource Circularity Outcomes

The environmental benefits extend beyond energy savings during operation. The green concrete is achieving embodied carbon emissions reduction due to the use of cement replacement of 50%, as cement production produces approximately 0.9 kg CO_2 per kilogram of cement. In addition to reducing raw material extraction energy needs for steel recycling, it also reduces landfill waste. Overall, the use of envelope insulation, smart lighting, and PV also contributes to lowering operational carbon emissions. Circular water management through condensate recovery and hydroponic irrigation systems has reduced the demand on freshwater resources. Strategies for sustainable waste management, such as recycling and composting, also contribute to promoting resource-efficient and sustainable occupant behaviors. Thus, the combined strategies employed to create an environmentally conscious building design constitute a comprehensive environmental framework to reduce embodied carbon, improve operationally efficient buildings, conserve water, and minimize waste.

4.5 LEED Certification Assessment and Policy Alignment

To evaluate the sustainability performance of the proposed housing unit on an international scale, the housing unit was reviewed based on the LEED rating system. The LEED Certification Levels

can be seen in Figure 4, while the achieved point distribution is illustrated in Figure 5. A total of 54 LEED points were obtained, which corresponds to LEED Silver certification. The LEED assessment was conducted based on **LEED v4.1 criteria** [21] as an internal evaluation. The scoring reflects estimated compliance with credit requirements across key categories, providing a reliable indication of the sustainability performance level of the proposed housing prototype. Figure 5 illustrates the largest contributions in terms of the Energy and Atmosphere category (23 points) due to the optimal energy performance of the housing unit and its inclusion of renewable energy sources. In addition to these credits, the housing unit received credits in the Indoor Environmental Quality, Materials and Resources, and Location and Transportation categories as well. The LEED Silver certification demonstrates that the housing prototype meets internationally recognized sustainability benchmarks, while also meeting the requirements for SDG 7, SDG 11, SDG 12, and SDG 13, and supports the three pillars of Bahrain Vision 2030: sustainability, competitiveness, and fairness [20, 22].

In general, the combined validation of the structural integrity of the housing prototype, the environmental performance of the housing prototype, its economic feasibility, and the LEED certification confirms that scalable sustainable housing prototypes can be developed for the residential sector in Bahrain.



Figure 4 LEED certification levels

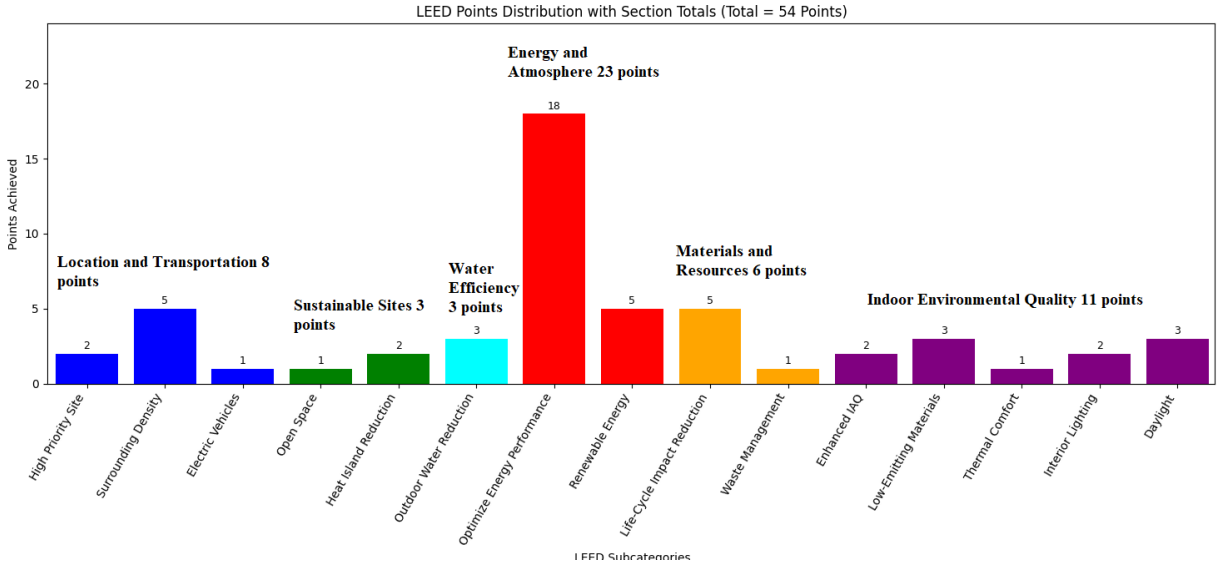


Figure 5 LEED point distribution achieved by the proposed housing unit

5 Conclusion

The housing model developed from this research provides an example of how sustainable housing can be created without negatively impacting the structural integrity or the financial viability of a project. An assessment of structural integrity was carried out on the model using ETABS. The test results showed that the 28-day compressive strength of green concrete was 20.22 N/mm², which is very close to the 21.34 N/mm² of the reference (conventional) concrete model, representing a small reduction of about 5% and completely compliant with BS 8110 standards for the design of

reinforced concrete structures. All load and deflection tests also demonstrated that the model meets all requirements for serviceability and ultimate limit state performance.

There are large environmental implications as well. With less cement being used, there will be a large decrease in the amount of embodied CO_2 emissions. In addition, the use of recycled steel and renewable energy will provide net savings of approximately 30-35% of the CO_2 produced per year by each dwelling unit in comparison to a conventional dwelling unit. This estimated reduction is based on a comparative assessment of annual operational energy consumption, considering Bahrain's electricity generation mix and typical residential energy usage patterns. The calculation includes both operational emissions savings from reduced electricity consumption and embodied carbon reductions from material substitutions, providing an approximate but realistic range of environmental benefits. Additionally, the model will produce a substantial amount of savings in terms of operationally derived energy due to the use of photovoltaics, occupancy-based LED lighting systems, and better insulated building envelopes to reduce the need for electricity generated from fossil fuels - an essential factor in Bahrain's cooling-dominated climate.

In terms of costs associated with the construction of the model, the use of green concrete has resulted in direct cost savings of about 11% versus traditional concrete and approximately 60% versus traditional steel reinforcement. Additionally, the model should result in large amounts of operational cost savings related to lighting and cooling. Although there may be a larger upfront investment required for renewable technologies, the model should result in lower lifecycle costs and therefore increased long-term economic competitiveness.

In addition to the performance aspects of the model, it also supports Environmental, Social, and Governance objectives by reducing greenhouse gas emissions, conserving natural resources, improving indoor comfort, and providing support for affordable housing in Bahrain. The model supports four of the Sustainable Development Goals (SDGs): Goal #7, Affordable and Clean Energy; Goal #11, Sustainable Cities and Communities; Goal #12, Responsible Consumption and Production; and Goal #13, Climate Action. Furthermore, the model supports three of the four pillars of Bahrain Vision 2030: Sustainability, Competitiveness, and Fairness.

Overall, the research demonstrates that the incorporation of sustainable materials and smart systems into conventional residential types is both technically feasible and strategically important for developing climate-responsive development in the Gulf region. The model presented here provides a practical, policy-aligned, and replicable framework for future public housing and sustainable urban development in Bahrain and other similar climates.

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Comparative Analysis of Generative AI-Augmented Machine Learning Models for Embodied CO_2 Prediction in Multi-Story Structural Systems

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Keywords: Embodied CO_2 Emissions, Cross-Laminated Timber, Steel-Concrete Structures, Generative Artificial Intelligence, Gaussian Mixture Model, Kernel Density Estimation, Large Language Model, Machine Learning

Abstract. The building sector contributes significantly to global carbon emissions, particularly through embodied carbon associated with structural materials such as concrete, steel, and timber. This study presents an integrated structural artificial intelligence framework for predicting embodied CO_2 emissions in multi-story buildings. Three structural systems, Cross-Laminated Timber (CLT), steel-concrete, and hybrid CLT-steel-concrete, were modeled at 5, 10, 25, and 50 stories using ETABS and verified in accordance with the Saudi Building Code. Material quantities were extracted to calculate embodied CO_2 emissions based on established emission factors and carbon storage effects of CLT. Due to the limited size of the original dataset (12 instances), three generative artificial intelligence techniques, Large Language Model (LLM), Gaussian Mixture Model (GMM), and Kernel Density Estimation (KDE), were employed to expand the dataset to 100 samples. Five regression models were trained and tested using a 70/30 split. Results indicate that LLM and GMM preserved the statistical structure of the original data and achieved near-perfect predictive performance (R^2 = 0.999), while KDE showed comparatively lower generalization accuracy. The findings demonstrate that generative AI can effectively overcome small-data limitations and support reliable embodied carbon prediction in sustainable structural design.

Introduction

The building sector represents a major source of global CO2 emissions as well as being responsible for a considerable proportion of both operational and embodied carbon throughout a building's life cycle. Operational emissions from heating, cooling, and electricity consumption have historically received more focus than embodied carbon generated during raw material extraction, manufacturing, transportation, and construction, although embodied carbon has become increasingly important to achieve carbon neutrality objectives. With the use of energy-efficient technologies reducing operational emissions, embodied carbon may account for the majority of total lifecycle emissions in many types of buildings, particularly high-rise and performance-optimized buildings [1]. Therefore, minimizing embodied carbon through optimization of material choice and structural configuration has now become an important goal within sustainable construction.

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Structural systems significantly affect embodied carbon since the load-bearing materials typically employed, e.g., concrete, steel, and timber, exhibit very different characteristics with respect to production processes, energy intensities, and emission factors. However, due to their structural reliability and flexibility, reinforced concrete and steel structures continue to be employed extensively; however, the production process of cement and the manufacture of steel are both intensive in terms of carbon emissions. On the other hand, cross-laminated timber (CLT) exhibits lower embodied emissions and provides the additional advantage of biogenic carbon storage; thus, providing an attractive option for sustainable building [2-3]. Hybrid systems employing CLT together with steel and concrete aim to provide an acceptable compromise between structural efficiency and environmental performance [4-5]. A comparative assessment of these structural systems at varying building heights is necessary to provide engineers and architects with information to make informed decisions regarding low-carbon structural design. Structural safety and serviceability must meet regulatory requirements. In this case, the Saudi Building Code mandates compliance with strength and serviceability limit states. In addition, advanced software packages such as ETABS allow for the detailed modelling of multi-storey buildings, thereby allowing for the accurate determination of structural response and the quantity of material required for embodied carbon calculation. Furthermore, the integration of embodied carbon into performance-based sustainability assessments is supported by this integration.

In the last few years, many researchers have used machine learning (ML) for predicting how structures will behave, as well as their potential environmental impacts [6-8]. The most common regression models used by civil engineers are linear regression, polynomial regression, ridge regression, random forests regression, and support vector machines. These regression models have shown to be very accurate at making predictions that can also be easily interpreted [9]. While there are many advantages associated with using machine learning techniques to enable data driven structural design [10] it is typically limited due to the size of the dataset being analyzed; therefore, the possibility of "over fitting" and poor generalization is very likely. Generative Artificial Intelligence Methods have been introduced recently as potential solution to the challenge of small sample sizes. Probabilistic methods like the Gaussian Mixture Model (GMM) and the non-parametric methods like the Kernel Density Estimator (KDE), can generate synthetic data by modeling the underlaying probability distributions [11-12]. Furthermore, Large Language Models (LLM) may also be a method for producing structured data. While generative models such as GANs and VAEs generate larger and more diverse sample sizes than other methods and provide greater model robustness [13-15]; no research has tested whether generative models are an effective means of predicting embodied carbon in structural systems.

The study will compare CLT, steel-concrete, and hybrid systems across various building heights and evaluate the predictive performance of different combinations of generative AI-regression models. The study will contribute to the development of a data-driven methodological approach to low-carbon building design by bringing together structural engineering, sustainability assessment, and artificial intelligence.

Methodology

The research approach incorporated into this project utilizes structural evaluation, quantifying the embodied carbon content, Generative Artificial Intelligence (AI), and Machine Learning Modeling in an integrated methodology. The three structural systems studied are; Cross-Laminated Timber (CLT) frames, Steel-Concrete Composite Frames, and Hybrid-Steel-Cross-Laminated Timber (Hybrid) structures as illustrated in Figure 1. Using the ETABS software program, each structural type was modeled at four different building heights (5-stories, 10-stories, 25-stories, and 50-stories). Each model was analyzed according to the Saudi Building Code to insure compliance with both strength limit states and serviceability limit states. To evaluate the ultimate load resistance, the code-defined load combinations were applied to evaluate structural safety. The

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vertical displacements of the structural models due to both the total dead loads and live loads were also evaluated to determine if the models met the serviceability criteria. Only those models meeting all code requirements were then utilized in the subsequent carbon assessment.

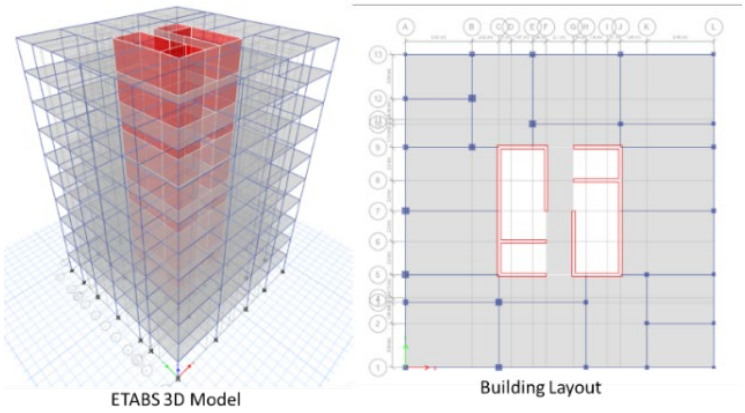


Figure 1 Building Model

Following structural verification, material quantities were extracted from the ETABS models, including the volume of structural concrete (m^3), the weight of steel reinforcement and structural steel members (kN), and the volume of CLT elements (m^3). The steel weight obtained in kilonewtons was converted into mass in tons by dividing by gravitational acceleration (9.8 m/s^2). Embodied CO_2 emissions were then calculated using the relationship: The amount of CO2 (in tons) = [Volume of all building materials x (Total tons of CO2 produced in relation to a specific volume of each type of building material) +/− X] x Factor for Safety. In this study the variable X representing CO2 emissions that may have resulted from transporting the building materials, or positive carbon sinks due to the use of recycled materials, was not considered, therefore the factor for safety was assumed to be 1. The overall CO2 emissions produced by a building can therefore be calculated simply by multiplying the quantity of each type of building material used times the respective CO2 emission factor.

The values used for emission factor included 1.9 tons of CO_2 per ton of steel manufactured, 410 kilograms of CO_2 per cubic meter of structural concrete (assuming about 15 percent cement by volume), and 676 kilograms of CO_2 per cubic meter of CLT (carbon storage capacity). The density of the CLT was assumed to be 490 kilograms per cubic meters so that volume-based calculation could be performed consistently. Each building configuration's net embodied CO_2 emissions were calculated as the sum of the emissions from steel and concrete minus the CO_2 sequestered in CLT components. The calculated CO_2 emissions were then expressed as carbon content through conversion utilizing the molecular weight ratio between carbon and carbon dioxide, where Carbon (tons) = CO_2 (tons) × (12/44). Additionally, the calculated CO_2 emissions were converted to Parts Per Million (PPM) to indicate atmospheric impact, via the formula PPM of CO_2 = (total amount of carbon / 2.12×10^9) × air fraction. This relationship indicates that one part per million (ppm) of CO_2 represents 2.12×10^9 tons of carbon, and the air fraction was assumed to be 0.38. This conversion provides a theoretical representation of the relative contribution of structural material emissions to atmospheric concentration.

The structural modeling and carbon quantification process resulted in twelve unique data sets that corresponded with three different structural systems of varying height (four building heights). Each data set contained four input variables, including the number of stories, volume of concrete, mass of steel, and volume of CLT, and one output variable representing the net embodied CO_2 emissions of each system. Since there were so few data points, an insufficient amount of data existed to support machine learning training and testing processes, and generative AI was utilized

to increase the number of data points from twelve to one hundred for each structural system. Three generative methods were applied independently to produce three expanded datasets of 100 samples (see figure 2) using a Gaussian Mixture Model (GMM) which is a probabilistic model that represents the joint probability distribution as a linear combination of Gaussian distributions, Kernel Density Estimation (KDE) which provides a non-parametric way to estimate the underlying data distribution without imposing a specific structure or type on it, and a Large Language Model (LLM) that uses the learned statistical relationships from the original data set to generate structured numerical data.

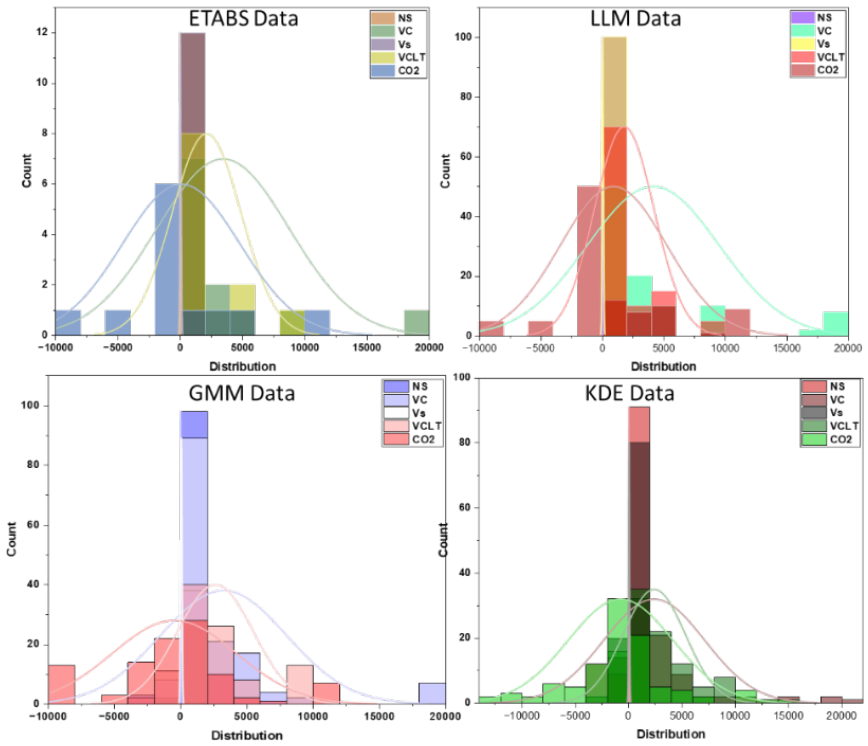


Figure 2 ETABS data and generative dataset

To assess the predictive ability for embodied CO2 emissions across different materials in terms of generalizability, the synthetic datasets created via each generative AI approach were randomly subdivided into a 70 % training subset and a 30 % testing subset. Six regression models, Linear Regression, Polynomial Regression, Ridge Regression, Random Forest Regression, and Support Vector Machine, were trained and tested to estimate embodied CO2 emissions as a function of the four input variables. Standard regression metrics were used to evaluate the performance of each model (i.e., Coefficient of Determination, R^2; Root Mean Square Error, RMSE; and Mean Absolute Error, MAE). Finally, an analytical comparison was made to determine which generative AI method resulted in the most reliable artificially generated dataset and which regression model had the best predictive performance under the same 70/30 training-testing conditions.

In addition to synthetic data evaluation, a validation step was performed using the original ETABS dataset, where trained models were tested against real data to assess generalization capability.

Results and discussion

This section presents the structural verification results, embodied carbon analysis, correlation assessment, and comparative machine learning performance using datasets generated by Large Language Model (LLM), Gaussian Mixture Model (GMM), and Kernel Density Estimation (KDE). The statistical relationships of the original ETABS dataset are illustrated in Figure 3, while

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the regression performance comparisons are shown in Figures 4-6 and summarized quantitatively in Table 1. All augmented datasets were divided into 70% training and 30% testing subsets to evaluate predictive generalization.

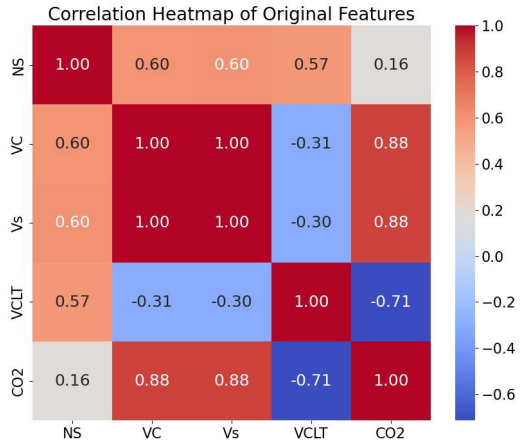


Figure 3 Correlation heatmap of the original ETABS dataset

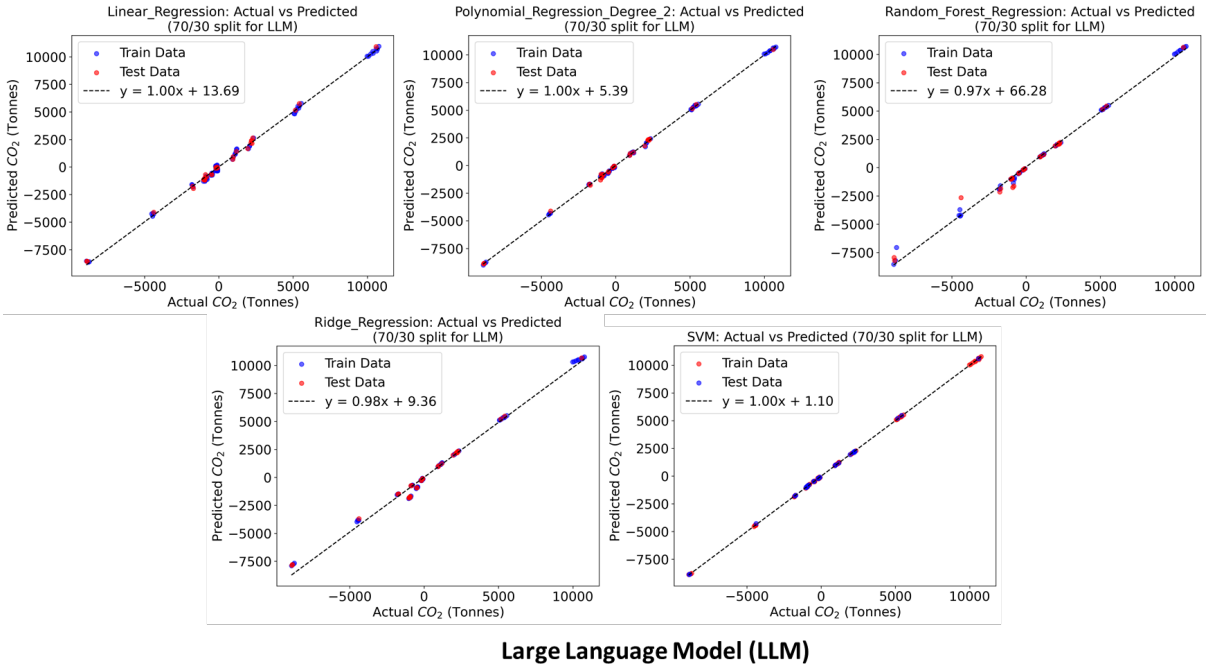


Figure 4 Actual vs. Predicted CO_2 Emissions for Regression Models Trained on LLM-Generated Data

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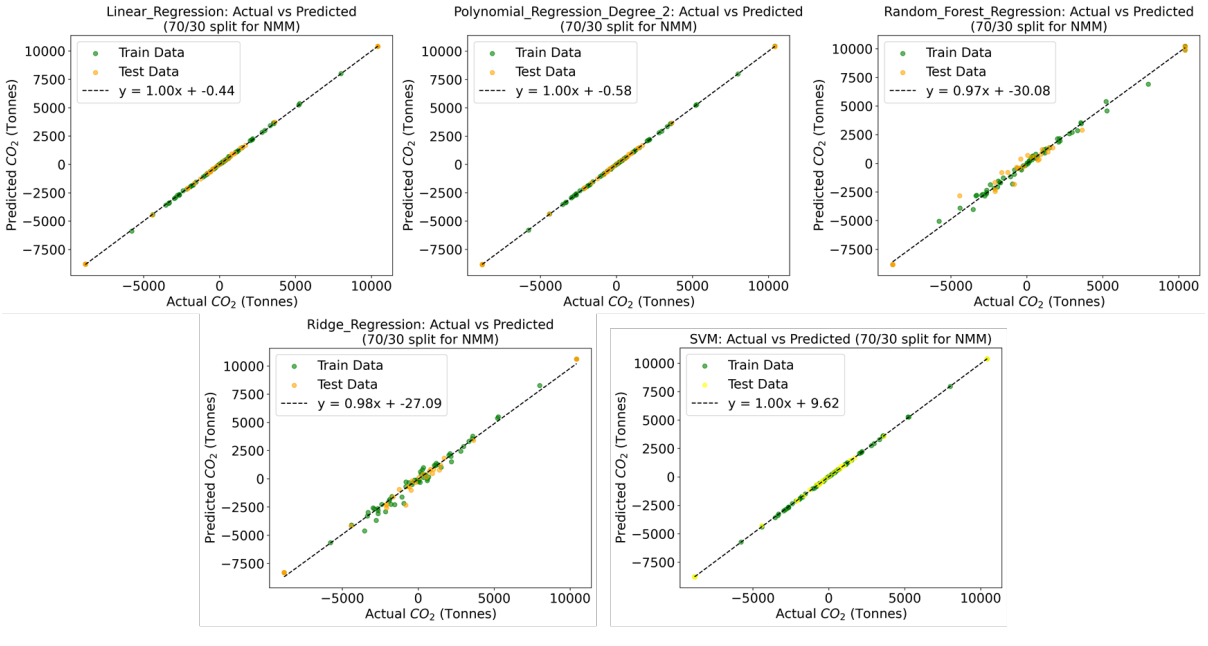


Figure 5 Actual vs. Predicted CO_2 Emissions for Regression Models Trained on GMM-Generated Data

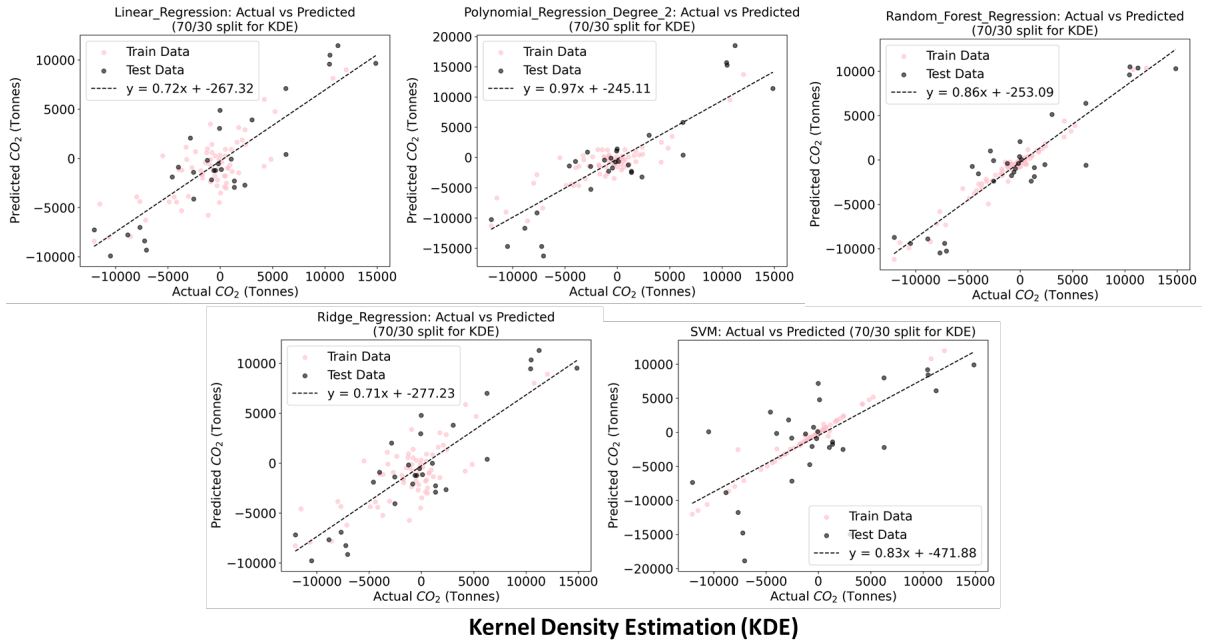


Figure 6 Actual vs. Predicted CO_2 Emissions for Regression Models Trained on KDE-Generated Data

All the building configurations analyzed structurally with ETABS met the strength and serviceability limit state requirements set forth by the Saudi Building Code. Therefore, maximum stress values and maximum allowable vertical deflections were maintained throughout all structural components and the full range of building heights. Thus, it was validated that differences in embodied carbon resulted from the differences in materials rather than structural inadequacies. The correlation matrix displayed in Figure 3 is shown to have a strong influence on the embodied CO2 emissions due to material quantity. The high positive correlation of CO2 to both volume of

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concrete and steel (r = 0.88) as well as a negative correlation of CO2 to CLT volume (r = -0.71) is consistent with the theory that wood has a carbon sequestering effect. The number of stories correlates directly with CO2 but very weakly, suggesting that the influence of material type will be greater than the number of floors alone. This suggests that the near perfect correlation between concrete and steel volume indicates proportionate scaling of structural materials, which supports the results of the highly linear behavior exhibited in the subsequent regression model.

The results of the different generative AI methods' predictive performances are shown by the metrics in Table 1 and show significant differences. All regression models showed extremely high levels of accuracy for the LLM generated dataset. The Support Vector Machine (SVM) model was the most successful model in terms of overall performance as it had a testing R^2 of .9999 and had very low RMSE values. Polynomial Regression and Linear Regression were very good at prediction, as their testing R^2 values were both above .996. Ridge and Random Forest Regression were not as good as the first three methods, however they still produced very accurate predictions. The similarity of the training and testing error shows that there is little chance of over fitting the model to the LLM generated data and that the deterministic relationship between the structural materials and carbon emissions was well represented in the data.

The data that was generated using a Gaussian Mixture Model also produced similar performance characteristics as the polynomial regression model. It is the best performing of the three regression methods, with R^2 of .99994 and a very low RMSE value. Linear Regression and SVM were close behind with their own very small RMSE values. All of these were much lower than the other two tested models, Ridge and Random Forest Regression. While they both had moderate to large increases in error when compared to linear regression-based models, the overall error was still very good. This was due to the fact that the probabilistic cluster structure of the Gaussian Mixture Model was able to simulate the statistical properties of the original structural dataset so well, which resulted in very accurate predictions.

Table 1 Performance comparison of regression models

Large Language Model (LLM)						
	Train			**Test**		
Model	**RMSE**	**MAE**	**R^2**	**RMSE**	**MAE**	**R^2**
Linear Regression	200.92996	171.82092	0.99804	202.25977	171.24207	0.99684
Ridge Regression	381.19087	246.00931	0.99295	467.59906	309.32782	0.98312
Polynomial Regression	79.63273	61.86297	0.99969	116.35748	92.07674	0.99895
Random Forest Regression	252.48353	89.90636	0.99691	442.67733	205.28133	0.98487
Support Vector Machine	35.25015	31.02154	0.99994	35.41812	27.14594	0.99990
Gaussian Mixture Model (GMM)						
	Train			**Test**		
Model	**RMSE**	**MAE**	**R^2**	**RMSE**	**MAE**	**R^2**
Linear Regression	46.49683	38.77234	0.99990	47.65374	40.61004	0.99990
Ridge Regression	424.82707	331.28970	0.99145	422.10817	310.18034	0.99235
Polynomial Regression	26.50872	19.23303	0.99997	37.92508	28.81839	0.99994
Random Forest Regression	297.07578	198.86586	0.99582	510.24840	371.20500	0.98882
Support Vector Machine	39.03366	35.78558	0.99993	62.39389	49.78869	0.99983
Kernel Density Estimation (KDE)						
	Train			**Test**		
Model	**RMSE**	**MAE**	**R^2**	**RMSE**	**MAE**	**R^2**

Linear Regression	2491.52209	1917.97196	0.62121	2810.94031	2172.94686	0.80523
Ridge Regression	2492.07709	1919.63080	0.62104	2799.31556	2160.60210	0.80684
Polynomial Regression	2007.28348	1584.16511	0.75414	3821.05909	3062.85457	0.64010
Random Forest Regression	861.66142	690.26364	0.95470	2533.78624	1943.14948	0.84174
Support Vector Machine	697.90405	213.29759	0.97028	5957.11533	4564.49338	0.12523

The KDE-produced data set resulted in a regression model that had a significantly lower performance than both LLM and GMM. Both of the Linear Regression and Ridge Regression models produced low R-squared values for the training data (about 0.62) and moderate R-squared values for the test data (around 0.80). However, each of the models also produced very large Root Mean Square Error (RMSE) values. This indicates a weak relationship in the structural dataset. While Polynomial Regression provided better performance on the training data, it produced a lower performance on the testing data. Therefore, this suggests that Polynomial Regression was unable to generalize well to new data. Similarly, Random Forest generated excellent results on the training data; however, it performed poorly on the testing data, which suggests instability in the Random Forest model. The Support Vector Machine produced very poor results on the testing data, while producing an extremely high R-squared value for the training data. Therefore, it is clear that there is overfitting occurring in the Support Vector Machine model. Overall, these results suggest that the Kernel Density Estimation introduced randomness into the structural data set that destroyed some of the natural linear relationships present in the data set. The comparison to LLM and GMM shows that both are superior to KDE in preserving a statistical structure for reliable CO_2 predictions. The GMM had less error on some regressions, but LLM was also very stable in its performance overall. The results support the conclusion that although generative AI is capable of addressing issues with small data sets; however, the method used will significantly affect the reliability of predictions in the application of sustainable structural engineering.

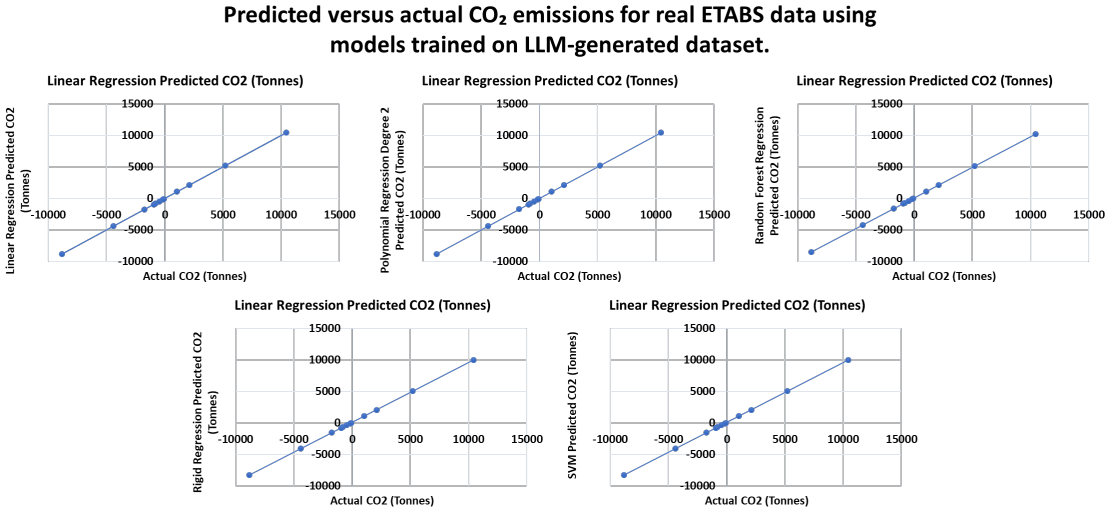


Figure 7 Actual vs predicted CO_2 emissions for real ETABS data using LLM-trained models.

Figure 7 presents the comparison between predicted and actual CO_2 emissions for the original ETABS dataset using models trained on the LLM-generated data. The results show a strong agreement, with data points closely following the ideal 1:1 line, indicating high prediction accuracy. This confirms that the models are not only fitting the synthetic data but are also capable of generalizing well to real-world data. Overall, the figure demonstrates the robustness and reliability of the proposed generative AI–based framework for embodied carbon prediction.

Conclusion

This research developed an artificial intelligence-structural framework for both predicting and evaluating embodied CO2 emissions from multi story buildings. Three structural systems; CLT, steel-concrete, and hybrid of CLT, steel and concrete, were modeled in ETABS at heights of 5, 10, 25, and 50 stories and validated against the Saudi Building Code to demonstrate their structural feasibility as all configurations met the strength and serviceability provisions. The embodied carbon assessment showed that concrete and steel provided most of the overall emissions, while the carbon reduction associated with the use of CLT was quantifiable through sequestration. A correlation analysis revealed that there existed a strong positive relationship between the volume of concrete/steel used and CO2 emissions ($r = 0.88$) and a strong negative relationship between the volume of CLT used and CO2 emissions ($r = -0.71$). As such, material composition has a greater impact on carbon performance than building height.

In order to address the issue of having a limited amount of sample data (12), three generative AI approaches were taken to increase the size of the dataset to 100. The results from LLM, GMM, and KDE datasets were compared to determine how well each technique was able to predict the dependent variable. All the models performed extremely well during the prediction phase; specifically, both LLM and GMM were nearly perfect. As an example, the SVM model that was developed using LLM data had a testing R^2 value of .99999 and low RMSE values, while the polynomial regression model that was developed using the GMM data had a testing R^2 value of .99994. In comparison, the KDE generated data produced much lower levels of prediction accuracy than the LLM or GMM generated data, with testing R^2 values of approximately .8 for the linear models and poor generalization in the SVM models. Overall, Generative AI has been successful in small-data structural carbon prediction situations, but the choice of generative model is key. LLM and GMM preserved the statistical properties of the structural dataset to allow for highly reliable regression analysis, whereas KDE showed poor generalization capability. The framework proposed above provides a data-driven approach for integrating artificial intelligence with embedded carbon assessment and structural analysis to support low-carbon building design.

Furthermore, validation using real ETABS data confirmed that models trained on LLM-generated datasets demonstrate strong generalization capability beyond synthetic data.

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Integrating Cool Roof Technologies for Sustainable Urban Resilience: A Saudi Arabian Perspective

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Keywords: Urban Heat Island Mitigation, Cool Roof Technologies, Sustainable Public Space Design, Arid Climate Architecture, Vision 2030 Urban Planning

Abstract. This study explores the integration of cool roof technologies as a passive design strategy for mitigating the Urban Heat Island (UHI) effect and enhancing energy efficiency in Saudi Arabia's arid urban environments. Focusing on the thermal performance of roofing materials—specifically solar reflectivity and thermal emissivity—the research analyzes international and regional case studies to evaluate the viability of cool roofs within the context of Vision 2030. Findings show that cool roofs can reduce rooftop surface temperatures by up to 30°C, contributing to energy savings of 15–25% and improved indoor thermal comfort. Large-scale applications, such as those in NEOM and the Red Sea Project, further validate their potential. However, climatic factors such as dust accumulation and seasonal solar variation influence performance. The study concludes that integrating cool roofs with sustainable public space design offers a practical and impactful approach to climate resilience in Saudi Arabia.

1. Introduction

The intensifying global climate crisis has led to significant temperature increases in global scale, particularly acute effects observed in arid regions such as the Kingdom of Saudi Arabia [1]. The urban heat island (UHI) phenomenon has emerged as a critical environmental challenge in rapidly urbanizing Saudi cities, including Riyadh, Jeddah, and Dammam [2]. This effect is primarily attributed to the concentration of populations in dense metropolitan areas, increased surface sealing due to infrastructure development, and a shift in the urban thermal balance resulting from extensive land use transformation [3].

The consequences of UHI in Saudi cities are multifaceted: increased peak energy demand due to higher air conditioning loads, deterioration in air quality due to elevated ground-level ozone and particulate matter, heightened risks of heat-related illnesses, and a significant rise in the ecological footprint of urban environments [4]. According to the Saudi Energy Efficiency Center, electricity consumption for cooling constitutes over 70% of peak demand in the summer months, primarily driven by the urban heat amplification effect. These challenges underscore the urgent need for sustainable mitigation strategies within the built environment [5].

Building-integrated solutions such as green roofs and reflective "cool roof" technologies have garnered attention in this context [6]. However, implementing rooftop greening in Saudi Arabia poses technical and environmental constraints, including increased structural load, complex drainage requirements, and high maintenance demands in extreme desert climates. Although new constructions under initiatives like the Saudi Green Building Code (SBC 601) aim to enhance energy efficiency and resilience to climatic extremes, newly built structures represent only a

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fraction of the total urban building stock [7]. Consequently, exploring retrofitting strategies for existing buildings is imperative as a core approach to mitigating UHI effects and enhancing urban thermal comfort across Saudi cities.

2. Literature Review

2.1. Cool Roof Technologies in Arid Urban Environments

In arid and high-temperature climates such as Saudi Arabia, cool roofs have emerged as a viable passive strategy to mitigate the UHI effect and reduce building cooling loads [8]. A cool roof is engineered to maintain lower surface temperatures than conventional roofing materials. This thermal performance is primarily achieved through enhanced solar reflectivity (albedo) and infrared emissivity—two critical surface properties that regulate heat absorption and re-radiation [9].

Solar reflectivity, commonly called albedo, quantifies the fraction of incident solar radiation reflected by the roof surface. While albedo varies across wavelengths—from ultraviolet to infrared—it is typically measured as an average value across the solar spectrum using standard test methods such as ASTM E903, C1549, or E1918 [10]. High-albedo surfaces, particularly those exceeding 0.65 in reflectance, can reflect a substantial portion of solar radiation, significantly lowering rooftop temperatures by up to 25–35°C during peak daytime hours (Figure 1).

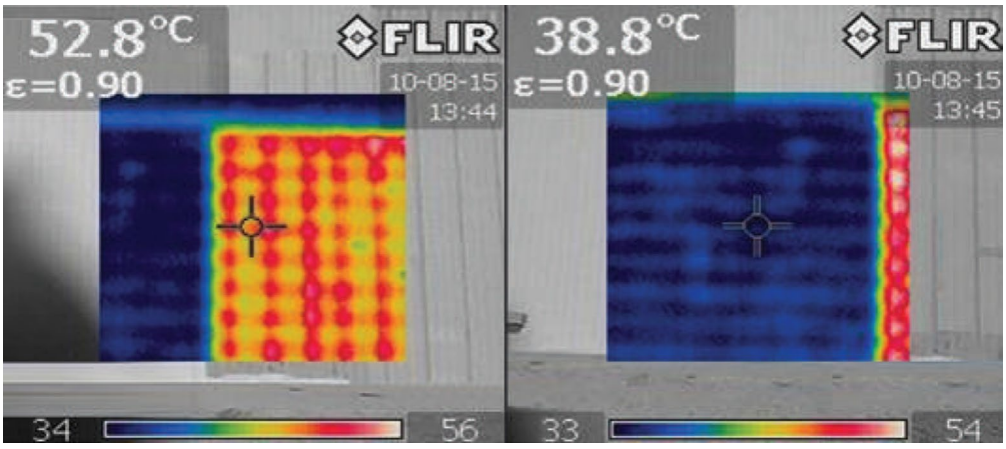


Figure 1. 14°C surface Temperature difference with a Cool Roof in Saudi Arabia (Source: Jazeera Paint)

In parallel, thermal emissivity—defined as the ratio of thermal radiation emitted by a surface relative to that emitted by a blackbody at the same temperature—plays a crucial role in dissipating absorbed heat [11]. Typically measured using ASTM E408 or C1371 standards within the 5 to 40 μm wavelength range, materials with high emissivity ($e > 0.85$) facilitate effective nocturnal cooling by radiating stored thermal energy back to the atmosphere [12]. (Figure 2)

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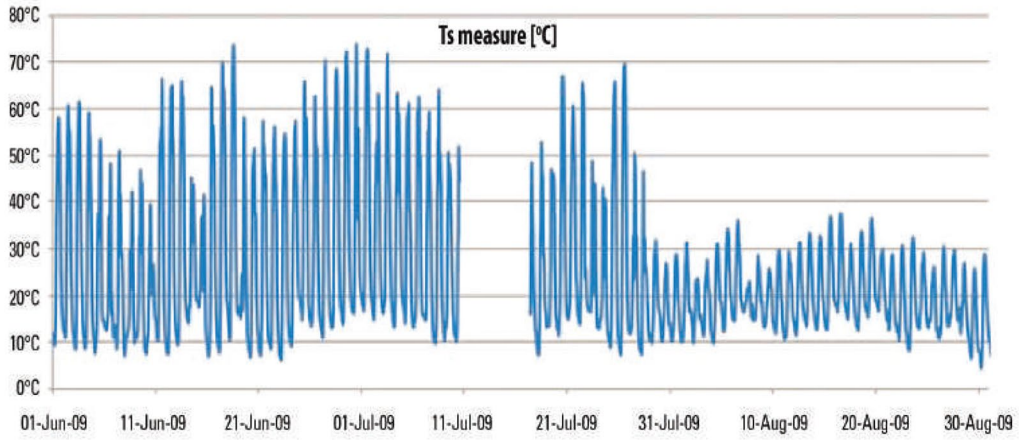


Figure 2. Temperature Difference Study before and after using Cool Roof in Saudi Arabia (Source: Jazeera Paint)

In Saudi Arabia's built environment, where summer temperatures frequently exceed 45°C and cooling energy demand constitutes approximately 70% of total electricity use during peak periods, applying cool roof systems offers substantial energy savings and thermal comfort benefits [13]. Integrating reflective coatings, tiles, or membranes in new and retrofitted buildings aligns with national sustainability agendas such as Vision 2030 and the Saudi Green Initiative, targeting reductions in carbon emissions and energy intensity in the construction sector [14].

2.2. Current Cool Roof Application in Saudi Arabia

The adoption of cool roof technologies in Saudi Arabia is steadily increasing, propelled by the nation's strategic commitment to energy efficiency and sustainable urban development as articulated in Vision 2030. In response to the extreme summer temperatures that often exceed 45°C and place substantial demand on cooling systems, cool roofs offer a passive, cost-effective solution to enhance indoor thermal comfort and mitigate the UHI effect. Both residential and commercial sectors have begun integrating cool roofing systems in major urban centers such as Riyadh, Jeddah, and Dammam [15]. These include reflective coatings, light-colored membranes, and thermally emissive roofing tiles that reduce solar heat gain and lower cooling energy consumption (Figure 3).



Figure 3. Cool Roof Example in Saudi Arabia

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The implementation of cool roof strategies has also gained traction in large-scale developments. Iconic projects such as NEOM and the Red Sea Project have incorporated cool roof specifications into their sustainable construction frameworks, setting new benchmarks for environmentally responsive design in desert climates [16]. These projects prioritize climate-resilient materials and advanced building envelopes that align with global sustainability standards. Furthermore, academic research in Saudi Arabia has contributed to validating the effectiveness of cool roofs. For example, a study in the Eastern Province demonstrated significant indoor temperature and HVAC load reductions, with no observed increase in moisture-related risks such as condensation or microbial growth.

The Saudi market has responded positively to this emerging demand, with increased availability of high-albedo and high-emissivity roofing products tailored for local environmental conditions [17]. However, challenges remain, particularly concerning the impact of dust accumulation, which can reduce the reflectivity of cool roof surfaces over time. Therefore, regular maintenance regimes and material innovation are essential to sustain long-term performance [18]. Despite the initial cost premiums, the long-term energy savings and environmental benefits strongly justify the integration of cool roofs into Saudi Arabia's evolving architectural paradigm. Their growing application reflects a broader shift toward passive design strategies that enhance urban sustainability and reduce the nation's dependency on fossil-fuel-based energy systems.

3. Methodology

This study employs a qualitative analytical methodology to investigate the potential of cool roof technologies in mitigating the UHI effect and achieving energy savings within the climatic context of Saudi Arabian cities. The research begins by establishing a theoretical foundation of cool roof systems. It focuses on their thermal performance specifically, high solar reflectance (albedo) and thermal emissivity, as critical parameters influencing surface heat retention and ambient urban temperatures [19].

A comprehensive review of existing literature and case studies encompassed international benchmarks and emerging applications within the Kingdom of Saudi Arabia. Key sources include peer-reviewed journal articles, government reports, and data from national sustainability initiatives such as the Saudi Green Building Code (SBC 601) and Vision 2030 sustainability targets [20]. Particular emphasis was placed on examining built examples from high-temperature zones, including Riyadh, Jeddah, and Dammam, where surface temperatures often exceed 50°C in summer months and cooling accounts for approximately 70% of total electricity consumption during peak periods [21].

Through comparative analysis, this study evaluates the measurable impacts of cool roof materials on surface temperature reduction, energy demand, and indoor thermal comfort. The methodology also incorporates performance metrics reported in local pilot projects and experimental studies, such as reductions in rooftop surface temperature by up to 30°C and corresponding energy savings of 15–25%. In addition, the study investigates technological feasibility, economic considerations, and environmental implications associated with retrofitting existing building stocks with reflective or emissive roofing systems in Saudi Arabia's urban environment. By synthesizing regional data and global best practices, the study aims to determine the contextual viability of cool roof strategies as an adaptive response to climate change and rapid urbanization in the Arabian Peninsula.

4. Analysis: Potential for Reducing UHI Effect

To evaluate the potential of cool roofs as a strategic intervention for mitigating the UHI phenomenon in arid urban environments, this study conducted an in-depth review of existing empirical studies and simulation-based models focused on the relationship between rooftop albedo adjustment and urban microclimate change [22]. These studies, drawn from various climatic

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contexts and scales, collectively provide insights into how cool roofs can influence near-surface air temperature, surface thermal behavior, and urban energy demand (Table 1).

Table 1. Microclimatic Effects of Cool Roofs

Researchers	Studies	Results	City/Country
Ziaeemehr et al. (2023)	- To simulate the local effect of albedo	- An average decrease of 2°C and up to 4°C may be possible by increasing the albedo by 0.40 in urbanized areas	Sacramento, USA
Ascione et al. (2019)	- To assess the impact of cool roofs on near-ground air temperature	- 2m air temperature reduction through the implementation of cool roofs only amounts to 0.3°C for the neighborhood	Phoenix, USA
Burgstall et al. (2021)	- To assess the influence of albedo on a street canyon under weather scenarios	- The boundary layer is a 10 × 10 m street canyon - High albedo materials could reduce the air temperature of a reference environment by 4.3°C for a TMY and 6°C for a heat wave scenario.	Zürich, Switzerland
Elnabawi et al. (2022)	- To estimate the effect on air temperature of the two scenarios of albedo	- Scenario 0.63: The air temperature depression at 2m height at noon LST varied between 0.5 and 1.5°C. - Scenario 0.85: The air temperature decrease varied between 1 and 2.2°C.	Athens, Greece
Jandaghian et al. (2025)	- To examine the microclimatic effects of retrofitting green and cool roofs - To estimate energy balance	- The maximum perturbations are –1.27 °C for cool roofs - The average daily temperature perturbation for cool roofs relates to meteorological conditions. - Annual energy penalty for an uninsulated building, with an annual increase in demand of 2%	London, UK
Domínguez-Torres et al. (2021)	- To estimate energy savings for residential buildings at a regional level	- A high-scale implementation of cool roofs could potentially reduce the amount of space cooling and heating electrical consumption by 2% for residential use	Andalusia, Spain

One of the foundational studies in this field by Ziaeemehr et al. (2023) investigated how modifications to a city's overall effective albedo, achieved through high-reflectivity roofing materials, impacted regional temperatures during both summer and winter. The analysis revealed that approximately 2–4 °C reduced summer daytime temperatures in urban areas where reflectivity was increased, while winter reductions ranged from 0.5–1.5°C. Although conducted in a temperate climate, this study offers a critical baseline for extrapolating cooling benefits in high solar gain regions such as Saudi Arabia, where summertime surface temperatures regularly exceed 70°C on conventional rooftops [23].

Ascione et al. (2019) examined the effects of green-integrated cool roofs—vegetated systems with high albedo properties—on air temperature at 2 meters, approximating pedestrian exposure [24]. The analysis demonstrated a limited temperature drop of around 0.3°C, indicating that while cool roofs effectively reduce rooftop surface temperature and contribute to overall urban heat reduction, their direct influence at the pedestrian level is minimal unless integrated within broader urban cooling frameworks such as reflective pavements or shaded public spaces. This finding is particularly relevant for Saudi Arabian cities, where outdoor thermal comfort at the pedestrian level is a critical urban design challenge due to extreme heat and low shading indices.

The importance of climate variability in cool roof performance is emphasized in the study by Burgstall et al.(2021), which utilized multiple meteorological scenarios, representing both average and extreme heat years, to evaluate the thermal response of urban areas to roof reflectivity changes [25]. While standard-year scenarios showed modest cooling, extreme heat scenarios showed significant temperature reductions of up to 6.0°C, suggesting that cool roofs could play a crucial role in climate resilience planning for cities like Riyadh, which experienced record-breaking high temperatures exceeding 50°C in recent years (Saudi Press Agency, 2022). The results imply that

the benefits of cool roofs are amplified during climatic anomalies, making them a robust adaptive measure under future climate change projections.

Elnabawi et al. (2022) employed the MM5 mesoscale atmospheric model to simulate two urban albedo scenarios (reflectivity of 0.63 and 0.85) for Athens, a Mediterranean city with climatic parallels to parts of coastal Saudi Arabia [26]. Their simulations indicated that increasing rooftop reflectivity to 0.63 led to temperature reductions of 0.5–1.5°C during peak solar hours, while a reflectivity of 0.85 achieved reductions of 1.0–2.2°C. These results align with expected performance ranges for high-albedo roofing materials such as white acrylic coatings or ceramic tiles, which are already being tested in selected Saudi projects under the Ministry of Municipal and Rural Affairs' building envelope efficiency programs.

Another significant contribution comes from Jandaghian et al. (2025), who modeled the urban thermal effects of retrofitting 90% of London's office building rooftops with reflective materials [27]. Despite the city's cooler climate, the retrofitting led to a seasonal temperature reduction ranging from 0.3–1.27°C, with an annual average decrease of 0.7°C. While these values are lower than those observed in warmer climates, the study is valuable for assessing cumulative impacts over time and justifying large-scale retrofit policies. In Saudi Arabia, where nearly 70% of the existing building stock was constructed before adopting energy performance regulations, retrofitting remains a key strategy for national energy transition efforts.

Domínguez-Torres et al. (2021) took a region-wide energy demand modeling approach in Andalusia, Spain, by estimating potential energy savings from the large-scale application of cool roofs [28]. Using satellite imagery to calculate albedo based on roof color and area, the researchers developed predictive heating and cooling loads models. Their findings showed that implementing cool roofs across the region could reduce residential electricity consumption by approximately 2%. In the context of Saudi Arabia, where cooling alone accounts for over 70% of residential electricity use during peak summer months, the extrapolated benefits of cool roofs could translate into billions of kWh saved annually, reducing pressure on the national grid and aligning with energy diversification goals under Vision 2030.

These studies collectively highlight that while the temperature reductions at the pedestrian level may be moderate in some cases, the broader climatic and energy-saving impacts of cool roofs can be substantial, particularly in hot, arid environments like Saudi Arabia. Importantly, the effectiveness of cool roofs is context-dependent, influenced by atmospheric conditions, urban morphology, seasonal solar angles, and the scale of implementation. Consequently, this research supports the view that when strategically deployed in conjunction with other passive and active cooling systems, cool roofs can serve as a core component of Saudi Arabia's climate adaptation and sustainable urban development strategies.

5. Discussion

The findings of this study underscore the importance of adopting an integrated sustainability framework in the design of public spaces, particularly in arid urban contexts such as those in Saudi Arabia. By synthesizing ecological, economic, and social dimensions into a cohesive design approach, the study demonstrates that sustainable public spaces can address both environmental challenges and societal needs. In cities like Riyadh, where extreme heat, rapid urbanization, and resource constraints intersect, applying cool roofs, energy-efficient materials, and participatory design processes can significantly enhance thermal comfort, reduce energy demand, and reinforce cultural identity. The five design types proposed—ranging from resource-conscious systems to participatory placemaking—are most effective when applied interdependently, allowing public spaces to function not only as areas of leisure but as dynamic systems contributing to urban resilience. Ultimately, the discussion highlights that sustainable public space design must move beyond isolated interventions, instead embracing a holistic strategy that aligns with Saudi Arabia's Vision 2030 goals for climate adaptation, energy efficiency, and social inclusivity.

6. Conclusion

This study concludes that integrating ecological, economic, and social sustainability principles is essential for developing resilient and adaptive public spaces in rapidly urbanizing environments such as those in Saudi Arabia. By identifying and applying five interrelated sustainable design types—recursive systems, wholeness, energy and resource limitations, placemaking, and participatory design—the research provides a practical framework for addressing the multifaceted challenges of urbanization, including climate stress, energy overconsumption, and social fragmentation. The findings emphasize that a holistic and context-specific approach is critical; sustainable public spaces must simultaneously respond to environmental constraints, reflect cultural identity, and foster community engagement. This tripartite integration enables urban environments to mitigate ecological degradation and promote long-term livability and inclusivity. As Saudi Arabia advances its Vision 2030 objectives, these insights offer timely and actionable guidance for architects, planners, and policymakers aiming to transform public spaces into engines of sustainable urban development.

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From Information to Interaction: Analyzing the Social Functions of Urban Media in Smart Public Spaces

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Keywords: Urban Media, Smart Public Space, Civic Engagement, Interactive Installations, Al Khobar Urban Development

Abstract. This study investigates the role of urban media in transforming public spaces within the context of Al Khobar, Saudi Arabia, a city advancing rapidly under the Vision 2030 smart city initiative. By examining the integration of interactive digital technologies—such as media façades, kiosks, and mobile-connected installations—the research explores how these elements facilitate civic engagement, cultural expression, and real-time information exchange. A literature review, field analysis, and comparative study of six international case studies form the methodological foundation, evaluating the social functions of urban media through indicators such as information provision, participatory art, and communication. Findings indicate that successful implementation depends on contextual adaptation, technological responsiveness, and user interactivity. For Al Khobar, urban media serves as a catalyst for inclusive, culturally resonant, and technologically integrated public environments. The study concludes by emphasizing the potential of urban media to enhance spatial experience and urban publicness in emerging smart cities.

1. Introduction

In the contemporary era marked by rapid advancements in digital technology, urban environments are undergoing transformative changes [1]. Traditional one-way communication mediums are increasingly inadequate in addressing the dynamic needs of modern cities [2]. Instead, there is a shift towards interactive, real-time digital media systems that not only disseminate information but also foster participatory engagement and sensory interaction among urban inhabitants [3]. Al Khobar, a prominent city in the Eastern Province of Saudi Arabia, exemplifies this transformation. As part of the Kingdom's Vision 2030 initiative, which aims to diversify the economy and enhance the quality of life, Al Khobar has embraced digital innovation to redefine its urban landscape [4]. The city's commitment to smart city development was recognized when it ranked 99th in the International Institute for Management Development's Smart City Index for 2024, marking its debut in this global assessment [5].

The digital infrastructure in Saudi Arabia has seen significant growth, with internet penetration reaching 99% and mobile internet speeds averaging 215 Mbps, nearly double the global average. This robust connectivity supports the proliferation of digital media platforms, enabling citizens to engage with urban spaces in novel ways [6]. For instance, interactive public installations and

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responsive architectural façades are becoming integral components of the urban fabric, facilitating real-time communication and enhancing the sensory experience of city dwellers [7].

Moreover, the widespread adoption of social media in Saudi Arabia underscores the population's readiness to engage with digital platforms [8]. As of January 2024, there were 35.10 million social media users in the Kingdom, accounting for 94.3% of the total population [9]. This high level of digital engagement presents opportunities for urban planners and designers to integrate social media interfaces with physical spaces, promoting community participation and fostering a sense of belonging [10]. In Al Khobar, these developments are not merely technological advancements but are instrumental in shaping a more inclusive and interactive urban environment. By leveraging digital media, the city aims to create public spaces that resonate with the sensory perceptions and experiences of its citizens, thereby enhancing social communication and community engagement.

2. Literature Review

2.1 The Elements of Urban Media

Urban media encompasses a spectrum of digital technologies integrated into the urban fabric, facilitating dynamic interactions between citizens and their environment [11]. These technologies—ranging from interactive displays and responsive lighting to augmented reality installations—serve as conduits for information exchange, transforming public spaces into participatory platforms that enhance communal experiences.

The term "media" originates from the Latin "medium," signifying an intermediary or conduit [12]. In the urban context, media functions to bridge gaps between disparate elements—individuals, communities, and the built environment—thereby fostering connectivity and reducing communicative distances [13]. This intermediary role is pivotal in cultivating inclusive urban spaces that resonate with the diverse needs of their inhabitants (Table 1) [14].

Table 1. Media Application of Urban Media

Medium of Urban Media		Applications
Urban Installation	Digital Screen	Media boards, media signages, etc.
	Media Façade	Building facades, etc.
	Urban furniture	Smart street lights, etc.
Personal Media	Smart Phone	Applicable in conjunction with other media
	Kiosk	Media poles, bus shelters, etc.

In Al Khobar, the integration of urban media aligns with the city's strategic vision to evolve into a smart city, as evidenced by its inclusion in the 2024 IMD Smart City Index, ranking 99th globally [15]. Initiatives such as the "Heart of Khobar" project exemplify this trajectory, incorporating smart technologies to enhance urban living and promote sustainable development [16]. The city's high internet penetration rate, exceeding 99%, coupled with widespread smartphone usage, provides a robust foundation for the deployment of urban media [17]. These digital infrastructures enable real-time data collection and dissemination, empowering citizens to actively engage with their surroundings and participate in the co-creation of urban experiences [18].

Furthermore, the application of urban media in Al Khobar's public spaces—such as interactive installations along the Corniche and smart lighting systems in communal areas—demonstrates the potential of these technologies to enrich social interactions and foster a sense of community [19]. By embedding digital layers into the physical environment, urban media transforms static spaces into dynamic arenas for cultural expression and civic engagement [20]. Urban media in Al Khobar serves as a transformative force, reconfiguring the city's public spaces into interactive, inclusive,

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and responsive environments (Figure 1). This evolution reflects a broader shift towards smart urbanism, where technology and human experience converge to shape the future of urban living.



Figure 1. Media Façade of Adeer Tower

2.2 The Relationship Between Urban Media and Social Functions

Urban media in Al Khobar serves as a dynamic interface between the city's physical spaces and its inhabitants, facilitating social interactions and enriching communal experiences [21]. These media installations—ranging from digital kiosks and interactive screens to media façades and responsive urban furniture—transform public spaces into participatory environments that foster communication, cultural expression, and community engagement (Table 2) [22].

Table 2. Social Functions and Relationships of Urban Media

Social Functions	Social Relationships
Information provision	Reflecting the characteristics of networks as real-time information transmission Media that responds to the function of the street as a 'mobile space'
Play and art	Inducing participation of city residents by implementing the city as a place for cultural experience through combination with media art
Communication	Urban media is a combination of network and place, and creates a place for active social communication in the city.

The integration of urban media aligns with Saudi Arabia's Vision 2030, which emphasizes the development of smart cities and the enhancement of quality of life through technological innovation [23]. Al Khobar's inclusion in the 2024 IMD Smart City Index, ranking 99th globally, underscores its commitment to leveraging digital technologies to improve urban living.

Projects like the Mujassam Wattan competition have introduced public art installations such as "Alarda" and "Alkhobar Memory," which not only beautify the urban landscape but also serve as focal points for social interaction and cultural dialogue. These installations exemplify how urban media can encapsulate local heritage while promoting community cohesion [24].

Furthermore, the widespread use of personal digital devices and social media platforms in Saudi Arabia facilitates continuous engagement with urban media [25]. Interactive kiosks and digital signage provide real-time information, wayfinding assistance, and platforms for public feedback, thereby enhancing the functionality of public spaces and encouraging active citizen participation. Urban media in Al Khobar plays a pivotal role in shaping the social dynamics of the city [26]. By

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embedding digital technologies into the urban fabric, these media installations create inclusive, interactive, and culturally resonant public spaces that align with the broader objectives of sustainable and participatory urban development.

3. Methodology

This study explores the role of interactive urban media as communicative interfaces within the public spaces of Al Khobar, shifting away from traditional one-way media toward participatory, multisensory engagement. Through a contextual qualitative approach, the research analyzes recent developments—such as the Dana Beach Walk and the Corniche promenade—that integrate responsive lighting, digital screens, and interactive installations designed to stimulate civic dialogue and enhance spatial experience.

Observational analysis and stakeholder interviews are employed to assess how these media influence public interaction, social connectivity, and perceptions of urban space. The study also incorporates insights from national strategic frameworks, particularly Vision 2030, which prioritizes digital infrastructure and smart city development. Al Khobar's inclusion in the 2024 IMD Smart City Index (ranked 99th globally) underscores its commitment to such innovations.

Public engagement is further examined through social media analysis, leveraging Saudi Arabia's 99% internet penetration and widespread platform use to evaluate how citizens interact with urban media initiatives [27]. This methodological structure enables a comprehensive understanding of how digital urban media can address communication gaps and foster a more participatory urban environment.

4. Analysis: Urban Media appearing in Public Spaces of the City

4.1. Public Space of the City

Public space is not defined by predetermined boundaries or formal physical limits, but rather emerges through the collective engagement, presence, and actions of the public. It is socially constructed, evolving as individuals interact, gather, and express themselves within the urban fabric. The distinction between private and public in this context is not rooted in fixed ownership but in the degree of openness and accessibility; public space encompasses all that is not private, serving as a shared domain for communal life.

In this study, public space within the city—specifically in the context of Al Khobar—is defined as an open and inclusive environment where the public dimension of urban life is actively expressed. These are spaces that encourage participation, interaction, and the negotiation of shared experiences. As such, public space is not only a physical setting but also a medium through which civic identity, cultural expression, and social relationships are shaped and reinforced within the city. This perspective positions public space as essential to fostering a sense of urban publicness, particularly in rapidly transforming environments like Al Khobar that are increasingly integrating smart technologies and inclusive design strategies.

4.2. Case Studies

This study aims to examine the relationship between the media characteristics and social functions of urban media, as previously outlined, by applying these concepts to selected international case studies specifically situated within urban public spaces. Table 3 presents the extent to which the social functions of urban media are manifested within public spaces, categorized into four levels—high, medium, low, and none—and denoted by the symbols ●, ◎, ○, and – respectively.

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Table 3. The Social Function of Urban Media appearing in the City's Public Space

Case Study 01	Media Pole at Gangnam Special Street (2019), Seoul, South Korea					
Application type	Media Signs, Kiosks					
	Social Functions	Urban Installation			Personal Media	
		Digital Screen	Media Façade	Urban furniture	Smart Phone	Kiosk
	Information provision	●	-	-	-	●
	Play and art	◎	-	-	-	●
	Communication	○	-	-	-	◎
Case Study 02	Sangam Digital Media Street (2011), Seoul, South Korea					
Application type	Media signs, intelligent street lights, bus shelters					
	Social Functions	Urban Installation			Personal Media	
		Digital Screen	Media Façade	Urban furniture	Smart Phone	Kiosk
	Information provision	●	-	●	-	●
	Play and art	○	-	◎	-	◎
	Communication	○	-	○	-	○
Case Study 03	Galleria Hall West (2014), Seoul, South Korea					
Application type	Media Façade					
	Social Functions	Urban Installation			Personal Media	
		Digital Screen	Media Façade	Urban furniture	Smart Phone	Kiosk
	Information provision	-	●	-	-	-
	Play and art	-	○	-	-	-
	Communication	-	○	-	-	-
Case Study 04	Dexia Tower (2016), Brussels, Belgium					
Application type	Media board, media facade, kiosk					
	Social Functions	Urban Installation			Personal Media	
		Digital Screen	Media Façade	Urban furniture	Smart Phone	Kiosk
	Information provision	○	●	-	-	○
	Play and art	●	●	-	-	●
	Communication	○	◎	-	-	◎
Case Study 05	Enteractive (2016), Los Angeles, USA					
Application type	Media board, media facade					
	Social Functions	Urban Installation			Personal Media	
		Digital Screen	Media Façade	Urban furniture	Smart Phone	Kiosk
	Information provision	○	◎	-	-	-
	Play and art	●	●	-	-	-
	Communication	◎	◎	-	-	-
Case Study 06	Color by Numbers (2006) Stockholm, Sweden					

Application type	Media facade, mobile phone				
	Social Functions	Urban Installation			Personal Media	
		Digital Screen	Media Façade	Urban furniture	Smart Phone	Kiosk
	Information provision	-	○	-	○	-
	Play and art	-	●	-	●	-
	Communication	-	○	-	◎	-

5. Discussion

The comparative analysis of international case studies demonstrates that urban media, when effectively integrated, can enhance the social functions of information sharing, participatory art, and civic communication within public spaces. Projects like Enteractive (Los Angeles) and Dexia Tower (Brussels) show high engagement due to interactive content and media façades, while others like Galleria Hall West (Seoul) offer limited public interaction, underscoring that design intent and contextual relevance are key to media effectiveness. The inclusion of personal devices, as seen in Color by Numbers (Stockholm), highlights the potential of hybrid interaction—combining urban installations with mobile technology—to expand accessibility and participation. For Al Khobar, these findings underscore the importance of designing urban media not merely as visual features but as tools for fostering communication, cultural identity, and civic involvement, especially in light of its Vision 2030 smart city goals and advanced digital infrastructure.

6. Conclusion

This study investigated the role and social functionality of urban media within public spaces, with a particular focus on the evolving urban environment of Al Khobar, Saudi Arabia. Through an analytical framework that combined literature review, contextual observation, and international case studies, the research identified how urban media technologies—ranging from digital screens and media façades to mobile-integrated systems—contribute to public interaction, cultural expression, and real-time information exchange.

The comparative assessment of global precedents demonstrated that the effectiveness of urban media in fostering civic engagement is contingent upon its contextual integration, design strategy, and interactivity. Projects with participatory digital components and narrative-rich content exhibited stronger social outcomes, particularly in terms of public communication and identity formation.

For Al Khobar, which is rapidly advancing toward smart city development under Vision 2030, the findings offer a strategic foundation for incorporating urban media as a catalyst for inclusive, participatory, and culturally embedded public space design. By embedding digital media systems into the city's urban fabric with intentionality and responsiveness, Al Khobar can cultivate more vibrant, connected, and socially engaged urban environments that reflect both technological progress and the collective aspirations of its citizens.

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Adapting Urban Heat Island Mitigation Strategies from Japan to Saudi Arabia: A Comparative Policy and Design Framework

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Keywords: Urban Heat Island (UHI), Climate-Responsive Architecture, Saudi Arabian Urban Planning, Sustainable Building Design, Policy Adaptation Framework

Abstract. This study investigates the applicability of Japan's urban heat island (UHI) mitigation strategies to the climatic and urban context of Saudi Arabia. Through a comparative policy analysis and content evaluation of Japan's *Heat Island Phenomenon Mitigation Outline* and *Architectural Design Guidelines*, the research identifies four strategic pillars—reduction of anthropogenic heat, improvement of surface cover, optimization of urban form, and promotion of sustainable lifestyles—as transferable principles. The study highlights how these can be adapted to Saudi cities using passive design, district cooling systems, and xeriscaping techniques. A key outcome is the proposal for a Saudi-specific Heat Island Evaluation Framework (S-HIEF), modeled after Japan's CASBEE-HI, to quantify building performance and support climate-resilient urban planning. By integrating culturally and climatically responsive strategies into Saudi Arabia's Vision 2030 urban agenda, the study provides a foundation for future regulatory, architectural, and policy-level interventions to enhance thermal comfort and reduce energy loads in arid environments.

1. Introduction

The urban heat island (UHI) phenomenon is where urban centers exhibit significantly higher temperatures than surrounding rural or suburban areas [1]. This temperature disparity is driven primarily by dense built environments, excessive use of impermeable surfaces, anthropogenic heat emissions, and a lack of vegetative cover [2]. The UHI effect contributes to increased energy demand, elevated greenhouse gas emissions, deteriorating air quality, and adverse public health outcomes, particularly heat-related illnesses [3]. While UHI has been extensively documented in temperate and subtropical climates such as Japan and Korea, its impact in arid regions like Saudi Arabia is magnified and structurally different due to extreme ambient temperatures and limited urban greening [4].

In the Kingdom of Saudi Arabia, the UHI effect is becoming increasingly pronounced as urbanization accelerates in major cities such as Riyadh, Jeddah, Dammam, and Madinah [5]. According to Alghamdi et al. (2021), UHI intensity in Riyadh can exceed 7.5°C between urban and suburban zones, particularly during summer [6]. This intensification is primarily attributed to using heat-retaining materials (such as asphalt and concrete), low surface albedo, and a high dependency on mechanical cooling systems [7]. Moreover, a 2023 report by the Saudi National Center for Environmental Compliance indicates that air temperatures in central urban blocks have

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risen at an average rate of 0.3°C per decade, posing long-term threats to environmental sustainability and public health resilience [8].

By contrast, Japan has long recognized UHI as a national environmental concern and has developed a sophisticated, multi-sectoral approach to its mitigation [9]. The Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) established a series of guidelines, including the Heat Island Phenomenon Mitigation Outline (2004) and the Architectural Design Guidelines for Heat Mitigation, to provide comprehensive strategies addressing urban morphology, surface material reflectivity, ventilation corridors, and green infrastructure [10]. These guidelines have contributed to measurable reductions in surface temperatures in Tokyo, Osaka, and Fukuoka, where integrated policies have been implemented at the municipal and national levels (Figure 1).

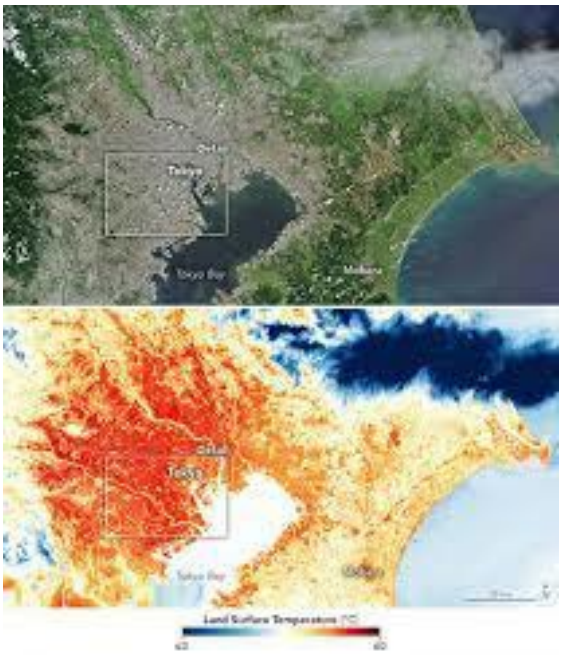


Figure 1. Satellite Image of Urban Heat Island Phenomenon in Tokyo, Japan

Given the growing urgency of climate adaptation in Saudi cities, especially in the context of Vision 2030, which emphasizes urban livability and environmental sustainability, there is a strong rationale to examine successful international models such as those of Japan [11]. However, rather than direct adoption, it is imperative to contextualize and reinterpret these models in light of the Saudi climate, culture, building codes, and urban morphology [12].

Therefore, this study aims to (1) systematically analyze the structural composition and operational strategies of Japan's UHI mitigation policies and (2) explore their applicability and adaptive potential for Saudi Arabia [13]. By doing so, the paper seeks to provide a foundation for developing Saudi-specific design and planning guidelines that are both climate-responsive and culturally attuned [14].

The methodology adopted for this research is a comparative policy analysis supported by qualitative content evaluation of official Japanese documents. The ultimate objective is to offer evidence-based recommendations for architectural design and urban planning strategies in Saudi Arabia that can effectively mitigate UHI effects, reduce urban energy loads, and enhance thermal comfort in public and private spaces.

2. Literature Review

2.1 Measures to Alleviate the Urban Heat Island Phenomenon in Japan

To address the intensifying impacts of the urban heat island (UHI) phenomenon, the Japanese government recognized the need to consolidate previously disjointed efforts across national

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ministries, local governments, and urban agencies [15]. In March 2000, Japan established an inter-ministerial coordination mechanism called the Comprehensive Measures Meeting as part of the Three-Year Plan for Regulatory Reform [16]. This body was tasked with formulating a national-level strategic response to UHI mitigation [17]. By 2004, this effort culminated in enacting the Outline of Measures to Alleviate the Heat Island Phenomenon, which provided a robust and systematic framework for urban cooling across Japan. The outline was designed as a technical guide and a policy instrument to unify municipal action under shared goals and regulatory standards (Figure 2).

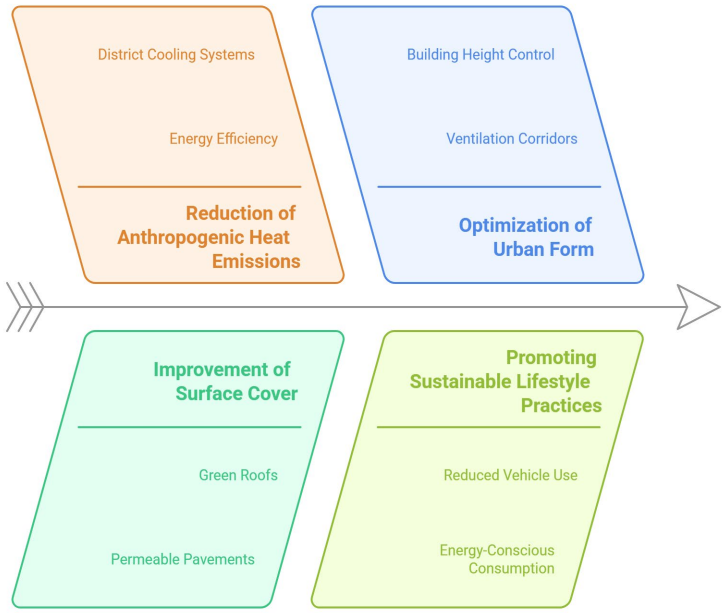


Figure 3. Analyzing Urban Heat Island Mitigation Strategies

The Japanese framework is organized into four core strategic pillars to reduce urban thermal loads while promoting long-term environmental resilience [18]. The first pillar, reduction of anthropogenic heat emissions, focuses on minimizing heat output from air conditioning systems, vehicular traffic, and industrial processes by enhancing energy efficiency and encouraging district cooling systems [19]. For example, Tokyo's "Heat Island Countermeasure Guidelines" promote adopting low-emission building systems and high-efficiency HVAC technologies [20].

The second pillar, improvement of surface cover, targets increasing urban albedo and evapotranspiration capacity through strategies such as green roofs, rooftop gardens, vertical greening, permeable pavements, and urban afforestation. Empirical studies in Osaka and Fukuoka have shown that rooftop greening can reduce surface temperatures by 2–4°C during peak summer periods.

The third pillar, optimization of urban form, emphasizes the importance of preserving urban ventilation corridors, controlling building heights and massing to avoid excessive heat accumulation, and ensuring adequate street-level airflow [21]. This is particularly evident in coastal cities like Yokohama, where design interventions aligned with wind direction and open space zoning have demonstrated measurable improvements in thermal comfort indices [22].

The final pillar, promoting sustainable lifestyle practices, encourages behavioral changes among citizens, such as reduced reliance on private vehicles, use of natural ventilation, and energy-conscious consumption patterns [23]. Public awareness campaigns, educational programs, and green building certifications have been introduced to institutionalize these behaviors.

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Importantly, many of these policy directions are closely tied to architectural and urban design practices—including selecting reflective building materials, optimizing façade geometry, orientation for passive cooling, and integrating landscape infrastructure into the built environment.

This integrated model is a valuable benchmark for other nations facing similar urban thermal challenges, particularly Saudi Arabia, where extreme heat conditions and rapid urban expansion demand a regionally adapted yet equally systematic approach.

2.2 Application Potential for Saudi Arabia

The transferability of Japan's heat island mitigation strategies to the Saudi Arabian context requires a careful reinterpretation of core principles in light of the kingdom's unique climatic, urban, and socio-cultural conditions [24]. While Japan's approach is rooted in temperate and humid subtropical climates with moderate seasonal variation, Saudi Arabia faces prolonged extreme heat, minimal precipitation, and high solar irradiance levels [25]. These environmental conditions, combined with rapidly urbanizing cities such as Riyadh, Jeddah, and Dammam, intensify the urban heat island (UHI) phenomenon and necessitate tailored mitigation strategies grounded in passive cooling, reflective technologies, and sustainable land-use planning [26].

The four pillars of Japan's *Outline of Measures to Alleviate the Heat Island Phenomenon*—namely, the reduction of anthropogenic heat, improvement of surface cover, optimization of urban form, and promotion of sustainable lifestyles—can be meaningfully adapted to Saudi Arabia with appropriate adjustments. First, anthropogenic heat reduction in Saudi Arabia should prioritize integrating district cooling systems and retrofitting buildings with high-efficiency HVAC units operating under extreme temperatures. The widespread use of mechanical cooling in the kingdom, often accounting for over 70% of total electricity consumption during peak months (Saudi Energy Efficiency Center, 2022), makes energy efficiency a critical UHI mitigation strategy. Second, surface cover enhancement through increased vegetative infrastructure, although limited by water scarcity, can be strategically implemented via xeriscaping, native plant selection, and treated greywater for irrigation. Projects such as Riyadh Green have demonstrated that when properly integrated with water management systems, urban greening can lower ambient temperatures by up to 2°C in surrounding microclimates. Policy incentives for rooftop greening, shaded pedestrian corridors, and vertical vegetation walls could be feasible interventions within the architectural and planning domains. Third, urban form optimization is particularly applicable in Saudi Arabia, where expansive road networks, high-rise glass towers, and dense commercial blocks often obstruct wind corridors and contribute to heat stagnation. Lessons from Japan—such as building alignment with prevailing wind directions, modulation of building heights, and strategic zoning of open spaces—can inform the development of Saudi-specific urban design codes that promote natural ventilation and reduce localized heat buildup. Finally, lifestyle transformation remains a gradual but essential pillar. Public campaigns promoting walkability, the use of public transit, and behavioral shifts toward energy-conscious living must be embedded within broader national initiatives such as Vision 2030's Sustainable Cities Program. Furthermore, Saudi Arabia's commitment to environmental sustainability—evident in its Green Saudi and Green Middle East initiatives—provides an enabling policy environment to embed UHI mitigation within urban development frameworks. While direct transplantation of Japanese policies may be limited by climatic divergence, the core strategic directions offer a valuable framework for formulating Saudi-specific guidelines. These should combine passive architectural strategies, advanced energy systems, landscape integration, and regulatory incentives to create climate-resilient, thermally comfortable, and livable urban environments across the Kingdom [27].

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Table 1. Application Of Japan's Heat Island Strategies To Saudi Arabia

Japan's Heat Island Mitigation Pillars	Saudi Arabia Adaptation Strategy
1. Reduction of anthropogenic heat	To reduce energy demand, integrate district cooling systems and retrofit buildings with high-efficiency HVAC units. This is essential because over 70% of electricity is used for cooling during peak periods.
2. Improvement of surface cover	Apply xeriscaping, native plant species, and greywater irrigation; initiatives like Riyadh Green show a 2℃ reduction in localized ambient temperatures.
3. Optimization of urban form	Revise urban codes to support ventilation corridors, adjust building heights, and plan open spaces to reduce heat stagnation in cities like Riyadh and Jeddah.
4. Promotion of sustainable lifestyles	Under the Vision 2030 Sustainable Cities Program and the Green Saudi Initiative, promote walkability, public transit use, and energy-conscious behavior.

3. Methodology

This study adopts a comparative policy analysis methodology, grounded in a qualitative content evaluation of Japan's nationally endorsed urban heat island (UHI) mitigation strategies. The analyzed core documents included the Heat Island Phenomenon Mitigation Outline and the Architectural Design Guidelines published by Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT). These sources were systematically examined to identify key principles such as enhancing surface albedo, integrating urban vegetation, promoting natural ventilation pathways, and applying reflective or permeable materials in architectural design. Each policy component was thematically categorized, and its structural features were interpreted in terms of its intended environmental outcome.

Subsequently, these principles were critically assessed for their applicability within the climatic, material, and urban development context of Saudi Arabia. The study focused on cities such as Riyadh, Jeddah, and Dammam, where the UHI effect has intensified due to rapid urban expansion, high thermal mass of construction materials, and limited green infrastructure. Climatic data from the Saudi National Center for Meteorology and urban planning reports from the Ministry of Municipal, Rural Affairs, and Housing (MOMRAH) were incorporated to evaluate local environmental parameters. Additionally, empirical findings from peer-reviewed Q1 journals—such as Building and Environment, Sustainable Cities and Society, and Energy and Buildings—were used to cross-reference the effectiveness of similar mitigation strategies in other arid regions. This methodological approach aims to derive regionally adaptable, evidence-based urban design guidelines that support thermal comfort, energy reduction, and environmental resilience in alignment with Saudi Vision 2030.

4. Analysis

4.1 Architectural Design Guidelines for Mitigating the Heat Island Phenomenon in Japan

Following the formal adoption of the Heat Island Countermeasure Outline by the Heat Island Countermeasures Liaison Meeting on March 30, 2004, Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) released a specialized set of Architectural Design Guidelines in July 2004. These guidelines were developed as a non-regulatory, advisory tool to encourage building owners, designers, and developers to proactively contribute to reducing urban thermal loads through environmentally responsive architecture. The guidelines represent the culmination of empirical studies and policy research conducted by the Heat Island Countermeasures Review Committee, which synthesized scientific findings and field data to identify key building-level interventions that have measurable impacts on urban thermal mitigation.

The architectural design guidelines emphasize voluntary adoption rather than regulatory enforcement, underscoring the importance of decentralized, site-specific strategies in mitigating the heat island effect. Rather than focusing solely on internal building performance, the guidelines advocate for integrated planning for the thermal interactions between buildings and their surrounding microclimates. This includes reducing the radiative and convective heat flux from

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buildings into the urban environment and enhancing the site's ability to maintain favorable thermal conditions. The Comprehensive Assessment System for Built Environment Efficiency - Heat Island category (CASBEE-HI) was developed to support evaluation and benchmarking. This tool allows designers to quantitatively assess the effectiveness of proposed strategies using a standardized environmental performance index, helping bridge policy guidelines with measurable environmental outcomes.

The guidelines are structured around five core categories, each addressing a specific environmental variable that contributes to UHI reduction:

1. Ventilation: Design strategies that enhance urban wind flow, including building orientation, setbacks, and preservation of ventilation corridors to improve natural cooling and heat dispersion.
2. Shade: Promote shading devices, vegetation, and façade elements that reduce direct solar radiation on external and internal surfaces, thus lowering surface and ambient temperatures.
3. Land Surface Covering: Permeable and vegetative surfaces, such as green roofs, bioswales, and permeable paving, enhance evapotranspiration and reduce surface heat retention.
4. Building Exterior Materials: Adoption of high-albedo materials and coatings that reflect solar radiation and reduce the accumulation of sensible heat on building surfaces.
5. Restraint of Building Equipment Arrangement: Minimizing the external thermal impact of mechanical systems (e.g., condensers, generators) by careful spatial configuration and shading to limit anthropogenic heat emissions into the surrounding environment.

These guidelines serve as an integrated design reference, especially for urban projects in high-density areas where UHI effects are most pronounced. Although they do not carry legislative weight, they have been widely referenced in municipal planning efforts and sustainable building certifications across Japanese cities. They provide a science-based foundation for site- and context-specific architectural responses to urban heat. This approach is relevant to countries like Saudi Arabia, where extreme climatic conditions necessitate thermal-resilient urban development.

4.2 CASBEE-HI as an Evaluation Tool and Its Applicability in Saudi Arabia

The Comprehensive Assessment System for Built Environment Efficiency for Heat Island Mitigation (CASBEE-HI) is a building environmental performance evaluation tool developed in Japan to systematically assess the effectiveness of architectural design strategies to mitigate the urban heat island (UHI) effect. Unlike broader sustainability tools such as LEED or BREEAM, CASBEE-HI specifically targets the thermal impact of buildings on their immediate microclimate, making it an especially relevant instrument for densely populated urban areas with heightened surface and ambient temperatures. Its design enables stakeholders to easily quantify the degree of UHI-responsive planning in architectural and landscape decisions, thereby serving three main functions: (1) supporting climate-sensitive design development, (2) enabling comparative performance ratings, and (3) informing municipal-level mitigation policies.

The CASBEE-HI framework has a clearly defined evaluation scope, spatial boundary conditions, weighted scoring metrics, and performance indicators. Key evaluation items include rooftop greening ratios, heat-reflective materials, surface permeability, solar shading devices, and mechanical system placement. Each item is quantitatively scored based on its effectiveness in reducing surface temperature, promoting evaporative cooling, or minimizing anthropogenic heat emissions. The tool is designed for a broad spectrum of stakeholders, including building owners,

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architects, local authorities, certification agencies, and environmental advocacy groups, ensuring professional and civic engagement in climate-resilient urban development.

Introducing a localized CASBEE-HI-type evaluation tool in the Saudi Arabian context could significantly advance sustainable architectural practices, particularly in megaprojects such as NEOM, King Salman Park, and Qiddiya, where environmental innovation is central to project identity. Saudi Arabia's extreme climatic conditions, characterized by prolonged heat waves and solar radiation exceeding 800 W/m² during summer months, make it imperative to assess not just internal energy performance but also the external thermal footprint of buildings. Adapting CASBEE-HI principles to local conditions would allow Saudi architects and planners to evaluate passive cooling strategies, such as reflective stone aggregates, vegetated courtyards, thermal mass buffering, and courtyard ventilation, which are already embedded in traditional Najdi and Hijazi architecture.

Moreover, the Saudi government's interest in integrating green building certification with subsidy mechanisms, such as in housing programs by the Ministry of Municipal and Rural Affairs and Housing (MOMRAH), makes a performance-based evaluation model particularly timely. CASBEE-HI's approach to quantifying environmental load reduction, especially via unused roof surfaces and waste heat recovery models, aligns well with Saudi Arabia's Vision 2030 objectives on energy efficiency, resource optimization, and livable city planning.

In conclusion, while CASBEE-HI was developed for Japan's temperate climate, its methodology presents a strong foundation for developing a Saudi-specific Heat Island Evaluation Framework (S-HIEF). Such a tool would support environmental policy enforcement and provide a scientific, standardized approach for building performance assessments that prioritize urban thermal health across the Kingdom.

5. Discussion

The comparative analysis conducted in this study illustrates that Japan's comprehensive approach to mitigating the urban heat island (UHI) phenomenon offers valuable insights for adaptation in Saudi Arabia. While Japan's strategies were developed for temperate climates, their core principles—reducing anthropogenic heat, improving surface albedo, enhancing ventilation, and integrating vegetative systems—retain relevance in arid environments when recalibrated to local conditions. The evidence suggests that Saudi Arabia's rapid urban expansion and extreme thermal loads require a similarly structured but climate-specific framework to address UHI impacts at both the policy and design levels.

In particular, the architectural design guidelines introduced by Japan, centered around five key categories—ventilation, shading, land surface covering, exterior materials, and equipment placement—can be adapted to Saudi cities through passive design strategies rooted in local vernacular architecture. These include wind towers, shaded arcades, thermal mass walls, and reflective material use. Furthermore, the emphasis on performance-based evaluation, as demonstrated by the CASBEE-HI system, highlights the need for a localized assessment tool in Saudi Arabia. A Saudi-specific Heat Island Evaluation Framework (S-HIEF) could support national sustainability targets by quantifying the effectiveness of UHI mitigation strategies, guiding green building certification, and informing subsidy allocations for climate-responsive developments.

Overall, the study confirms that while direct policy transplantation is infeasible due to climatic and cultural differences, Japan's UHI framework's structural methodology and evaluative rigor provide a strong foundation for formulating effective urban heat mitigation strategies in Saudi Arabia. Future applications should explore localized pilot projects and regulatory integration to test the real-world impact of these adapted strategies.

6. Conclusion

This study presented a comparative investigation of Japan's urban heat island (UHI) mitigation policies and their adaptation potential within the environmental, cultural, and urban context of Saudi Arabia. By analyzing the Japanese *Heat Island Phenomenon Mitigation Outline* and the associated *Architectural Design Guidelines*, the research identified a robust, multi-layered framework built upon four strategic pillars: reduction of anthropogenic heat, improvement of surface cover, optimization of urban form, and promotion of sustainable lifestyles. Although developed for temperate and humid climates, these pillars retain conceptual relevance for arid regions such as Saudi Arabia, provided they are contextualized to address local climatic extremities, construction materials, urban morphology, and socio-cultural behaviors. Saudi cities such as Riyadh and Jeddah, where surface temperatures regularly exceed 45°C, would benefit significantly from localized implementations of these principles, especially in reducing building energy loads, improving microclimatic conditions, and enhancing urban livability.

Furthermore, the paper underscores the importance of adopting a systematic and quantifiable approach to performance evaluation through tools like Japan's CASBEE-HI. The study advocates for developing a Saudi-specific Heat Island Evaluation Framework (S-HIEF) that reflects the Kingdom's distinct environmental challenges while incorporating regionally appropriate passive cooling techniques, high-albedo materials, vegetative strategies, and architectural typologies derived from traditional forms. Such a framework would serve as a design support tool and a mechanism for certifying climate-responsive developments, allocating government subsidies, and guiding national sustainability policies in alignment with Saudi Vision 2030. By embedding thermal comfort and heat island mitigation into the urban development process through performance-based design and planning, Saudi Arabia can transition toward a more resilient, efficient, and sustainable urban future. Future research should aim to develop localized performance criteria, conduct pilot applications in representative cities, and evaluate post-occupancy outcomes to refine the proposed framework and support its integration into national building codes and urban policy systems.

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Humanizing Urban Edges for City Imageability: Evidence from Al-Khobar City of Saudi Arabia

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Keywords: Imageability, Urban Edges, Waterfront, Human-Centric Design, Wayfinding, Al-Khobar City

Abstract. Edges are linear boundaries that define discontinuities, which determine how people look, walk, and perceive cities. This research question is: how natural and artificial boundaries of Al-Khobar city affect imageability, identity, and what kinds of human-based interventions can improve struggling boundaries? The study will assist in the development of people-centered edge analysis and the suggestion of the urban edge creation at Al-Khobar that increases legibility. In order to meet the objective, the study will involve a three-phase mixed-method research process and will involve a combination of nine semi-structured professional interviews, a questionnaire survey of twenty-three users, and the systematic edge inventory/ mapping. Results suggest that the eastern and southern waterfronts are legible and lively natural edges, whereas the western corridor may be interpreted as a restrictive edge and of low permeability for pedestrians. Professionals agreed upon a set of positive attractions and negative attractions, and the user too discovered that nature was the most trustworthy measure of an advantage, and indications of the anthropogenic world to be drawn to and memorize cities. The paper postulates the existence of such a parallel amenity that comprises a green buffer, edge-specific wayfinding, and humanization of the western side that does not lead to operational degradation. The contribution is a humanistic approach to the edge model of the Gulf cities in which imageability is related to inclusive and resilient public-realm design.

Introduction

Edges aid in cognition and daily navigation since they give a sustained visual and functional references which organize mental maps. In this research, the term imageability describes how easy individuals are to navigate and describe the city through a set of spatial visuals; the term identity describes the unique meanings and symbols that make a district distinctive; the term wayfinding is used to refer to the process of selecting paths and keeping track as one moves. The predecessor work associates robust edges with continuity and visibility disciplines contributing to orientation, and street-edge quality promoting safe and experience of human scale. To go beyond description, this research model the performance of the edges as explicable by a small number of quantifiable characteristics: (1) continuity (degree of continuity of the line of the edge), (2) permeability (degree to which the edge has safe crossings and access points), (3) constitutedness/intervisibility (degree to which buildings/activities face the edge and furnish eyes on the street) and (4) frontage and quality of the public realm (degree of shade, seating, lighting, maintenance, and support of activity), and (5) access and inclusion (These are the qualities that are reiterated in the literature

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of the urban design and waterfront and in particular situations in the Gulf environments where weather comfort, safety and scale of infrastructures may undermine the pedestrian experience. The current literature on imageability and waterfront identity, however, has less literature relating imageability and waterfront identity between experts and general users in the same Gulf city in addition to operationalizing and context-specific design responses to imageability and waterfront identity. The opposing edges of waterfront in Al-Khobah and the western corridor offer a chance to test an evaluation of people-based edge which combines measured features with the perceived view of waterfront legibility, identity, and wayfinding.

The edges have been historically core to the humanistic urbanism in that they assist people conceive of the end of a city, the compatibility of the districts, and have been more recently associated with the imageability to navigation, memory and even cognitive health, the edges being influence to livability when designed to support people, but not just to support traffic or security [1,2], and the earlier work on street edges, visibility and the public realm has discussed the roles of continuity of edges, inter-visibility and frontage quality to everyday wayfinding and social life [3,4]. Simultaneously, water-front studies in the Gulf and globally indicate that humanized water-edges can support the idea of anchoring city-identity and urban life [4,6], and Saudi development programs such as the best-known Jeddah waterfront reveal that proximity and inclusion require careful consideration through access, safety and identity, respectively [7], which highlighting those indicators are equally important [8] to avoid inequities. It is in this context that the Arabian Gulf waterfront of Al-Khobar is an expositional development in which the northern, "new waterfront" area provides a manufactured transition into Dammam, the western area is conditioned by highways and a military air base which inhibit permeability, and the southern area is conditioned by other (fig. 1), more recreational uses- conditions recorded in the case materials and field notes.

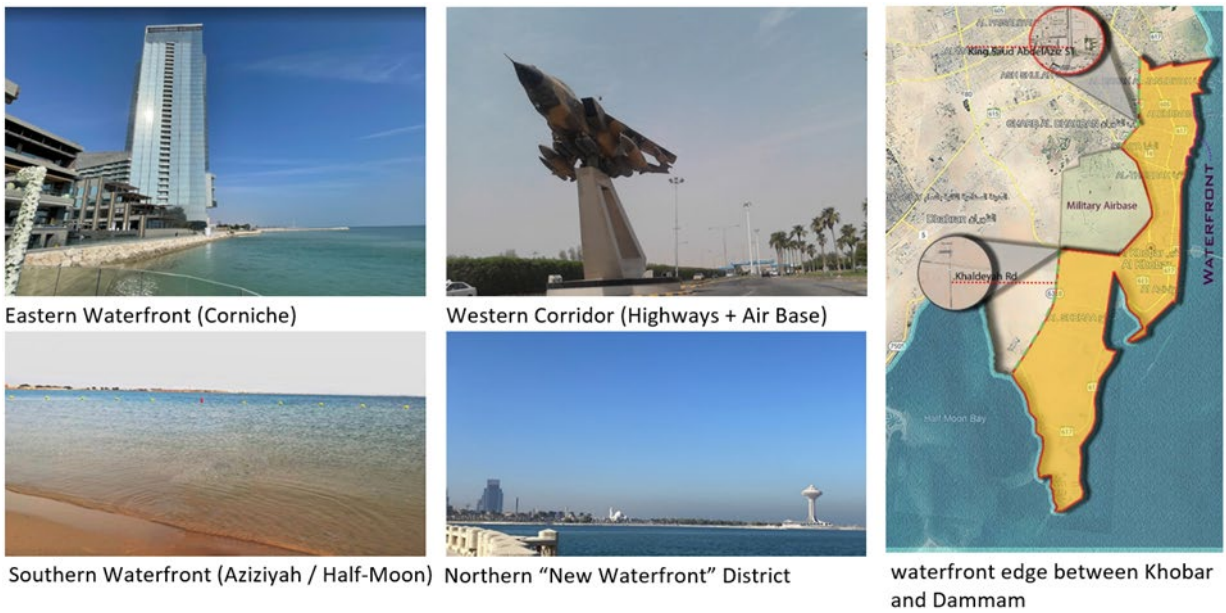


Fig. 1. *The visualization of the urban typologies of the waterfront in Khobar (Eastern Waterfront, Northern "New Waterfront" District, Western Corridor, Southern Waterfront).*

Read as a typology by nature of formation (main roads, land-use/district shifts, and highways), edge performance turns on constitutedness, permeability and intervisibility [9], frontage character and public-realm quality [4,10], and visibility fields that aid orientation [3]. The waterfront edges already perform strongly as legible, attractive civic realms; priority actions are to sustain continuity, shade, lighting and event management. Waterfront research and Gulf precedents support treating the Corniche and southern shore as identity anchors and programmed civic spaces

[5, 6, 11], while the emerging northern district requires people-centred street-quality and place-meaning to cohere as a recognizable area [12,13]. As Khobar invests in its edges, expected socio-economic value aligns with Saudi waterfront experience [7] but should heed access and inclusion cautions from 15-minute-city debates [8]

Table 1. *Typology of edge of Khobar, and design implications.*

Edge (location)	Nature/type	Defining features & functions	Impact on design & management
Eastern Waterfront (Corniche)	Natural civic edge	Oldest waterfront; continuous promenade and parks; active everyday public realm	High legibility and popularity; maintain continuity; manage crowding and event logistics
Northern "New Waterfront" District	Man-made district edge	Emergent district extending Khobar toward Dammam; seeks to replicate waterfront success	Identity still forming; unify frontage rhythm and wayfinding; add shade and small plazas
Western Corridor (Highways + Air Base)	Restrictive/functional edge	Two highways plus a military air base form a long, continuous boundary with very low pedestrian permeability	Avoid crowding the frontage; create a buffered parallel public edge with safe crossings and landscape; visually de-emphasize the restricted edge
Southern Waterfront (Aziziyah / Half-Moon)	Natural recreational edge	Usable beach/swimming and leisure uses; different cohorts and times	Successful for recreation; connect better to the core and fill access gaps; coordinate segment programming

According to the typology, the edge form in itself does not predict performance because the combinations of continuity, safe permeability, constituted frontages, and climatic comfort predicts the presence of an identity anchor (positive attraction) or the presence of a boundary that drives away and disorients users (negative attraction). This study proves these assumptions with the help of interview data and the survey of exploratory users (table 1).

The western corridor should be humanized via a parallel public edge with buffers, safe crossings and visual de-emphasis of restricted frontage, raising permeability and perceived safety without inducing crowding [9, 10]. The northern edge needs identity build-out, unified frontage rhythm, small plazas, shade, and legible wayfinding grounded in perception-based street-quality and meaning [12,13]. Across all edges, layering multisensory cues can reinforce cognitive mapping and placemaking [14], while equity guidance from 15-minute-city critiques should shape access and programming [8]. Suggested monitoring KPIs include permeability/inter-visibility scores, dwell time, use mix, and wayfinding success, enabling iterative improvement consistent with Gulf waterfront outcomes [7].

The gap in the research is the comparative examination of expert and general user perceptions of these edges, which is converted into context-specific design advice without reference to operational. The paper will discuss the role of natural and man-made edges in creating the imageability and identity of Al-Khobar and how the expert and user perceptions are similar or differ in perception of wayfinding, attraction, and treatment. It seeks to come up with a replicable, people-based edge evaluation and recommendation that will improve the legibility of the city by categorizing edges (Table 1), juxtaposing expert and user evidence, and translating the findings to design strategies that are specific to the Gulf setting.

Methodology

In this study, interviews (A1-A9) were carried out with built-environment specialists chosen because of their first-hand experience in the urban development, waterfront and mobility planning in Al-Khobah. The interviews were guided along the framework (i) legible and memorable edge cues, (ii) identity-building, (iii) conditions of safe permeability, and (iv) possible interventions within the constraints of the Gulf climatic and security conditions. Thematic analysis was used to

transcribe and analyze the interviews based on the initial inductive coding pass using the known attribute codebook, and the subsequent inductive sub-codes (e.g., a deviating focus). Codes were checked in consistency and claims were justified by using representative excerpts. The results are the synthesized themes, which are reported in Tables 2-5.

Observations were mapped, summarized into edge profiles (continuity, permeability, constitutedness/intervisibility, frontage quality, access/inclusion) and given to explain Table 1 typology. Transcripts of the interviews were coded to define the recurring positive and negative attraction mechanisms (Tables 2-3) and edge-specific identity/wayfinding cues (Tables 4-5). The summary of survey responses was provided in the form of descriptive percentages and uncomplicated cross-tab comparison (e.g., use of natural versus man-made cues). Triangulation of evidence: in cases where mapping, expert interpretation, and the opinion of the user intersected, it was considered to be the most effective foundation of design actions. The results are categorized in terms of (i) positive attraction factors that reinforce the edges and (ii) negative attraction conditions that necessitate buffering or redirection (iii) edge specific identity and wayfinding cues between waterfront and western corridor settings.

This study adopted a mixed-methods (executed in three-phase) approach to achieve the aim. Phase 1 (Framing) compiled criteria like edge strength, continuity, permeability, inter-visibility, access and human-use value from recent literature and finalized instruments (fig. 2).

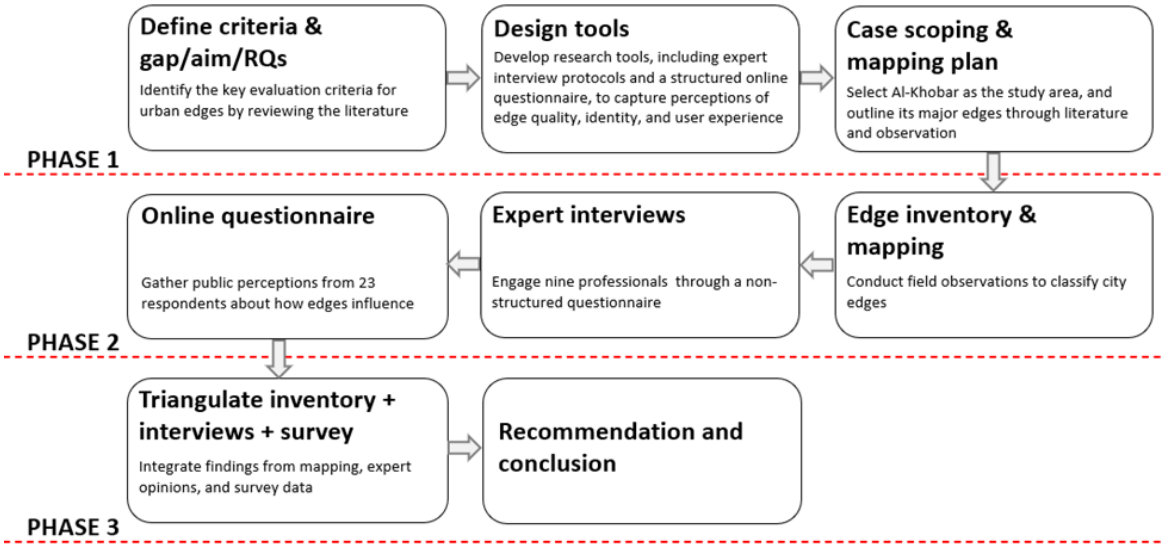


Fig. 2. *Methodological framework*

Phase 2 (Evidence) comprised a city-wide edge inventory or mapping separating natural and man-made edges; nine semi-structured expert interviews (three academician, researchers and practitioners respectively) probing successful or unsuccessful treatments, district identity, western-edge constraints, and the 'deviating focus' idea; and an online questionnaire survey (n = 23) capturing users' understanding of edges and their relative roles of natural, man-made elements, direction-giving, and identity marker. Phase 3 (Integration) triangulated interview codes and survey statistics to generate design actions parallel public edge with buffers and safe crossings, edge-aware wayfinding, and district-identity layers and to assemble a humanization playbook for Al-Khobar.

Result and Analysis

This part presents the results according to the analysis framework. First, we sum up interview themes that describe positive attractions (Table 2) and negative attractions (Table 3). Then we interpret waterfront sub-edges and cohort use (Table 4) and the constraints and feasible treatments

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of western corridors (Table 5). Fig. 4 Survey patterns Compare the identity and wayfinding features between general users based on similar natural and man-made cues, which are checked by survey patterns as exploratory checks.

The expert interviews (A1–A9) revealed strong consensus that natural, continuous, and activity-rich edges provide the most positive contribution to Al-Khobar's imageability and liveability (Table 2). Nearly all respondents emphasized that waterfronts, especially the Corniche and southern leisure edge represent inherently strong and legible boundaries because they align with nature and invite everyday use. Linearity was seen as a key condition for readability: when edges extend visibly and uninterrupted, users can orient themselves easily. Interviewees also linked wayfinding for newcomers and pathfinding for regular users directly to these long natural lines, describing how the sea or a continuous promenade offers intuitive direction cues. Several participants argued that districts and nodes with a clear architectural rhythm could likewise act as man-made edges if they possessed distinct identity and consistent frontage. Diversity in function was not viewed as fragmentation; rather, participants valued variety within continuity, where mixed uses keep the edge lively without losing clarity. Programming and micro-amenities such as shaded seating, small plazas, and night lighting were seen as tools that transform underperforming stretches into memorable places. Finally, the collective view was that nature supports psychological comfort: contact with green and blue spaces encourages calm and wellbeing, reinforcing why the Corniche is Khobar's most successful civic edge. Overall, the interviews confirm that maintaining continuous natural lines while layering human-scale functions best sustains an edge's social and spatial vitality.

Table 2. *Positive attraction makes an edge work*

Theme	Concise definition	Illustrative excerpt (from translations)	Codes supporting	Design implications for Al-Khobar
Natural edges desired	A natural edge: The natural feeling is powerful and good	"Waterfronts… create a very strong natural edge."	A1, A3, A4.1, A5, A6, A7, A8, A9	Maintain Corniche and southern shore as anchor edges; conserve views, shade, and access.
Linearity matters	Edges must read as long, continuous lines	"An edge is linear and extending, which defines an area."	A2.1, A1, A6, A7, A9	Maintain continuous stretches; avoid fragmented, stop-start treatments.
Wayfinding for new users	Edges used by first-time users only	"Sea on your right, you are heading north…"	A1, A2, A6, A7	Turn Corniche into the main orientation spine; strengthen with wayfinding.
Pathfinding of regulars	Edge structure habitual movement	Continuation of the reasoning of A1 about movement	A1, A2.2, A7, A9	Adding everyday walking/cycling/vehicular desire lines along edges.
Districts can be edges	Artificial spaces with identity are like edges	"A big node… distinct character… creates a successful edge."	A2.1, A2.3, A6, A7, A9	Establish the identity of the northern district (frontage rhythm, nodes, micro-landmarks).
Diversity in continuity	Different functions can share one edge	"Base edge remains… sectors vary by treatment."	A1, A4.1, A5.1, A6, A8	Subdivide the waterfront (family / quiet/active) but retain one legible edge.
Activities salience edges with programming	Activities make edges salient and loved	"More activities… improve the image of the city."	A2.2, A5.2, A6, A8	Introduce low-cost facilities (shade, seating, play, kiosks) to low-performing segments.
Nature & wellbeing	People prefer nature calm/health	Multiple mentions of Corniche use	A1–A5, A6–A9	Prefer green-blue comfort (microclimate, seating, night lighting).

A1–A9 denote interviewees. The excerpts are different in decimals (i.e. A4.1) of the same interviewee.

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Table 2 indicates that the most commonly mentioned processes of positive attraction are consistent with the mapped attributes: continuous natural lines (high continuity), inviting and shaded public realm (frontage quality) and active edge life (constitutedness). These processes facilitate legibility (individuals can read the boundary), strengthen identity (the waterfront develops into a civic referent), and offer also intuitive wayfinding indicators (the sea/promenade as an orientation spine).

Across interviews A1–A9 (Table 3), participants consistently recognized that not every urban edge should draw people in; some must instead repel or redirect activity to protect safety, privacy, or environmental balance. The clearest concern was the uneven legibility of Khobar's edges: outside the Corniche, most residents fail to perceive clear boundaries, underscoring the need for identity-building measures such as frontage rhythm, landmarks, and consistent wayfinding. The western corridor, dominated by highways and the military air base, was repeatedly described as a restrictive, inaccessible edge functionally necessary but socially inert. Experts emphasized that public functions must never be placed directly along sensitive or high-speed corridors; instead, they recommended creating buffered zones and visually de-emphasizing those frontages. Where safety allows, edges can gain strength through the addition of functional or aesthetic value for instance, small recreational pockets, markets, or landscape treatments that signal the city limit without inviting prolonged gathering. The concept of "deviating focus", proposed by several interviewees, encapsulates this balanced approach: develop a secondary, safer edge such as a landscaped trail or parallel public promenade that diverts attention away from the restricted line while maintaining orientation and continuity. In short, negative-attraction conditions in Khobar call for selective activation, buffering, and visual management rather than uniform beautification, ensuring each edge performs appropriately for its context and user safety. Overall, the proposed attention-diverting strategies that the experts suggested involved offering parallel edges that were safer to figure out and redirect attention, and the ability to retain legibility and have the context intact (Table 3).

Table 3. *Negative attraction- what undermines an advantage and reaction.*

Issue	What the problem is	Illustrative excerpt	Codes supporting	Design response for Al-Khobar
Unintentional/unclear edges	Outside the Corniche, users don't "read" other edges	(Synthesis: confusion identifying edges)	A1–A5, A6–A9	Use identity tools (frontage rhythm, landmarks, wayfinding) on north/west.
Privacy/sensitivity	Airbase frontage cannot host public life	"Restrictive… forbidden place… cannot enter."	A1, A4.5, A6, A7	Do not attract crowds to the line; buffer and visually de-emphasize.
Highways as weak civic edges	Functional, unsafe, hostile for pedestrians	"They only provide function… don't add to daily lives."	A4.1–A4.3, A7, A8	Shift focus to a parallel public edge away from the highway.
Add function where safe	Function can "make" an edge	"Activities… improve the image… strong paths."	A2.2, A5.1–A5.2, A6, A9	Introduce use clusters (markets, parks, shade loops) in safe segments.
Aesthetic signal where use unsafe	Use aesthetics where lingering is risky	(A4.2/A4.3: planting/art ok, but not for highways)	A4.2, A4.3, A8	Use visual cues (planting, lighting, art) to signal city limit, not to gather.
"Deviating focus" (parallel edge)	Build a second, safer edge inboard	"Introduce something physical… all eyes on the path…"	A2, A7, A8	Create a buffered linear park/trail parallel to the restricted corridor.
A1–A9 denote interviewees. The excerpts are different in decimals (i.e. A4.1) of the same interviewee.				

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Table 3 defines negative attraction to be the circumstances under which an edge has to discourage lingering or direct access because of safety, speed, privacy, or operational limits. This is best seen in the Al-Khobar where the low permeability and weak constituteness makes walking less comfortable and less memorable. The evidence suggests the interventions which should keep the orientation and clarity and redirect activity into the safer and human-sized parallel routes. A survey (n=23) was conducted online using a questionnaire aimed at comparing the general user perception and expert themes. In order to alleviate specialist prejudice, questions were formatted in simple language and contextualized to Al-Khobah using the Corniche/eastern waterfront, the northern new waterfront area, the southern Half-Moon/Aziziyah recreation edge, and the western highway airbase corridor, as frameworks. The instrument included: (1) knowledge of city edges and description of them, (2) wayfinding cues (natural lines, landmarks, streets), (3) cues associated with identity of the city/recognition, and (4) preference of edge improvements (shade, crossings, signage, seating). Basic demographics (visitor, age group and frequency of visits) were obtained. The responses were then studied on the basis of descriptive percentages and indicative cross-tabs; the results were viewed as exploratory, as the sample was small.

Al-Khobar's sea itself forms the continuous natural edge, while the different waterfront segments corniche, new northern district, and Half-Moon/Aziziyah represent purposeful functional variations rather than breaks. Participants emphasized that split functions enrich rather than weaken the edge, as each segment attracts distinct user groups and times of use. Families, children, and leisure seekers frequent the corniche, whereas single adults and youth are more drawn to swimming or sport zones, confirming that edges succeed when programmed for multiple cohorts. Experts also clarified that cultural norms and functional logic, not mere spatial integration, determine placement: open-swim activities are better suited away from the city core, while family promenades can coexist comfortably within it. Attention was also drawn to the northern district, where edges exist physically but lack symbolic clarity; respondents agreed that consistent frontage rhythm, micro-landmarks, and shaded plazas are necessary to consolidate identity and orientation. Overall, professionals regard Khobar's waterfront as a series of complementary sub-edges unified by the sea and differentiated by activity, demonstrating how contextual, cultural, and climatic factors define urban edge performance in Gulf cities. On the whole, the waterfront is a unified and differentiated sub-edges, which are determined by culture, climate, and purpose (Table 4).

Table 4. *Waterfront division, cohort, and identity.*

Issue	What the problem is	Illustrative excerpt	Codes supporting	Design response for Al-Khobar
Split vs. continuity	The sea is the continuous edge; split uses are fine	"Base edge remains; sectors vary by treatment."	A1, A4.1, A5.1, A6, A8	Keep promenade vs. swim distinction; connect via access & wayfinding.
Different cohorts	Different edges serve different users/times	"Filtration by gender, function, activities."	A2.2, A3.1–A3.2, A5.2, A6, A9	Program by time-of-day/cohort; separate quiet/family from active/sport zones.
City integration vs. culture	Function/culture, not co-location, drives choice	"Integration isn't the driver… culture won't accept central open-swim."	A2, A4.2, A7	Keep open-swim away from core; focus on connectivity rather than merging.
Northern identity	Needs coherent meaning and frontage rhythm	"Distinct character creates a successful edge."	A2.1, A2.3, A6, A7, A9	Add micro-landmarks, shade plazas, and consistent frontage rules.
A1–A9 denote interviewees. The excerpts are different in decimals (i.e., A4.1) of the same interviewee.				

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According to table 4, cohort differences (families vs youth/sport users vs visitors) do not reduce edge continuity rather, they divide programming along the same natural divide. Identity can be both homogenized (the sea as shared point of reference) and differentiated (the different sub-edges) without making the wayfinding less clear. The western corridor of Al-Khobar formed by two highways flanking the King Abdulaziz Air Base functions primarily as a restrictive, low-permeability boundary rather than a civic edge. Interviewees described it as a long, hostile environment for pedestrians that separates rather than connects urban districts. Because of its strategic and security-sensitive character, respondents emphasized that conventional public-realm activation is neither feasible nor desirable. Instead, the corridor should be treated through visual de-emphasis and buffering, maintaining privacy while softening its image with landscape screening and view management. Participants also noted a persistent identity gap, as most users do not consciously perceive the corridor as an edge; a subtle gateway logic through arrival markers, signage, or lighting could clarify spatial limits without encouraging gathering near restricted zones. The recurring recommendation was to adopt a two-line strategy: first, preserve the restricted edge's functional integrity, and second, introduce an inboard, human-scale parallel public edge, a shaded linear trail or greenway linked to adjacent neighbourhoods by controlled crossings. Such a design would restore legibility and connectivity while safeguarding the corridor's operational requirements, translating expert consensus into a pragmatic and context-sensitive framework for Khobar's western boundary. It was suggested to have a dual-edge approach, which not only maintains the limited boundary but also a shaded, human-scale trail or greenway within the urban environment to re-establish connectivity and understanding without jeopardizing security (Table 5).

Table 5. *Western corridor (highway + airbase) constraints and two-line solution*

Constraint	Why it matters	Illustrative excerpt	Codes supporting	Recommended response
Risk & Low permeability	Long, hostile boundary for walking	"Highways… not edges for people."	A4.1–A4.3, A7, A8	Similar parallel public edge (trail/greenway) set within the fabric; shaded, continuous.
Privacy, security	Critical facility precludes activation	"Restrictive… cannot enter… not a good edge."	A1, A4.5, A7	De-emphasize frontage; manage views; avoid gathering spots at the line.
Identity gap	Users do not read it as an edge	"Not perceived clearly."	A1–A5, A6–A9	Apply gateway logic with the consequence of no enduring near sensitive areas constructed
Desire lines vs. safety	Users still need legible routes	"Shift attention to the designed path."	A2, A6, A9	Controlled crossings; connect the parallel edge to connectors in the district.

A1–A9 denote interviewees. The excerpts are different in decimals (i.e., A4.1) of the same interviewee.

An online questionnaire was sent to 23 participants chosen at random with the help of the knowledge gained during the interview with the experts. It examined the general knowledge about urban edges through five themes, namely general awareness and design preferences, how edges affect movements and wayfinding, city identity and defining features, the importance of natural features, and the importance of man-made landmarks, including streets, buildings, and public space. The answers assisted in the comparison of the user perception and the expert view on edge functionality and identity in Al-Khobar.

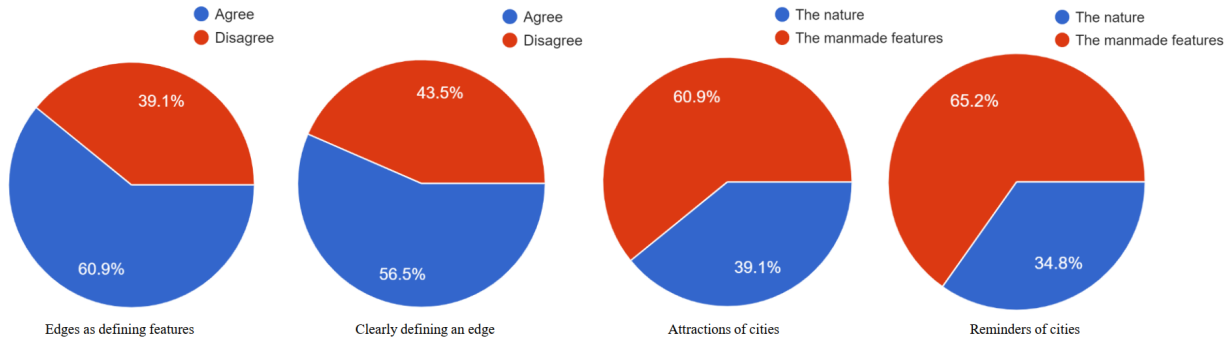


Fig. 3. *The perception of urban fringe and urban identity using natural and artificial characteristics by the users*

The results of the surveys show that the participants tend to acknowledge the importance of edges as factors that define the city's identity, but most of them believe that they are not always clearly delimited. Although natural environments are valued, the respondents perceive urban attractions and memories based on man-made environments, which emphasizes the dominant role of built environments in the perceptions and recollection of people regarding cities.

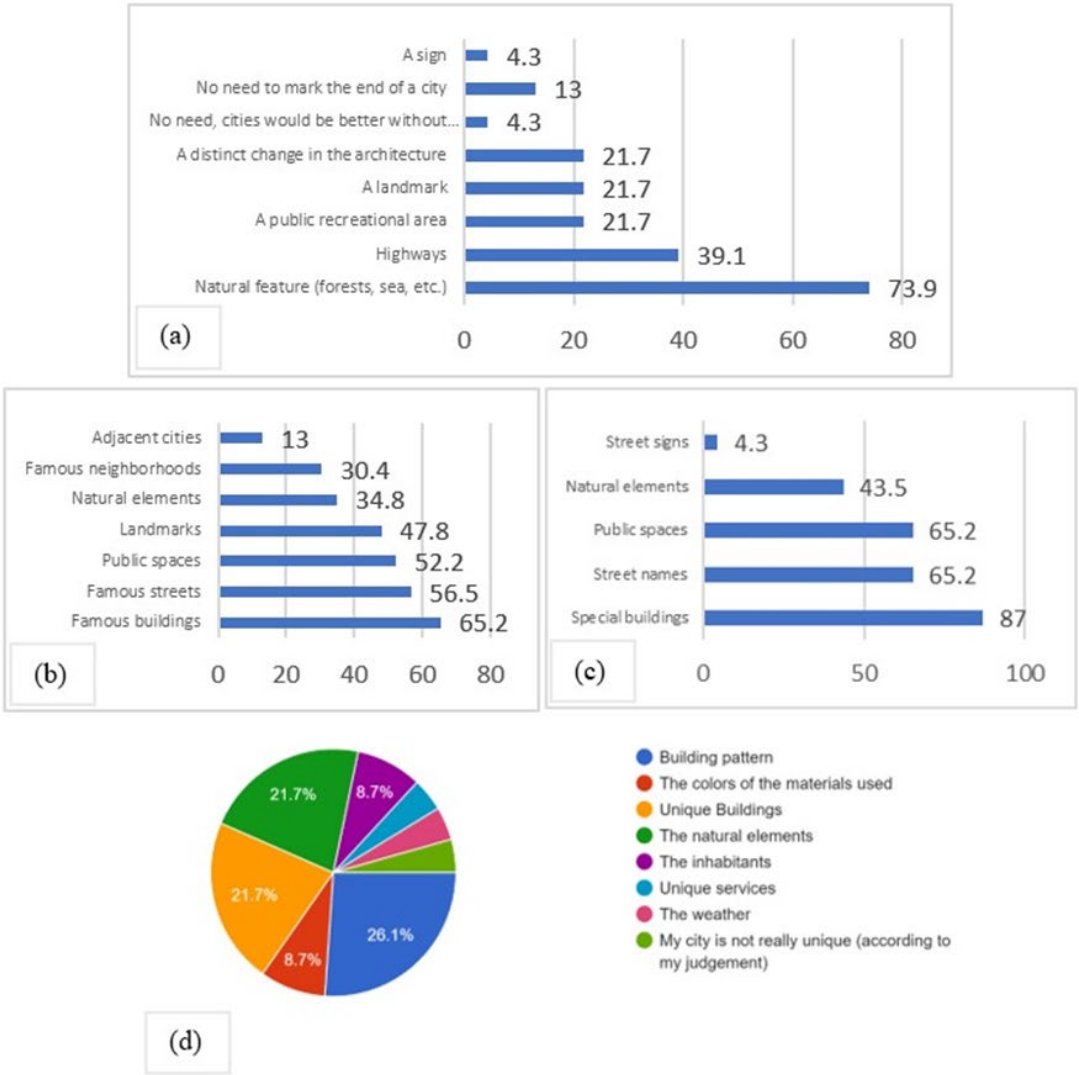


Fig. 4. *(a) Best way to mark an edge; (b) Sense of direction; (c) Describing directions (d) Public perceptions of features that uniquely define a city.*

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The results indicate that the city boundaries are most closely related to the natural elements like the sea or green grounds, according to the respondents (Fig. 4a), whereas the landmarks, the spaces, and highways are the secondary elements. In naming, describing, or characteristic features of cities, respondents focused on artificial environments, particularly well-known structures, streets, and parks, rather than the natural aspects (Fig. 4b & 4c). Combined, the findings suggest that built environments play a dominant role in shaping the recognition and recall of urban identity among people. The most frequent answers from respondents were the patterns of buildings, specific architecture, and natural features as the primary characteristics of a city's uniqueness. The secondary contributors were perceived as material colors and inhabitants. In general, the findings indicate that visual form and the environment have more influence on urban identity than social or climatic conditions (Fig. 4d).

Recommendations and conclusion

The western advantage of Khobar, which is determined by the two highways that enclose the King Abdulaziz Air Base, now functions as a confined and immeasurable boundary instead of civil space. The paper emphasizes its aesthetic brutality and inaccessibility to the public, which results in an identity discrepancy in the urban composition of the city. Owing to the strategic and security-sensitive nature of the corridor, it is not possible to directly activate the people. The strategy aims at landscape buffering, visual screening, and integration of topography in order to minimize the visibility of the airbase without compromising privacy and security. Unobtrusive gateway signage, markers, and light can aid in making the spatial boundaries clearer and enhance orientation without attracting people to congregate around the restricted areas. The proposed concept of adjacent parallel edge brings a colored linear path or greenway to the urban environment, which would connect the local areas and offer a healthier and less dangerous way to move and recreate. The establishment of small parks or rest areas in the empty or underutilized lots would further improve the liveliness of the corridor. By combining natural elements with well-placed urban interventions, the strategy transforms the western edge from a barrier into a coherent, functional, and visually softened boundary that complements Khobar’s broader urban identity.

In addition to the western corridor, there are indications of two complementary activities of the waterfront and the northern district. In the case of Corniche and southern leisure edge, continuity and comfort needs to be maintained in terms of shade, lighting, maintenance and programming that will accommodate several cohorts without interrupting the legible sea-line. In the northern, so-called new waterfront, district, identity must be enhanced by means of logical rhythm of frontage, tiny shaded plazas and micro-landmarks, and the clear wayfinding system linking major nodes to the waterfront spine. Multi sensory cues (lighting, material consistency, planting, and signage) should be implemented across all the edges to support cognitive mapping and be inclusive. Monitoring. To refine the edge interventions, the city can monitor indicative KPIs which include perceived permeability (safe crossings), intervisibility/constitutedness (presence of active frontage), dwell time, and basic wayfinding success (ability to describe routes), as an operational check. This case study shows that the performance of Al-Khobar edge is based on operational characteristics, such as continuity, safe permeability, constituted frontages/intervisibility, the quality of public realm, and availability to everybody, and explain variations in perceived legibility/imageability, identity value, and wayfinding support. The edges of waterfront prove to be such power centres of identity with continuous natural lines and daily activity whereas the western highway-airbase boundary functions as a requisite but socially deadening boundary which necessitates alternative logic of buffering and redirection. The paper provides an operational, people-based decisional advantage and a situational sensitive two-line intervention strategy by triangulating mapping, expert interpretation and user perception. There are the constraints of an exploratory survey sample size (n=23) and the geographical focus; the results cannot be considered statistically representative. The research ought to be further extended in the future through

surveying more individuals, including behavioral observation (e.g., route choice and dwell time), and analyzing pre-and post-intervention differences to determine whether interventions suggested can be effective in enhancing wayfinding success and perceived identity. The framework can be applied to other cities in the Gulf that have comparable waterfronts and infrastructure/security advantages, so long as local climatic, access standards and operational limits are clearly included.

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A Context-Sensitive Indicator Framework for Smart Campus Assessment: Importance–Performance Analysis at KFUPM

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Abstract. Smart campus initiatives are now a key strategy for universities that aim to improve sustainability, operational efficiency, and user experience through digital and IoT-based solutions. However, evaluating smart campus performance is methodologically challenging because "smartness" is multi-dimensional and strongly shaped by local context. This study uses a formative assessment approach to evaluate smart campus performance at King Fahd University of Petroleum and Minerals (KFUPM) using Importance–Performance Analysis (IPA). Thirteen smart campus indicators were developed from existing assessment tools and adapted to match KFUPM's transformation objectives. The indicators were organized into four domains: Energy & Environment, Mobility & Transportation, Smart Learning, and Campus Facilities & Services. Data were collected via a questionnaire that captured users' perceptions of the importance and current performance of each indicator. Findings show consistently high importance ratings across all indicators, while performance is lower and varies across domains. This gap indicates a mismatch between user expectations and current implementation. The IPA results highlight environmental monitoring and adaptive building systems as priority areas for immediate improvement, whereas access- and service-oriented applications show relatively stronger performance. Overall, the study demonstrates that IPA can support formative, user-centred evaluation and shows the value of context-sensitive indicator selection for diagnostic assessment and strategic decision-making in smart campus transformation.

1. Literature Review

Universities around the world are implementing smart campus initiatives as part of their digital transformation and sustainability efforts. Based on smart city and building concepts, the smart campus combines IoT, data management, and digital services to enhance learning, improve efficiency, reduce environmental impact, and elevate user experience. [1]. Smart campuses are conceived as socio-technical systems where digital infrastructure supports academic activities, campus operations, and wellbeing, not just as technologically advanced environments. [2]. As smart campus initiatives grow, the need for systematic performance assessment also rises. Literature offers various frameworks, models, and tools, featuring extensive indicators across domains like energy, mobility, learning, security, governance, and user services. [3], [4], [5].

Many tools aim to offer comprehensive assessment frameworks for the smart campus construct. While these provide high-level insights, they assume development follows a stable, universal path. Recent studies question the suitability of such standardized frameworks for campuses undergoing incremental, context-specific changes. Implementation varies across domains and evolves over time, shaped by institutional priorities, resources, and local conditions. [6], [7]. Applying comprehensive assessment tools may introduce irrelevant variance by including non-relevant or

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non-actionable dimensions, thus reducing interpretability and practical usefulness. Scholars emphasize user-centered, purpose-driven approaches. From evaluation theory, formative assessment offers diagnostic insight, learning, and improvement rather than summative judgment. In smart campus settings, it helps identify mismatches between expectations and performance to guide decisions, improvements, and phased actions. This reflects a shift from static measurement to a dynamic, adaptive process. [4].

Importance–Performance Analysis (IPA) offers a framework suited for this formative assessment. Originally developed in marketing and service quality research [8], IPA compares users' perceived importance of attributes with their perceived performance, helping identify priority areas for improvement, upgrade, or resource reallocation. Widely used in higher education and campus studies for its simplicity, interpretability, and alignment with managerial decisions [9], [10]. Recent smart campus studies have demonstrated the applicability of IPA for capturing user perceptions and translating them into actionable insights [11], [12].

Nevertheless, the effectiveness of IPA depends on how assessment indicators are selected and operationalized. Indicator selection is crucial in defining the smart campus construct and affects validity [10]. Overly broad indicator sets can weaken focus, while narrow one risks underrepresentation. Indicator scope should align with the assessment purpose and institutional context [10], [13]. King Fahd University of Petroleum and Minerals (KFUPM) has undertaken a series of strategic initiatives to transform its campus into a smart campus [14]. The activities were monitored using indicators from smart campus literature and assessment methods to promote change. The assessment viewed smartness as context-dependent, evolving with institutional priorities, stages, and solutions. This study calls the smart campus evaluation formative and context sensitive. It uses metrics aligned with King Fahd University of Petroleum and Minerals' transformation goals and stage, rather than a standard framework. Applying Importance–Performance Analysis, the study aims to (1) capture user perceptions, (2) identify areas for improvement, and (3) demonstrate IPA's value as a formative, validity-oriented tool for strategic decision-making during the smart campus transformation.

2. Methodology

This study aims to assess the performance of KFUPM's smart campus using a set of smart campus indicators grouped into relevant domains and subdomains aligned with KFUPM's smart campus transformation objectives and needs. To accomplish this objective, the study adopted a quantitative research design as outlined in Fig. 1. First, a comprehensive literature review identified well-established smart campus assessment indicators, methods, and frameworks for analysis. From the literature and evaluation tools, all smart campus indicators and their domains and subdomains were extracted using structured content analysis. The primary methodological step in the study was selecting smart campus assessment indicators based on contextual consideration and construct validity. Formative assessment rather than summative assessment means the smart campus is not static or exhaustively measured in the study. Instead, smartness is operationalized through a set of indicators aligned with KFUPM's specific initiatives and strategic priorities. Finally, an assessment survey instrument was developed based on the compiled smart campus indicators.

Survey Instrument and Data Collection

Data were collected through a structured questionnaire based on 13 smart campus indicators adapted from existing assessment tools and aligned with their main thematic categories. Indicators relevant to the KFUPM context were selected to assess smart campus performance (see Section 3). Each indicator was rated on a 7-point Likert scale for both importance and performance. Respondents provided two ratings per indicator: importance and performance. The response scales were defined as follows:

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- Importance: On a scale of 1 to 7, rate the importance of each smart campus aspect/indicator for improving and enriching student experience at KFUPM. ("1= Unimportant at all" to "7= Very important").
- Performance: On a scale of 1 to 7, rate how well KFUPM currently performs with respect to that aspect/indicator. (1= Not available at all, 2 = Dissatisfied, to 7 = Very satisfied)

The content validity of the 13 smart campus indicators was reviewed by three KFUPM faculty experts, and the questionnaire was revised accordingly. A pilot study was conducted in October 2025 within undergraduate and graduate students. The survey was then distributed via email, personal messages, and student group channels to maximize participation. KFUPM has a small number of about 6000 students and 990 faculty [15]. For 7000 population and using a 95% confidence level and a 7.5% margin of error, the required sample size (n) is about 161 valid responses. The paper reports on an ongoing project and presents partial data from 117 respondents.

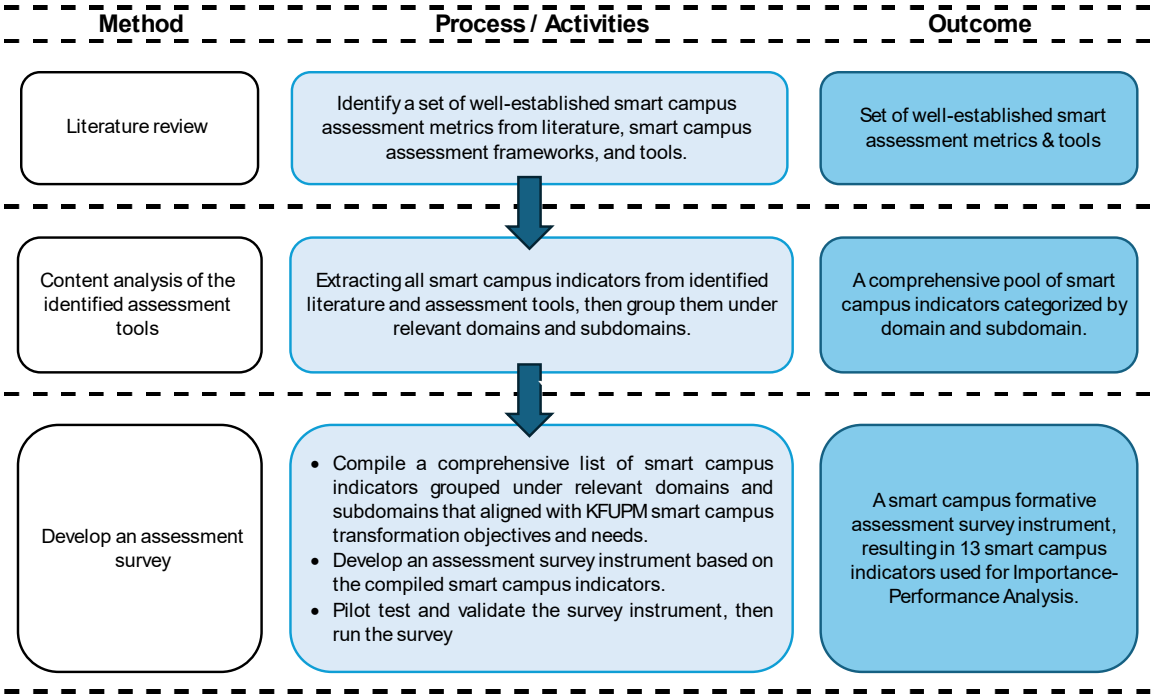


Fig 1 Outline of research methodology

Data Analysis

Data were analysed using importance–performance analysis. A well-established evaluative technique, IPA, examines the relationship between users' perceived importance of specific traits and their perceived performance, supporting organized prioritization and evidence-based decision-making. In smart campuses, IPA highlights key features that are not addressed, identifying areas that require immediate improvement and strategic interventions. In smart campus and higher education studies, IPA has been shown to support resource allocation, strategic planning, and service quality enhancement by distinguishing between attributes that should be improved, maintained, deprioritized, or potentially over-resourced [8]. In this study, IPA is employed as a formative assessment tool to support diagnostic interpretation rather than to rank performance.

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The importance–performance analysis (IPA) with IPA matrix classifies the smart campus indicators into four quadrants based on their mean importance and performance scores, as shown in Fig. 2. Quadrant I ("Maintain the Excellent Work") comprises indicators with both high importance and high performance, suggesting that existing efforts should be sustained. Quadrant II ("Do not Need Much Improvement") represents indicators with high performance but low importance, indicating potential inefficiencies in resource allocation. Quadrant III ("Low Priority") contains indicators with low importance and low performance, while Quadrant IV ("Need Major Improvement") includes indicators with high importance but low performance, indicating priority areas that require immediate attention and intervention [8]. This analytical approach supports the study's formative assessment objective by enabling nuanced differentiation among indicators and identification of priority and action areas and performance gaps aligned with campus-specific decision-making needs [16].

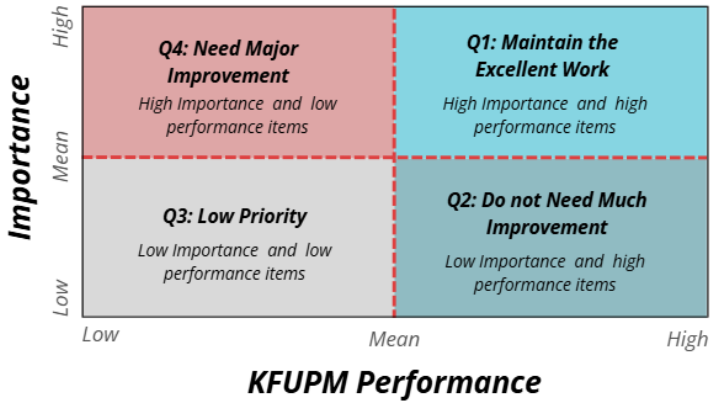


Fig 2 Importance – Performance Analysis (IPA) Matrix

3. Constructing the Smart campus Assessment Indicators for KFUPM

The selection of smart campus assessment indicators was a key methodological step in this study, guided by contextual considerations and aimed at ensuring construct validity. Since the study focuses on formative rather than summative assessment, it does not treat the smart campus as a static/fixed or exhaustively measurable construct. Indicators were adapted from existing smart campus literature and assessment tools but were not adopted wholesale from any single standardized framework. Instead, the selection followed a purpose-driven logic grounded in three criteria: relevance to the various dimensions of campus life, alignment with KFUPM's ongoing smart campus initiatives and objectives, and interpretability for formative assessment and decision-making action. This selective approach was intended to avoid underrepresentation of constructs on dimensions directly relevant to KFUPM's smart campus transformation objectives, while simultaneously minimizing construct-irrelevant variance arising from including indicators unrelated to institutional priorities. By restricting the scope of the indicator, the study operationalizes the smart campus construct for diagnostic evaluation and continuous improvement rather than benchmarking or summative judgment.

The smart campus assessment tool developed to assess the KFUPM campus is adapted from several previous studies [11], [17] that include a set of indicators to ensure coverage of both technical functions and user-facing experience. As shown in Table 1, the set of indicators used in the survey assessment instrument in this study comprises 13 indicators grouped under four smart campus thematic domains: Energy-Environment (EE), Mobility-Transportation (MT), Smart Learning (SL), and Campus Facilities & Services (FS). The set of indicators aligns with KFUPM's smart campus transformation objectives and needs.

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Table 1 Smart Campus Assessment Indicators relevant to KFUPM

Domain	Code	Indicator Name	Operational Definition (Survey Questions)	Reference
Energy & Environment (EE)	IND01	Quality of Indoor Environment	Classrooms and study spaces have air quality monitoring systems (temperature and humidity) that send alerts if conditions are uncomfortable.	[18]
	IND02	Outdoor Environment Monitoring & Advice	The University provides real-time information about outdoor conditions (pollution, heat, humidity, UV index) and related safety advice	[19]
	IND03	Occupancy-Based Lighting & HVAC	Indoor lighting and air conditioning are automatically adjusted depending on the number of room occupants.	[20]
	IND04	Automatic Water Systems	The University uses automated water systems (faucets, irrigation) to optimize water consumption.	[21]
	IND05	Smart Energy Harvesting	Smart renewable energy systems (solar, wind, etc.) are used by The University to support sustainability goals	[21]
Mobility & Transportation (MT)	IND06	Smart Parking Guidance	The university's parking system uses real-time data to direct drivers to available spaces.	[22]
	IND07	Public Transport Optimization	Walking and bus routes are adjusted based on real student movement patterns within the University.	[23]
Smart Learning (SL)	IND08	Class attendance	Student attendance is automatically recorded upon classroom entry.	[24]
	IND09	Automatic Phone Control in Classrooms	Mobile devices are automatically set to silent and limited-use mode when users enter a classroom.	[25]
	IND10	Class Activity Capture & Sharing	Class activities are digitally recorded and securely shared with enrolled students through the University's system.	[26]
	IND11	Remote Library Resource Retrieval	The University's library resources are accessible for remote search, reservation, and borrowing.	[27]
Campus Facilities & Services (FS)	IND12	Smart Building Access & Reservations	The University has an integrated platform that manages student bookings for labs, meeting rooms, and conference rooms.	[24]
	IND13	Personalized Activity Reminders	Students receive automatic reminders for upcoming classes or activities based on their location in the University.	[28]

4. Results and Discussion

4.1 Demographic Characteristics of Respondents

A total of 117 responses were collected, with 66.7% of respondents were male and 33.3% were female. Most respondents were graduate students (69.2%), followed by undergraduates (29.1%), and faculty members accounted for a small share (1.7%). Most respondents spent between one and three years at KFUPM (83.8%), indicating substantial exposure to campus facilities and services. The composition of the sample suggests that the results primarily reflect students' perceptions of campus smartness, consistent with the study's objective of assessing user-experienced performance rather than institutional self-evaluation. Given students' ongoing interactions with learning environments, facilities, and mobility systems, their responses provide a sound basis for formative assessment of smart campus implementation.

4.2 Indicator-Level Importance, Performance, and Gap Analysis

Table 2 shows that all indicators have high importance ratings, with a mean above 5.00, indicating strong and consistent user priorities. Indicators related to access and service convenience, particularly IND12 and IND11, rank highest in both importance and performance, resulting in relatively small gaps and better alignment with user expectations. In contrast, indicators within the Energy and Environment domain, such as IND01, IND02, and IND03, display very low performance scores despite high importance, leading to the largest gaps. Overall, the gap values

highlight that while digital access and service features are relatively well implemented, environmental monitoring and adaptive building systems remain the most critical areas requiring improvement.

Table 2 Indicator-level Importance-Performance Analysis results

Domain/Indicators	Importance			Performance			Gap	
	Mean	Median	IQR	Mean	Median	IQR	I-P	Rank
Energy & Environment (EE)								
Indoor Quality Monitoring & Alerts (IND01)	5.41	5.50	1.00	2.28	2.00	2.00	3.13	11
Outdoor Environment Monitoring & Advice (IND02)	5.31	5.00	2.00	1.89	1.00	1.00	3.43	13
Occupancy-Based Lighting & HVAC (IND03)	5.44	6.00	1.00	2.13	2.00	1.00	3.31	12
Automatic Water Systems (IND04)	5.57	6.00	1.00	4.16	4.00	2.00	1.42	3
Smart Energy Harvesting (IND05)	5.63	6.00	2.00	2.72	2.00	3.00	2.91	10
Mobility & Transportation (MT)								
Smart Parking Guidance (IND06)	4.56	5.00	3.00	1.94	1.00	1.00	2.63	6
Public Transport Optimization (IND07)	4.91	5.00	2.00	2.16	2.00	1.00	2.75	8
Smart Learning (SL)								
Class attendance management (IND08)	4.87	5.00	2.00	2.08	2.00	1.00	2.79	9
Automatic Phone Control in Classrooms (IND09)	4.51	5.00	3.00	1.85	1.00	1.00	2.66	7
Class Activity Capture & Sharing (IND10)	4.87	5.00	2.00	2.83	2.00	3.00	2.04	5
Remote Library Resource Retrieval (IND11)	5.67	6.00	2.00	4.35	4.00	1.00	1.31	2
Campus Facilities & Services (FS)								
Smart Building Access & Reservations (IND12)	5.58	6.00	1.00	4.56	5.00	1.25	1.03	1
Personalized Activity Reminders (IND13)	4.92	5.00	2.00	3.28	3.00	3.25	1.64	4
Average	**5.17**	**5.42**	**1.85**	**2.79**	**2.38**	**1.65**	**2.39**	**--**

Fig. 3 presents the distributions of Importance and Performance ratings across all indicators. As shown in the blue-colored diagram, Importance ratings are consistently high and tightly clustered,

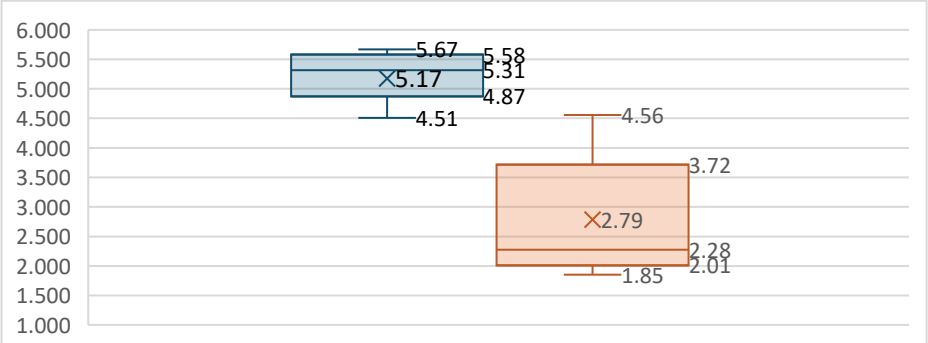


Fig 3 Importance and Performance boxplots

ranging from 4.51 to 5.67 with a mean of 5.17. The narrow interquartile range (IQR = 0.71) and median value indicate strong consensus among respondents, confirming that the selected indicators represent aspects widely perceived as essential to smart campus quality and functionality.

In contrast, Performance ratings are markedly lower and more dispersed, positioned on the orange-colored diagram. Scores range from 1.85 to 4.56, with a mean of 2.79 and a substantially wider IQR (1.71). The median performance score (2.28) lies closer to the lower quartile, indicating that many respondents perceive current implementation levels of smart campus as limited. The greater dispersion and longer upper whisker suggest that while some smart campus dimensions perform relatively well, these are not uniformly experienced across the campus. These contrasting results reveal a systematic mismatch between user expectations and perceived performance/delivery. From a formative assessment perspective, this pattern signals not failure, but unrealized potential, indicating that smart campus concepts are well understood and valued, yet not consistently translated into tangible implementations/outcomes.

4.3 Domain-Level Importance–Performance Gaps

Table 3 presents the results of the Importance-Performance Analysis as well as Cronbach's alpha test at the smart campus domains level. Domain-level analysis reveals uniformly high Importance scores across all four smart campus dimensions. Energy and Environment (EE) received the highest Importance rating (M = 5.47), followed by Facilities and Services (FS) (M = 5.25), Smart Learning (SL) (M = 4.98), and Mobility and Transportation (MT) (M = 4.74). In contrast, Performance scores are considerably lower, with Facilities & Services achieving the highest mean performance (M = 3.92) and Mobility & Transportation the lowest (M = 2.05). The Importance–Performance gap analysis further clarifies priority areas. The Energy & Environment domain exhibits the largest gap (2.83), closely followed by Mobility & Transportation (2.69), identifying these dimensions as the most critical areas for intervention. The Facilities & Services domain shows the smallest gap (1.33), suggesting a relatively mature level of implementation. These findings indicate that while service-oriented functions are more visible and better developed, environmentally responsive and mobility-related smart services and systems remain under-implemented relative to user expectations.

Table 3 Domain-level Importance-Performance Analysis results

Domain	Importance				Performance				Gap	
	Mean	Median	IQR	Cronbach's α	Mean	Median	IQR	Cronbach's α	I-P	Rank
EE	5.47	5.70	1.40	0.871	2.64	2.20	1.80	0.805	2.83	**4**
MT	4.74	5.00	2.50	0.728	2.05	1.50	1.00	0.861	2.69	**3**
SL	4.98	5.25	2.25	0.671	2.78	2.25	1.50	0.731	2.20	**2**
FS	5.25	5.50	1.50	0.347	3.92	4.00	2.25	0.411	1.33	**1**
Average	5.11	5.36	1.91	0.654	2.85	2.49	1.64	0.702	2.26	

Note: I-P: Importance-Performance

Cronbach's alpha was used to assess the internal consistency of indicators within each smart campus domain for both Importance and Performance ratings. Values of α greater than 0.70 were considered acceptable, indicating that the items within each domain consistently measured the same underlying construct. Table 3 shows that Cronbach's alpha for Importance and Performance is acceptable ($\alpha \geq 0.70$) for the Energy & Environment, and Mobility & Transportation domains. While the Smart Learning domain shows acceptable reliability for performance rating and marginally below acceptable for importance rating. Lower alpha values were found in the Campus Facilities & Services domains, reflecting the heterogeneous and multi-functional nature of their indicators. As the assessment is intended for formative and diagnostic purposes, Cronbach's alpha is treated as a descriptive measure rather than a strict inclusion criterion. However, it is indicative of the need to address this issue in the next /final summative assessment.

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4.4 Priority Classification for KFUPM Smart Campus based on IPA Analysis

The Importance–Performance Analysis (IPA) Matrix produces four action-priority quadrants, as shown in Fig. 4, which plots each indicator based on its mean Importance and Performance scores. Quadrant I ("Maintain the Excellent Work") includes IND04, IND11, and IND12, which show strong performance and small gaps, indicating that current efforts in access, library services, and utility automation should be maintained. Quadrant II ("Do Not Need Much Improvement") contains IND10 and IND13, which perform relatively well despite lower Importance, suggesting limited need for further investment. Quadrant III ("Low Priority") comprises mobility and classroom control indicators (IND06–IND09) with lower Importance and Performance, indicating limited current relevance to users. In contrast, environmental monitoring and responsive building systems (IND01, IND02, IND03, and IND05) fall into Quadrant IV ("Need Major Improvement"), combining high Importance with low Performance and representing the most critical areas for strategic intervention, particularly in improving environmental awareness, comfort, and building adaptability.

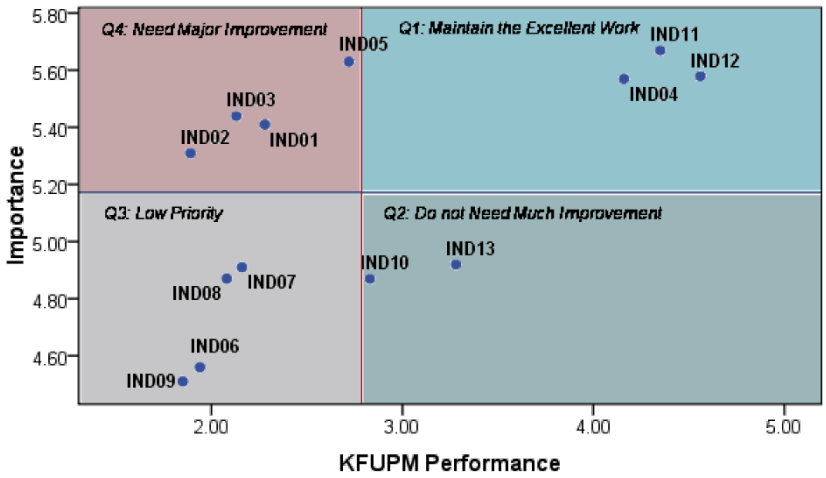


Fig 4 Result of Importance – Performance Analysis (IPA)

4.5 Strategic and Interpretive Implications

The results show that users assess KFUPM's smart campus performance mainly through its practical impact on daily experience rather than the mere presence of advanced technologies. While access and service-oriented applications are relatively mature, environmentally responsive systems and mobility solutions fall short of user expectations. From a planning perspective, the findings point to a clear strategy: maintain strong service delivery, prioritize investment in environmental monitoring and adaptive systems, and address mobility through user-centered solutions. The IPA results also confirm the relevance of the selected indicators and demonstrate the value of IPA as a formative assessment tool, as it identifies gaps between implementation and user priorities and supports adaptive, evidence-based decision-making during the ongoing smart campus transformation.

The key performance gaps in Quadrant IV, especially regarding indoor environmental quality (IND01) and occupancy-based HVAC control (IND03), indicate that KFUPM's smart campus development is primarily focused on digital services rather than on physical infrastructure. To address this, the university could implement a phased approach to integrating IoT sensors in high-traffic academic areas. For example, installing real-time CO2 and occupancy sensors connected directly to the Building Management System (BMS) would enable more responsive HVAC control.

As the study serves as a formative assessment, the findings are intended to support diagnostic interpretation rather than providing a summative rank against external institutions. From this perspective, the identified gaps in environmental monitoring do not indicate institutional failure, but rather point to specific, context-sensitive opportunities for strategic intervention. By focusing on these high-importance areas, the university can transition toward a 'living lab' model where the physical building's performance is responsive to user needs, directly supporting KFUPM's unique institutional transformation goals.

5. Conclusion

This study used a user-centered assessment, employing Importance–Performance Analysis, to evaluate KFUPM's smart campus. Defining the smart campus through relevant indicators showed that assessment scope and indicators can align with institutional goals, rather than relying on a complete framework. Findings indicate users value features related to environmental quality, learning, mobility, and services, but perceived performance is uneven, especially in Energy & Environment and Mobility domains. Access and service applications perform better and meet user expectations. Results suggest KFUPM should focus on improving environmental monitoring, indoor comfort, and adaptive systems while maintaining existing access and services. Methodologically, IPA proved useful as a formative tool, offering diagnostic insights into gaps and priorities to support decision-making. The alignment between gap analysis and IPA quadrants confirms the approach's robustness. The study highlights that formative assessment guides long-term, smart-campus transformation. Limitations include limited data, mainly from students and faculty; future research should expand the sample, include longitudinal data, incorporate stakeholder groups such as facility managers, and combine objective metrics with perception-based IPA to strengthen validity.

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Development of a Web-based Ranking Platform for Smart and Creative Cities (SCCRS): Towards the Emergence of Smart Creative Cities

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Abstract. In an era when cities around the world are striving to balance technological advancement with cultural sustainability, there is an urgent need for integrated tools to guide urban transformation. The present study proposes the *Smart Creative Cities Ranking System* (SCCRS), a web-based framework that merges smart city indicators with creative city dimensions to evaluate and promote urban development holistically and sustainably. It serves as a unified ranking model that combines digital infrastructure metrics with indicators from the cultural and creative industries, enabling cities to assess their performance and inform future planning. Innovation, culture, and digital systems assessment gaps exist in extant smart and creative city frameworks. To address this, the SCCRS model introduces three core thematic pillars: (i) digital-cultural infrastructure, (ii) creative tech ecosystems, and (iii) inclusive access. The findings reveal that effectively integrating smart technologies with cultural ecosystems tends to demonstrate stronger cultural participation, greater social inclusiveness, and improved quality of life. The SCCRS framework aligns closely with Saudi *Vision 2030*, supporting its goals of economic diversification, cultural development, and digital transformation. The model encourages cities to enhance digital infrastructure, foster arts-tech education, promote cultural entrepreneurship, and develop green cultural skills. Ultimately, the SCCRS provides urban planners and decision-makers with a practical and flexible tool to benchmark progress, shape inclusive policies, and stimulate innovation at the intersection of technology and creativity.

Introduction

In recent years, rapid urbanization and technological advancements have propelled the development of smart cities [1]. By 2050, it is estimated that nearly 70% of the world's population will reside in urban areas [2], necessitating smarter urban planning approaches to accommodate this growth. A key element in this transformation is "*smart people*", which emphasizes human creativity, social capital, and knowledge exchange as essential drivers of urban innovation [3]. This perspective has led to the emergence of smart creative cities, where the fusion of technology and human ingenuity fosters cultural and economic growth [4]. Research indicates that cities with robust creative industries tend to exhibit higher economic resilience, as creativity drives tourism, entrepreneurship, and cultural engagement [5].

The creative city paradigm underscores the importance of cultural industries and artistic innovation as economic engines [6]. The concept of the "*creative class*" argues that cities that attract creative professionals experience higher economic development [7]. The orange economy [8], captures the economic contributions of cultural and creative industries, accounting for over 6.1% of global GDP and employing nearly 50 million people worldwide [9]. However, despite the growing

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emphasis on creativity in urban development, extant studies lack a standardized framework for integrating smart technologies with creative economies to shape future cities.

A major challenge in urban planning and smart city development is the lack of a standardized ranking system to assess how well cities integrate technology and creativity to drive sustainable growth. While there are established indices for measuring smart city development, such as the IESE Cities in Motion Index and the Smart City Index, these frameworks primarily focus on infrastructure, governance, and digital connectivity. Similarly, cultural vibrancy is assessed through metrics such as the Global Creativity Index (GCI) [10] and UNESCO Creative Cities Network. However, no comprehensive index currently exists to measure how effectively a city integrates smart technology and creative industries. This research addresses this gap by developing a holistic framework and ranking system that evaluates the synergy between smart technologies and creative economies, offering insights for urban planners, policymakers, and researchers.

Given the increasing demand for urban innovation and sustainability, this study aims to bridge the knowledge gap by:

1. Developing a framework for integrating smart city technologies with creative urban economies.
2. Identifying key strategies for fostering creative industries within smart city ecosystems.
3. Proposing a ranking system that assesses cities based on their ability to merge technology and creativity to drive sustainable urban growth.

This research is theoretically and practically significant, contributing to the growing discourse on smart and sustainable cities. The study explores how human creativity can be systematically integrated into urban development to ensure that cities are not only technologically advanced but also culturally and economically dynamic. Aligned with Saudi Vision 2030, which prioritizes sustainable development, innovation, and cultural diversification, this study highlights how Saudi cities can leverage creative industries and digital transformation to drive inclusive growth. Saudi Arabia's cultural economy is projected to contribute $23 billion to GDP by 2030, driven by investments in tourism, heritage sites, and digital creativity. Saudi Arabia has launched major cultural initiatives, such as the Diriyah Gate Project and AlUla's cultural tourism strategy, which showcase the intersection of heritage, innovation, and sustainability. By introducing a ranking system for smart creative cities, this study provides decision-makers with an evidence-based tool to measure progress, enhance policy decisions, and foster best practices in sustainable urban development.

Literature Review

Research Gap: The Need for an Integrated Approach:

Existing ranking systems typically evaluate cities based either on their technological advancement or on the strength of their cultural and creative industries, but rarely consider how these two dimensions interact to drive innovation and urban development. This siloed approach results in a fragmented understanding of urban potential, making it difficult to assess cities that successfully integrate smart technologies with vibrant cultural ecosystems. While several global indices measure various aspects of technological progress and cultural creativity, each focuses on a specific domain, lacking a comprehensive perspective that unites both. Despite the growing convergence of technology and creativity in contemporary urban strategies, there remains no unified index that evaluates how well cities combine smart infrastructure with cultural and creative assets to foster inclusive growth and innovation.

This gap presents several challenges. Cities are currently without a comprehensive benchmarking tool to assess their performance in merging digital innovation with creative sector development. Policymakers and urban planners also lack comparative insights that could guide integrated strategies leveraging both technological advancement and cultural vitality. Furthermore,

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best practices from leading cities often remain under-documented, limiting the potential for international collaboration and knowledge exchange in the realm of smart creative urbanism.

In response to these gaps, there is a pressing need to develop a Smart Creative Cities Index—an evaluative framework designed to assess cities based on their ability to fuse technological capabilities with cultural and creative sectors. Such an index would include key metrics such as the availability of digital infrastructure that supports creative industries (for example, AI-driven design tools or blockchain-based art markets); the integration of cultural heritage into smart city planning through adaptive reuse enhanced by technology; the use of open data and digital platforms to foster artistic collaboration via virtual museums and digital creative hubs; and the role of technology in enhancing citizen engagement through interactive cultural experiences such as augmented reality exhibitions and tech-enabled public art. Establishing a Smart Creative Cities Index would enable urban stakeholders to better understand their strengths and weaknesses, identify areas for improvement, adopt transferable best practices, and promote innovation through the productive synergy of technology and creativity.

In conclusion, the literature on smart cities, creative cities, and the orange economy highlights their individual contributions to urban development. However, a comprehensive framework that integrates these domains remains missing. This study seeks to fill this gap by developing an SCCRS, offering a structured methodology for assessing urban areas based on digital infrastructure, cultural vibrancy, and creative entrepreneurship.

Methodology

Fig. 1 illustrates the systematic process of indicator selection, integration logic, scoring architecture, and tool conceptualization.

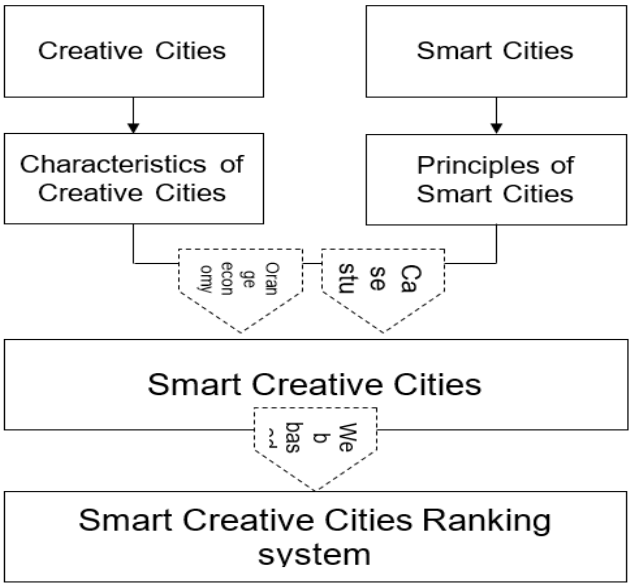


Fig. 1: SCCRS Methodology Components

Research Design:

The research design is structured into four interrelated phases. The first phase involves identifying relevant indicators from existing literature and global frameworks. In the second phase, these indicators are integrated into a cohesive framework that reflects the intersection of smart and creative city principles. The third phase focuses on constructing a scoring model to quantify and compare city performance based on the integrated indicators. The last phase involves conceptualizing a web-based tool that operationalizes the framework and provides a user-friendly platform for analysis, benchmarking, and strategic insight.

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Tool Conceptualization: Web-based Platform:

The selection process was guided by two primary domains: smart cities and creative cities. For the smart city component, indicators were drawn from globally recognized models, including the IESE Cities in Motion Index, the IMD Smart City Index, and the UN-Habitat Digital Cities framework. These sources informed the inclusion of key thematic areas, i.e., digital infrastructure, smart governance and mobility, environmental sustainability, and ICT-based urban services. On the creative cities side, the framework was shaped by indicators extracted from the UNESCO Creative Cities Network, the Inter-American Development Bank's Orange Economy framework, and contemporary urban cultural policy literature. This led to the inclusion of dimensions such as cultural participation, creative industries and employment, innovation ecosystems, public art and heritage, and cultural exports and events. A logic model was constructed to map how each indicator contributes to the overarching goal of SCC (see *Fig. 2*).

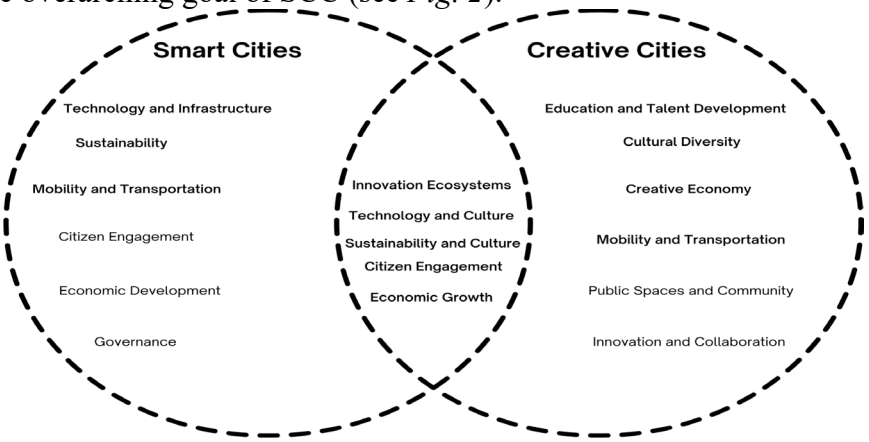


Fig. 2: Initial Integration Approach of SCCRS

The scoring methodology was developed as a multi-criteria decision analysis (MCDA) model, using a weighted aggregation approach. Each indicator was assigned a normalized score (0–100) and grouped under its respective domain. The weighting mechanism is as follows:

- Equal weighting was initially applied within each theme (e.g., Smart Governance = 20% of the Smart Cities domain).
- Expert-derived theoretical justification guided inter-domain weighting (e.g., Smart Cities = 50%, Creative Cities = 50%) to emphasize their synergy.

The backend is designed to accommodate open datasets and APIs from city data portals, global indices, and national statistics bureaus (e.g., GASTAT in Saudi Arabia).

Validation Strategy (Non-Empirical): While no survey or primary data collection was conducted in this phase, analytical validation was achieved through:

- Benchmarking against existing global indices (e.g., IESE CIMI, UNESCO UCCN reports).
- Case-based cross-checking with cities already labeled both creative and smart (e.g., Barcelona, Seoul).
- Scenario testing for hypothetical city profiles (low-tech high-culture vs. high-tech low-culture).

Future research is proposed to empirically test the model through participatory workshops or municipal partnerships.

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Local Context Adaptation: Saudi Arabia:

To ensure local relevance, the SCCRS framework was mapped against strategic objectives in Saudi Vision 2030, especially the Quality of Life Program and Digital Government Authority (DGA) initiatives. Key adaptations included:

- Indicators for Arabic digital content and traditional crafts digitization.
- KPIs from the Ministry of Culture and Smart City programs in Riyadh, NEOM, and AlUla.
- Inclusion of localized weights to reflect regional disparities.

Results

Platform Overview

While the platform core pillars and indicators are contained in Table 1, the functional modules are illustrated in *Fig. 3*.

Table 1: Proposed Smart and Creative Cities Indicators

Pillar	Indicator	Rationale
Digital-Cultural Infrastructure	% of public spaces with digital cultural installations	Bridges tech and art in urban design
Open Cultural Data	Availability of open-access cultural datasets	Encourages civic tech innovation and cultural transparency
Creative Tech Ecosystem	Number of creative-tech startups per 100,000 people	Merges smart economy and cultural economy metrics
Smart Mobility for Culture	% of cultural venues accessible by smart mobility	Integrates transport planning with access to culture
Inclusive Access	Digital inclusion programs for marginalized creatives	Promotes equity in creative economies through smart services
Green Cultural Practices	% of cultural festivals with sustainable certification	Links sustainability with cultural vitality
Real-Time Cultural Engagement	Use of mobile apps for cultural event navigation	Fosters engagement using real-time digital tools
Interdisciplinary Education	Number of programs linking tech and creative skills	Supports innovation through hybrid education

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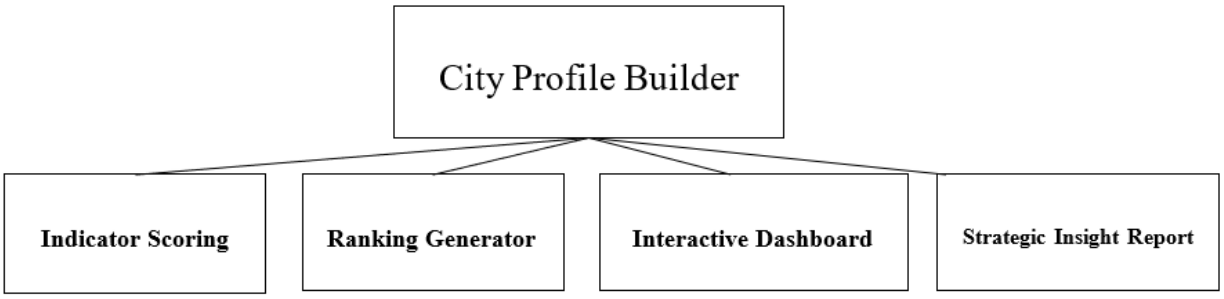


Fig. 3: Functional Modules of the SCCRS Platform

Key Results of the Platform Simulation

To test the platform's efficacy, a simulation was conducted using hypothetical and secondary data for five city profiles: two global cities (e.g., Barcelona, Singapore), two regional cities (e.g., Riyadh, Dubai), and one emerging creative hub (e.g., AlUla). The platform processed this data through its scoring engine, and several patterns emerged (see Table 2).

Table 2: Key Results of Platform Simulation

City	Key Strengths	Key Weaknesses	Remarks
Barcelona	• High creative participation • Strong public cultural engagement	Moderate performance in smart mobility	Represents a mature creative city with room to improve technological mobility integration
Singapore	• Leading in digital governance • Robust open data infrastructure	Low diversity in cultural offerings	Excels as a smart city, but is less inclusive of diverse cultural expressions
Riyadh	• Strong 5G infrastructure • Growing digital entrepreneurship ecosystem	• Weak grassroots cultural activities • Limited public art	Rapid digital development with a need for broader cultural accessibility
Dubai	• High innovation in tourism and event tech • Advanced digital services	Limited citizen-led cultural initiatives	Performs well in top-down creative initiatives, yet lacks community-based cultural programs
AlUla	• Strong heritage-based creative assets • Innovative eco-tourism practices	Small-scale limits tech infrastructure	Demonstrates the value of small cities through cultural uniqueness and sustainable innovation

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Barcelona achieved the highest scores in creative participation and public cultural engagement, although its performance in smart mobility was moderate. Singapore excelled in digital governance and open data infrastructure but exhibited relatively limited diversity in its cultural offerings. Riyadh demonstrated notable strengths in 5G infrastructure and digital entrepreneurship; however, it fell short in supporting grassroots cultural activities and public art accessibility. AlUla, despite its smaller scale, performed strongly in heritage-based creative assets and eco-tourism innovation, presenting a compelling case for the inclusion of smaller cities in smart creative city assessments. These simulation results validate the platform's capacity to capture nuanced urban realities and highlight its potential as a tool for informing context-specific urban development strategies.

Usability and Interface Feedback (Pilot Testing)

While the platform is in its pre-deployment stage, preliminary usability testing was conducted with academic researchers and urban planning practitioners. Key insights included: Users reported that the platform's dashboard offered ease of navigation, highlighting its intuitive design, clearly labeled tabs, and responsive visualizations. The customization potential of the tool was also positively received, as users valued the ability to adjust indicator weights, allowing the platform to adapt to varying governance models and local policy priorities. However, a common challenge identified was the limited availability of standardized data for certain indicators, such as cultural exports and digital inclusion metrics, particularly across different regions. To mitigate this issue, the platform provides data estimation guidelines and direct links to relevant open-access databases, enhancing its usability despite data disparities.

Local Application: Saudi Contextualization

A unique strength of the SCCRS platform lies in its adaptability to local priorities. In alignment with Saudi Vision 2030, the tool was adapted to include specific indicators such as:

- Number of digitized heritage sites
- Investment in Arabic digital media startups
- Availability of cultural incubators and creative hubs
- Digital infrastructure

These additions enabled more accurate assessments for Saudi cities, positioning the SCCRS as both a global benchmarking tool and a local development guide. In particular, cities like NEOM and The Line were modeled using futuristic, smart-creative hybrid profiles, showcasing high digital readiness and projected cultural innovation zones.

Discussion

The study has provided an affirmative answer to the intense necessity for a unified framework to integrate smart technologies with the creative industries in favor of supporting urban innovation and sustainability. On the basis of the literature and the opinions collected among the stakeholders, the SCCRS was formulated and tested. The findings presented that high-performance cities in terms of citizen satisfaction, inclusiveness, and resilience are most characterized by high digital infrastructure and cultural sectors.

The literature highlighted the disintegration of the ranking systems that exist. An example of this is the IESE Cities in Motion Index. IESE Cities evaluates smart infrastructure, whereas the UNESCO Creative Cities Network only evaluates cultural contributions. Nonetheless, neither of them is integrated; the gap was filled by findings, as it combined the two paradigms into one. Factors like the availability of public Wi-Fi, jobs in the creative industry, and the availability of smart mobility to cultural assets. These were found to be key variables in terms of their ability to measure the performance of smart creative cities. This has been the premise of [7] that the

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innovative component of our society is the creative class, and that cities that attract and subsequently retain creative professionals are more competitive.

Respondents stated that the notion of accessibility of online cultural platforms and similar mobile-based tools of navigation within the urban space made them tend to navigate within urban environments. These results corroborate [3], who stated that digital platforms make civic engagement more effective and access to culture democratic. The fact that digital literacy is positively connected with cultural vibrancy means that, in investing in smart cities, there is a need to focus on both human capital and technology growth.

In addition, the study emphasized interdisciplinary education and inclusive involvement. Innovation potential was scored higher in cities that scored higher in the tech and arts education combination programs. This is in line with what the European Commission focused on, its emphasis on multi-sectoral partnership in the orange economy. Cultural events that included practices associated with sustainability. This is consistent with the conclusions made by [11] on the environmental responsibilities of contemporary festivals. In that way, the SCCRS introduces the concept of green cultural practices within its analysis framework as a bridge between smart strategies and creative ones with the concept of sustainability.

Remarkably, there were regional differences as evidenced by the study. Respondents in Saudi Arabia, where digital infrastructure is being developed at a rapid pace under the leadership of Vision 2030. They were more hopeful of a synergy between culture and technology when compared to those in response to more peripheral digitally oriented backgrounds. Such a regional setting outlines why adaptation of the SCCRS model to regional specifications is essential in terms of local needs and local policy environments. Although it is strong, this research study also revealed some limitations. Conceptually, the SCCRS model is sound, but it has yet to be tested in real-life within the urban context. As literature suggests, pilot testing of the indicators in a real-world setting is required to adjust the indicator weightings and obtain contextual validity [12]. Also, disaggregation was not done in the study based on demographic factors like age or gender, and future studies are required to fill the gaps so that the SCCRS is as inclusive as possible.

The findings of the research on innovation and creativity cities in Saudi Arabia showcase an impressive advancement in various aspects, such as smart governance, mobility, environmental sustainability, building cultural infrastructure, etc. There are challenges, such as on digital inclusion, on green urban practices, and on the convergence between technology and creative sectors.

One of the most important results of the study is the acceptance of smart governance, especially in e-participation and digital services. The smart governance indicators were highly rated by the participants, indicating that Saudi Arabia had been successful in using the digital tools for citizen engagement. This finding is in line with the study of [13], who highlight the significance of e-participation and transparency in the functioning of smart cities worldwide. Their research reveals that promoting ICTs as a tool for public participation enhances the effectiveness of governance, as well as generating trust among the local community. But with Saudi Arabia receiving top scores on governance, these results continue to drive home the point that more effort is still needed to make sure all citizens, and in particular the most marginalized, are included digitally. As [14] highlighted, smart governance tools were increasingly implemented. However, it reported that inclusivity was still a major issue in several parts of the world, in some areas also due to a lack of digital literacy. For this reason, Saudi Arabia should work on narrowing the digital divide so that members in each of these groups can access these initiatives.

Regarding smart mobility, the results suggested an ambiguous receptivity towards smart mobility services such as RTPT and shared mobility. The fact that real-time public transport systems are one of the most efficient and effective means of mobility. This observation is consistent with [15], who found that smart mobility services were being adopted, with gender

differences observed in adoption patterns. Although Saudi Arabia is gradually integrating these services countrywide, there is an opportunity to increase the uptake of EV and shared mobility services.

The study highlighted that Saudi Arabia has achieved significant cultural infrastructure, with people scoring the level of museums, theaters, and galleries highly. Creative exports were also viewed positively, as one could tell from the importance attributed to cultural and creative sectors in the urban ecosystem. This result is in line with [13] that cultural infrastructure is fundamental to the emergence of creative and vibrant cities. They emphasize that cultural life and cultural spaces are also a fundamental issue of the smart city design. [13] further justify this perspective by emphasizing the importance of interdisciplinary educational programs fusing technology and the arts. Despite the creative economy of Saudi Arabia having potential, the usage of digital technology in cultural spaces is at an embryonic stage. The results of the present study highlighted that AR/VR tools and digital ticketing platforms were not massively used. It indicates that there is a lot of space for technological innovation in the cultural field.

Concerning the smart environment, the moderate ranking for CO_2 emissions and smart waste management systems in Saudi Arabia under a-share encourages more concern in this category. The environmental dimension of smart cities is underdeveloped compared to other sectors, as pointed out by [13], who argue that solutions to governance and mobility in cities are increasingly dominant in technological discourses, environmental sustainability continues as an enduring challenge. [14] stress the necessity of embedding green solutions into urban structure with special attention to smart waste and energy management systems. The moderate scores of environmental indicators in this study indicate difficulty in overcoming the challenges in this area, emphasizing the need for the development of a green culture policy and sustainable transportation solutions that are not only CO_2 stanchers but also enrich the urban environment.

Conclusion

The study proposed a new concept of the SCCRS. It is a new method of integrating digital infrastructure and the cultural and creative industries to evaluate and improve urban development. The results revealed significant advantages to having smart technologies complemented by the creative economies when enabling city vibrancy, inclusiveness, and sustainable development. Findings proved the importance of indicators such as digital access, cultural participation, interdisciplinary education, and real-time cultural engagement as the factors that greatly contribute to creative city settings. As an efficient and effective tool to measure the performance of cities and find the strategic areas to upgrade them, the SCCRS offers policymakers the capability to review cities and find areas of potentially great improvement. Both in terms of supporting creative startups, as well as integrating arts with smart infrastructure, and increasing the level of participation in digital platforms.

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The Role of Public Spaces in Shaping a Sense of Place: Insights from a Systematic Literature Review

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Keywords: Public Spaces, Sense of Belonging, Genius Loci, Sense of Place, Place Making

Abstract. This systematic literature review investigates the role of public spaces in shaping a sense of place, a concept encompassing individual perceptions, attachments, and identities tied to specific locations. By synthesizing insights from 47 peer-reviewed studies, the research highlights how public spaces parks, plazas, streets, and communal areas serve as critical venues for fostering social cohesion, cultural identity, and emotional well-being. Key factors influencing the sense of place include design attributes (e.g., accessibility, landscaping, and visual harmony), sensory experiences, cultural relevance, and community participation. The findings emphasize the diverse roles of public spaces in supporting activities such as socializing, leisure, and cultural performances, while addressing the needs of varied demographic and socioeconomic groups. This review provides valuable guidance for urban planners, policymakers, and designers to create inclusive, sustainable, and meaningful public spaces that reflect the unique character of communities and enhance urban vitality.

1. Introduction

The concept of a "sense of place" in public spaces holds growing significance in urban planning, sociology, and psychology, as cities seek to cultivate environments that foster community connection and personal attachment. Public spaces parks, plazas, streets, and other communal areas serve as fundamental elements in shaping this sense of place, which is often defined as an individual's perception, attachment, and identity associated with specific locations [1], [2]. These spaces are not merely physical constructs but are imbued with social, cultural, and symbolic meanings that collectively influence how people relate to and interact within them. As urban areas face increasing challenges related to population density, cultural diversity, and rapid urbanization, understanding the dynamics of public spaces in fostering a sense of place is essential for creating vibrant, inclusive, and resilient communities.

Research has demonstrated that public spaces play an integral role in shaping the social fabric of communities by providing arenas for interaction, expression, and the exchange of ideas [3]. Public open spaces such as community parks are vital urban components that foster social cohesion, encourage outdoor activity, and enhance collective well-being [4]. These communal areas often become hubs of cultural identity and memory, where the experiences of past generations merge with the present, enhancing the emotional connection residents feel toward their cities [5]. Moreover, a well-designed public space can evoke feelings of security, belonging, and personal identity, contributing to the overall well-being of individuals [6], [7].

The sense of place is further influenced by environmental and sensory experiences, as elements such as auditory and visual aesthetics impact people's engagement with their surroundings [8].

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Understanding how sensory dimensions contribute to a sense of place allows urban designers to tailor public spaces that foster comfort, enjoyment, and relaxation [9].

Urban design literature suggests that the concept of sense of place has shifted beyond mere attachment to physical spaces, encompassing a broader appreciation for the cultural, historical, and ecological contexts within which these spaces exist [10]. For example, Shamai and Ilatov [11] argue that location alone is insufficient to create a meaningful sense of place; rather, it is the integration of community values, personal involvement, and historical relevance that transforms a space into a "place." The concept of affordances, where different age groups or cultural backgrounds perceive and utilize the same physical features in unique ways, further illustrates the multiplicity of experiences public spaces offer. As cities continue to evolve, the role of public spaces in fostering a sense of place becomes increasingly significant in maintaining social cohesion and urban vitality [12].

2. Methodology

The systematic literature review (SLR) was guided by four research questions addressing the relationships between activities, physical attributes, satisfaction levels, demographic factors, and sense-of-place formation in open public spaces. A structured search was conducted in Scopus and Google Scholar to ensure comprehensive coverage of peer-reviewed literature. The search was performed in August 2024 and included publications available up to that date. Boolean operators were used to combine two search strings:

String 1: (“public space*” OR “outdoor space*” OR “open space*” OR “communal space*”)

String 2: (“place identity” OR “sense of place” OR “sense of belonging” OR “genius loci” OR “place attachment”).

The search yielded 552 records (Scopus n = 539; Google Scholar n = 13). Prior to screening, 12 duplicate records were removed. Automated database filters were then applied to exclude non-English and non-journal publications, including conference proceedings, book chapters, and review articles (n = 165), and subject-area refinement excluded records outside architecture and urban studies (n = 140). After these removal steps, 235 records remained for title and abstract screening. Title and abstract screening resulted in the exclusion of 147 records that did not align with the conceptual focus on open public spaces and sense-of-place constructs, leaving 88 reports for full-text assessment. Full-text evaluation led to the exclusion of 41 studies for the following reasons: absence of explicit focus on open public spaces (n = 21), unrelated to architecture or urban sectors (n = 5), and unrelated study scope (n = 15). A final set of 47 studies met all eligibility criteria and were included in the qualitative synthesis. The review process followed the PRISMA 2020 framework, and inclusion/exclusion counts at each stage are illustrated in Figure 1.

Screening and data extraction were conducted by the primary author using predefined eligibility criteria applied consistently across all stages. Each of the 47 included articles was treated as a single unit of analysis. Quantitative comparisons therefore reflect aggregated descriptive patterns across studies. Table 1 presents a summary of the 47 selected studies, outlining their authorship, publication year, geographical context, methodological approach, and key findings related to the role of public spaces in shaping sense of place.

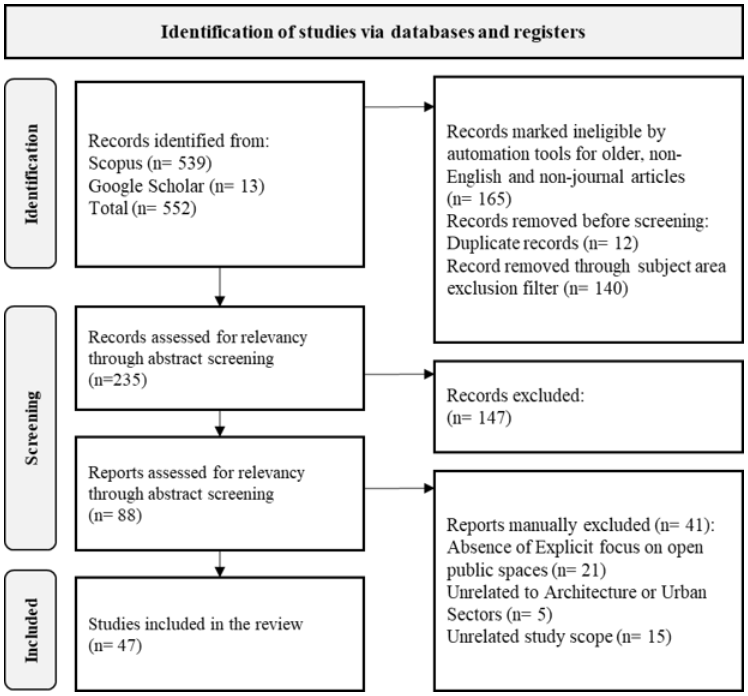


Figure 1 PRISMA flow diagram created by the authors

3. Results and Findings

Publication per country: The geographical distribution of publications demonstrates a marked concentration of research activity within Asia and Oceania, as evidenced in Table 2. Countries such as Indonesia (11%) and Australia (11%) account for a substantial proportion of contributions, followed by India (9%), Iran (6%), and Japan (4%), indicating a relatively cohesive regional engagement in sense-of-place scholarship. While the United States (13%) and the United Kingdom (9%) lead contributions in North America and Europe respectively, the European output appears more fragmented across multiple national contexts. As reflected in Table 2, the pattern suggests that Asia and Oceania exhibit a more consolidated research presence in comparison to the comparatively dispersed European contributions.

Publication by year: The temporal distribution of publications further reveals a dynamic trajectory over the period 2013–2024, as illustrated in Table 3. The data indicate noticeable fluctuations, including a decline around 2021, followed by a significant upward trend culminating in a publication peak in 2024. This pattern, shown in Table 3, suggests a resurgence of academic interest in sense-of-place research within open public spaces, highlighting its increasing relevance in contemporary urban discourse.

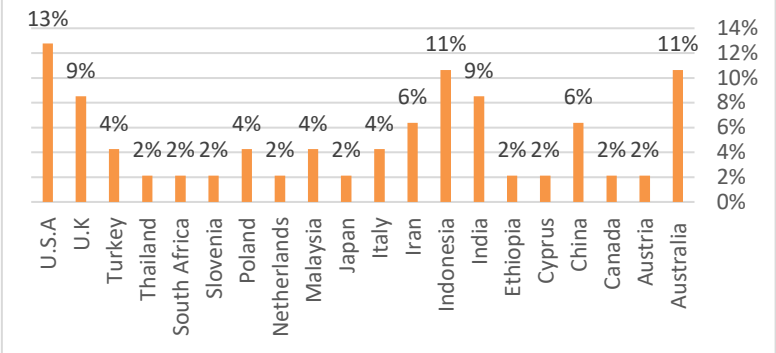


Figure 2 Publication by Country

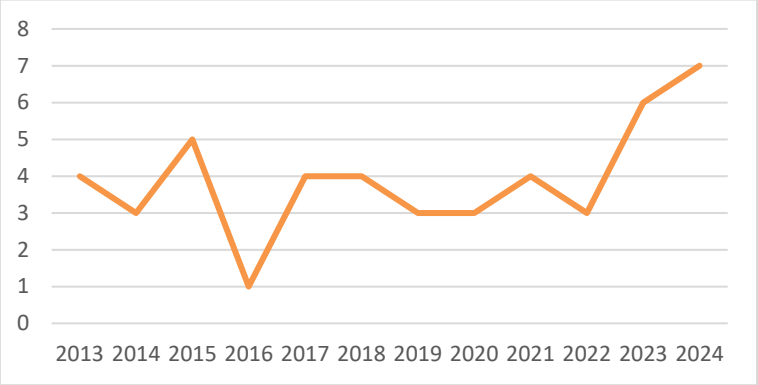


Figure 3 Publication by Year

Table 1 List of Selected Studies and Paper ID

ID	Author	Year	Context	Methods	Paper Finding
1	F. S. Hoseini & M. Mokhtari [13]	2013	Iran	Questionnaire survey & field observation.	Quality of public spaces like Tarbiat Street in Tabriz increases social life and place attachment, fostering community involvement.
2	B. Mohapatra & A. R. Mohamed [14]	2013	India	Structured questionnaire & factor analysis.	Attachment to neighborhood parks in Bhubaneswar enhances community participation in management.
3	C. Rishbeth & M. Powell [15]	2013	United Kingdom	Walking audio recordings & narrative analysis.	Migrants' attachment to places is influenced by memory and continuity in unfamiliar environments.
4	M. Garrido[16]	2013	Philippines	Participant observation & in-depth interviews.	In Metro Manila, segregation between social classes is perpetuated through symbolic practices in public spaces.
5	R. Amirjani & E. Zarghami[17]	2014	Iran	Descriptive analysis & library research.	Designing urban public spaces based on citizen satisfaction enhances place attachment and community engagement.
6	M. Sepe [18]	2014	Italy	PlaceMaker method & case studies.	Preserving place identity through urban design enhances the sustainability of public spaces.
7	J. K. Swim, S. J. Zawadzki, J. L. Cundiff & B. Lord [19]	2014	United States	Survey questionnaire & mediation analysis.	Strong environmental identity fosters community support for the preservation of open spaces.
8	S. Pancholi, T. Yigitcanlar & M. Guaralda [20]	2015	Australia	Case study & site observation.	Public spaces in innovation districts like Kelvin Grove Urban Village help foster a sense of belonging, but are dependent on social and economic flows.
9	D. Mantey [21]	2015	Poland	Survey questionnaire.	Public spaces positively influence place attachment and social relationships in urban housing estates like Zacisze.
10	N. Marshall & K. Bishop [22]	2015	Australia	Literature Review	Placemaking initiatives may create place attachment but require interdisciplinary research to understand their broader impact.
11	B. Karsono, Deni, Nurhaiza & M. Iqbal [23]	2015	Malaysia	Questionnaire survey & interview.	The Malacca Riverfront Promenade fosters place attachment through comfort and security, enhancing social interaction.
12	K. Main & G. F. Sandoval [24]	2015	United States	Case study & interviews.	Immigrants in Los Angeles transform public spaces to reflect their identities, creating spaces of belonging.
13	B. Karsono, S. S. Indira & Deni [25]	2016	Malaysia	Questionnaire survey & observation.	Unique and secure environments in public spaces are critical for fostering strong place attachment.
14	M. Muminovic [26]	2017	Australia	Case study & discourse analysis.	Sustainable urban regeneration in Canberra enhances place identity through public space revitalization.
15	A. Alzahrani, K. Borsi & D. Jarman [27]	2017	United Kingdom	Case study & surveys.	Comparative study of two London squares shows placemaking enhances social value through community engagement.
16	S. Polat & N. Dostoglu [28]	2016	Turkey	Case study & interviews.	Civic consciousness and urban memory are supported by public open spaces, crucial for sustaining urban identity.
17	E. E. Toolis [29]	2017	United States	Theoretical analysis.	Critical placemaking helps reclaim public spaces, fostering dialogue and inclusivity.

18	A. Addas & C. Rishbeth [30]	2018	Saudi Arabia	Case study & interviews.	Migrants and locals in Jeddah use public spaces for socializing and place attachment, with differences based on displacement experiences
19	M. Ziyaee [31]	2018`	Italy	Case study & matrix analysis.	Urban identity is shaped by cultural landscapes, and these should be preserved during urban regeneration.
20	N. Ujang, M. Kozlowski & S. Maulan [32]	2018	Malaysia	Interviews & field observation.	Place attachment strengthens social interaction in public spaces, creating meaningful places.
21	R. Newell & R. Canessa [33]	2018	Canada	Survey questionnaire & regression analysis.	Geovisualizations enhance understanding of place relationships, aiding in community planning.
22	J. Piyapong, R. Riruengrong, I. Wipawee, N. Siriphan & A. Passanan [34]	2019	Thailand	Questionnaire survey & in-depth interviews.	Public spaces in coastal communities strengthen community relations and sense of place.
23	P. J. Ellery & J. Ellery [35]	2019	Australia	Theoretical analysis.	Placemaking strategies foster a stronger sense of community and place.
24	D. G. Özkan & S. Yilmaz [36]	2019	Turkey	Questionnaire survey & factor analysis.	Social and physical factors in Trabzon urban squares significantly increase place attachment.
25	Z. Goosen & E. J. Cilliers [37]	2020	South Africa	Qualitative enquiry & theoretical framework development.	Third places play a key role in enhancing social sustainability and community identity.
26	J. Hardi, L. S. Arifin & Y. B. Dwisusanto [38]	2020	Indonesia	In-depth interviews & grounded theory analysis.	Lack of emotional attachment limits communal space use in low-cost flats in Jakarta.
27	V. Žlender & S. Gemin [39]	2020	Slovenia	Survey questionnaire & structural equation modelling.	Strong sense of place towards peri-urban green spaces promotes sustainable behavior in Ljubljana and Edinburgh.
28	S. Sun & Y. Yu [40]	2021	China	Questionnaire survey & structural equation modelling.	Deji Plaza in Nanjing enhances city image but lacks local identity, affecting placeness negatively.
29	Y. Song, R. Wang, J. Fernandez & D. Li [41]	2021	United States	Online review mining & LDA topic modelling.	Machine learning shows diverse visitor experiences on the Las Vegas Strip, with positive overall perceptions of public spaces.
30	A. Zahid & D. Misirlisoy [42]	2021	Pakistan	Questionnaire survey & Likert scale analysis.	Walled City of Lahore demonstrates strong identity and memory contributing to urban place attachment.
31	K. Solarek & E. Grochowska [43]	2021	Poland	Historical analysis & case study evaluation.	The urban design of Chiba City, Japan, enhances place attachment and emotional value through experiential recognition.
32	T. Zhang, J. Liu, H. Chen & M. K. Ng [44]	2022	China	Questionnaire survey & structural equation modelling.	Communal spaces in high-rise housing in Guangzhou and Hong Kong improve mental health through enhanced sense of place.
33	C. Kim & D. Kwak [45]	2022	Japan	Questionnaire survey & factor analysis.	Urban design projects in Chiba City positively affect emotional values and experiential recognition of place.
34	T. Ashfina, P. Garg & P. S. Chani [46]	2022	India	Questionnaire survey & statistical analysis.	Traditional public spaces in Kerala sustain place identity and foster social cohesion in urban settings.
35	M. Pazhuhan (Panahandeh Khah), H. Azadi, D. Lopez-Carr, J. Barbir, I. Shahzadi & C. Fürst [47]	2023	Iran	Questionnaire survey & descriptive statistical analysis.	Small residential squares in Tehran enhance social sustainability and sense of place more effectively than larger squares.
36	I. Asmal & R. Latief [48]	2023	Indonesia	Socio-spatial analysis & behavioral mapping.	Family communal spaces in coastal settlements in Indonesia strengthen social cohesion and community resilience.
37	S. P. Dash & N. L. Thilagam [49]	2023	India	Qualitative literature review.	Creative placemaking enhances social interaction and emotional connection in public spaces, fostering social cohesion.
38	S. P. Dash & N. L. Thilagam[50]	2023	India	Qualitative literature review.	Creative placemaking fosters social cohesion through community engagement and emotional attachment.

39	P. Pourbahador & M. Brinkhuijsen [51]	2023	Netherlands	Policy analysis & expert interviews.	Municipal strategies in Amsterdam protect the sense of place through heritage management but face challenges from tourism pressures.
40	T. Mukwidigwi, M. Naidu, S. Govender & G. Membele [52]	2023	South Africa	Participatory GIS & semi-structured interviews.	Monuments in Durban and Chatsworth significantly influence identity formation and memory-making in public spaces.
41	G. S. Duden, J. Reiter, C. Bauer, C. Haslinger, M. Mroz & A. Rohmann [53]	2024	Germany	Go-along interviews & thematic analysis.	Urban spaces in Germany influence migrant identity and belonging, depending on inclusivity and familiarity of the space.
42	J. T.-w. Ho [54]	2024	Hong Kong	Action research & semi-structured interviews.	Architectural restoration of a Hakka household in Hong Kong activates place identity through community engagement and restoration efforts.
43	N. Weerasuriya [55]	2024	Australia	Conceptual analysis.	Language plays a crucial role in youth belonging in Australia, especially for multilingual youth navigating cultural identities.
44	H. Ramkissoon, R. Van Der Veen, A. Salaripour, Z. S. Reihani & A. Aflaki [56]	2024	Iran	Online survey & structural equation modelling.	Sensory experiences positively influence place attachment and civic participation in Rasht, Iran.
45	J. Zhang, Z. Zhang & Y. Liang [57]	2024	China	Questionnaire survey & structural equation modeling.	Accessibility significantly impacts place attachment, with satisfaction playing a mediating role in urban open spaces in Jiamusi, China.
46	M. Budruk, K. Andereck & M. Sampson [58]	2024	United States	Quantitative survey & confirmatory factor analysis.	Event recreationists exhibit stronger place attachment than dispersed recreationists, highlighting the social bonding aspect
47	X. Chen, M. H. Marzbali & A. Abdullah [59]	2024	China	Questionnaire survey & PLS-SEM analysis.	Urban park attractiveness enhances perceived safety and strengthens place identity, with time spent as a mediator.

Urban context of Public Spaces: The distribution of study contexts reveals a clear predominance of residential environments within the literature, with 17 studies (36%) categorized under this setting, as shown in Table 2. This concentration underscores the centrality of residential contexts in examining mechanisms of community interaction, social cohesion, and the development of place attachment. Commercial spaces constitute the second most represented category, accounting for 11 studies (23%), reflecting their dual role as economic engines and socially interactive urban nodes. Historical public spaces follow closely with 10 studies (21%), highlighting the scholarly emphasis on their significance in reinforcing cultural identity and sustaining collective memory. The remaining 9 studies (19%), as indicated in Table 2, encompass a range of diverse contexts, including mixed-use and multifunctional open spaces, suggesting that while alternative spatial typologies are acknowledged in the literature, they occupy a comparatively secondary position relative to residential settings.

Table 2 Urban context of Public Spaces

Urban Context of Public Spaces	Paper ID	Number of papers	Percentage
Residential	2,3,9,11,12,18,20,22,26,27,32,33,35,36,37, 38,45	17	36%
Commercial	4,5,8,14,15,21,28,29,39,42,43	11	23%
Historical*	1,6,10,16,17,19,23,30,34,40	10	21%
Others*	7,24,25,26,27,46,47,41,44	9	19%

Physical Attributes in Public Spaces: As illustrated in Table 3, landscaping emerges as the most prominently emphasized physical attribute, representing 26% of the reviewed studies and underscoring its pivotal role in enhancing aesthetic quality, environmental performance, and symbolic meaning. Empirical findings demonstrate that well-integrated greenery not only improves microclimatic conditions but also reinforces cultural identity, thereby strengthening user engagement and satisfaction within public spaces [40]. Accessibility accounts for 13% of the literature, emphasizing the importance of inclusive and well-connected urban environments. Elements such as pedestrian continuity, shaded walkways, and integration with public transportation systems are identified as essential factors in encouraging frequent visitation and facilitating social interaction, as evidenced in the Kuala Lumpur context [32]. Furthermore, fit with context (12%) and visual harmony (11%) collectively highlight the necessity of aligning public space design with local cultural, social, and architectural characteristics to ensure contextual relevance, functional longevity, and sustained usability.

Table 3 Physical Attributes in OPS

Physical Attributes of Public Spaces	Paper ID	Number of papers	Percentage
Furniture	1,3,5,6,8,13,24,28,35,37,39	11	8%
Lighting	5,6,19,11,14,17	6	4%
Cleanliness	6,11,16,18,19,37	6	4%
Shading Areas	1,5,22,27,	4	3%
Visual Harmony	1,3,5,6,10,21,24,28,34,40,33,45,47,42,44	15	11%
Accessibility*	1,4,11,12,19,20,24,25,27,28,29,31,35,37,39,41,42,44,45	19	13%
Facilities	2,7,15,20,22,26,28,29,32,33,34,35,41,44,45,46,44	14	10%
Fit with Context	4,9,13,19,23,27,28,29,30,31,33,34,39,40,41,42,46,	17	12%
Landscaping*	1,5,16,17,19,28,29,35,41,43,2,3,7,12,14,24,27,36,40,45,47,8,6 ,11,13,15,20,23,25,26,30,33,37,38,39,42,44,	37	26%
Acoustical Environment	6,17,25,36,44	5	4%

Activities performed in Public Spaces: As presented in Table 4, walking emerges as a dominant activity within open public spaces, accounting for 20.40% of the reviewed studies. Walking is strongly associated with improvements in urban quality of life, as it enhances accessibility, encourages physical activity, and facilitates social interaction. Empirical evidence suggests that pedestrian-oriented environments contribute to strengthening sense of place by promoting

community engagement, informal encounters, and overall urban vitality [13]. Cycling, represented in 14.20% of the studies, further emphasizes the function of public spaces in advancing sustainability and supporting healthy lifestyles. Research indicates that well-designed cycling infrastructure enhances spatial connectivity and encourages consistent use, effectively integrating mobility and recreational functions within urban public realms [23]. Socializing, identified in 22.40% of the studies, underscores the fundamental role of public spaces in fostering interpersonal relationships, reinforcing social cohesion, and sustaining collective urban life.

Table 4 Activities performed in OPS

Activities Performed in OPS	Paper ID	Number of papers	Percentage
Walking	1,3,4,5,6,9,10,11,18,31,27,21	10	20.40%
Cycling	8,7,6,27,11,21,5	7	14.20%
Socializing*	4,9,10,19,20,21,25,26,32,33,36	11	22.40%
Cultural performances	42,10,6,17,30,22	6	12.24%
Eating	9,7,19,13,4	5	10.20%
Leisure	18,27,33,47,26,22,9,12,17,29	10	20.40%

Overall Satisfaction in Public Spaces: Figure 4 indicates that 57% of users report high satisfaction with open public spaces, reflecting strong emotional connection and functional performance. Moderate satisfaction accounts for 36%, while only 7% report low satisfaction. These results suggest generally positive user perceptions and are consistent with established concepts of place identity, sense of belonging, and place attachment. For instance, Isa et al. [60] highlight that high-quality public spaces not only enhance user satisfaction but also strengthen place identity and belonging. This relationship is mediated by the physical and social qualities of the spaces, which create inclusive and engaging environments. Similarly, Saymanlier et al [61].

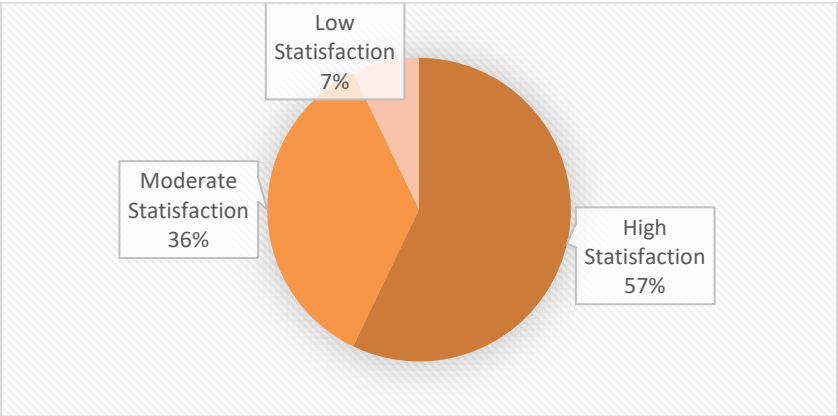


Figure 2 Overall Satisfaction

Impact of the Activities in OPS on the Sense of belonging Satisfaction: As shown in Table 5 presents a cross-tabulation of activities performed in open public spaces and their corresponding satisfaction levels (higher satisfaction, no significant difference, or lower satisfaction). A Chi-square test was conducted to evaluate the association between the type of activity and satisfaction level. A cross-tabulation analysis was conducted to explore the distributional relationship between types of activities performed in open public spaces and reported satisfaction levels. The analysis produced a Chi-square value of $\chi^2 = 21.71$ ($df = 12$, $p = 0.0408$). Given that the unit of analysis in this study is published research articles rather than independent individual respondents, these

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inferential statistics are interpreted as indicative of descriptive patterns rather than definitive causal relationships.

Table 5 The Impact of the Activities in OPS on the Sense of belonging Satisfaction

Activities performed in Open Public Spaces	Rating of Sense Of Belonging		
	High level	Moderate level	Low level
Walking	8	2	--
Cycling	5	2	--
Active Socializing	3	5	3
Passive Socializing (observation)	2	3	5
Cultural performances	1	2	3
Eating	4	--	1
Leisure	2	4	4

Conclusion

This review moves beyond identifying isolated design attributes by synthesizing the mechanisms through which open public spaces contribute to the formation of sense of place. The findings suggest that physical attributes do not operate independently; rather, they function as enabling conditions that structure social practices, which in turn generate meaning, attachment, and identity.

Mechanisms: From Design to Attachment

The synthesis indicates a sequential mechanism linking physical design attributes into social interaction patterns and into emotional attachment. For example, accessibility and pedestrian continuity increase the likelihood of walking and cycling activities. These activities facilitate repeated exposure, informal encounters, and passive observation, which strengthen familiarity and social recognition. Over time, these interactions contribute to emotional bonding and place attachment. Similarly, landscaping and visual harmony enhance environmental comfort and aesthetic coherence. This environmental quality encourages longer duration of stay and social clustering, thereby reinforcing shared experiences and collective memory formation. In this sense, design attributes act as structural affordances that enable social practices, while meaning and attachment emerge from the social processes occurring within these spatial frameworks.

Boundary Conditions and Contextual Variation

The review also highlights important boundary conditions. Cultural context influences how public spaces are interpreted and used. In societies with strong collective traditions, public spaces may serve as platforms for communal rituals and cultural performances, reinforcing identity at a group level. In contrast, in more individualistic or commercially driven contexts, spaces may prioritize consumption-oriented activities, potentially limiting deeper attachment formation. Governance structures and socioeconomic inequality further moderate outcomes. Lower-income groups appear to rely more heavily on public spaces for accessible leisure and social interaction, suggesting that equity in design and maintenance is critical for inclusive sense-of-place formation.

Implications for Urban Design and Management

For practitioners, the findings imply that designing for sense of place requires moving beyond aesthetic enhancement toward facilitating social practice. Urban designers should prioritize:

- Continuous pedestrian networks that promote walking-based interaction
- Flexible furniture and multipurpose facilities supporting active and passive socializing
- Context-sensitive landscaping aligned with cultural identity
- Inclusive accessibility ensuring equitable participation

Management strategies should also consider maintenance quality, lighting, and safety perceptions, as these influence sustained engagement and emotional security. Importantly, attachment cannot be engineered solely through symbolic design elements; it emerges through repeated and meaningful use. Therefore, programming and activation strategies (e.g., cultural events, community participation initiatives) are as critical as spatial configuration.

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Design Transformations of Shopping Centers in the Era of E-Commerce: A Behavioral Study in the City of Riyadh

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Abstract. Shopping centers in Riyadh are experiencing major transformations driven by the rapid expansion of e-commerce and online shopping along with the shifts of consumer behavior. This study examines how digital transformation influences the design of shopping centers and identifies factors that sustain the relevance of physical retail environments. Through a comparative analysis of three shopping typologies in Riyadh: Taibah Souq (1989), Granada Mall (2005), and Solitaire Complex (2024) representing traditional, modern, and contemporary phases of shopping center design, the research employs field observations, interviews, and surveys to analyze behavioral patterns and design characteristics. Survey results from 63 Riyadh residents reveal that while 73% prefer online shopping, 68.3% affirm continued value in physical mall visits for sensory, real-life experiences, product inspection, and social interaction. The analysis demonstrates an evolution from socially driven traditional markets to organized enclosed malls, culminating in experiential mixed-use complexes emphasizing leisure, social activities, and digital integration. Main attractions include environmental comfort, accessibility, dining and entertainment amenities, and spatial quality. Findings indicate that shopping has transformed from a transactional necessity into a holistic experiential activity. The study recommends enhancing social and sensory dimensions in retail design, improving indoor environmental quality, integrating technology, focusing on sensory-based retail categories, preserving cultural identity in traditional market redevelopment, and reconceptualizing retail spaces as experiential platforms. This research contributes insights into the physical-digital retail relationship in the Saudi context and provides design strategies for creating resilient shopping environments in the context of digital transformation, supporting the goals of sustainable urban development outlined in SDG 11 (Sustainable Cities and Communities).

Introduction

In recent years, shopping centers in the Kingdom of Saudi Arabia, particularly in Riyadh as the capital city, have undergone significant transformations in both form and function. They are no longer limited to their traditional role as sites of commercial exchange; rather, they have evolved into multifunctional urban environments that accommodate social, cultural, and recreational activities. However, these transformations face accelerating challenges resulting from the rapid growth of e-commerce and shifts in consumer behavior, which necessitate a re-evaluation of the role of shopping centers.

A report by Arabian Centers, (2021) [1] indicates that digital competition has become increasingly prominent in the Saudi market. This development has contributed to the widespread adoption of online shopping culture and a reduction in the market share of some physical retail stores. The report further reveals that approximately 42% of consumers in Saudi Arabia prefer online shopping when prices and services are comparable, highlighting the magnitude of the

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challenge facing shopping centers in attracting visitors and maintaining their engagement with physical retail environments. Despite this, operational data from the same report demonstrate a continued demand for major shopping centers, with visitor numbers increasing by 164% in the first quarter of the 2022 fiscal year compared to the previous year, while occupancy rates exceeded 92%. These indicators suggest a more complex relationship between digital and physical retail, raising critical questions about the nature of the experiences that continue to motivate consumers to visit shopping centers in the digital age.

Previous studies have highlighted the importance of spatial configuration and experiential qualities in shaping shopping behavior and social interaction, while recent research has examined the impact of e-commerce and digital technologies on retail environments. However, despite growing international scholarship, limited research has examined different retail typologies and consumer behavior within the Saudi context. This study addresses this gap by examining three shopping environments in Riyadh representing different stages in the evolution of retail architecture. The objective of this study is to investigate how digital transformation and changing consumer behavior influence the design and spatial experience of shopping centers in the city.

Research Problem

Shopping centers worldwide are experiencing accelerated structural transformations as a result of the rapid growth of e-commerce. This shift has led to a noticeable decline in the performance of traditional shopping centers, accompanied by increasing rates of retail closures and commercial vacancies, particularly in Western markets such as the United States. Statistics published by the U.S. Census Bureau (2020) indicate that e-commerce accounted for more than 16% of total retail sales in 2020, compared to less than 1% in 2001, while the number of Amazon users reached approximately 124 million in 2019. These developments have resulted in the closure of thousands of retail stores and the bankruptcy of several major retail chains, with projections suggesting that up to 25% of shopping malls may close within five years [2]. These transformations have coincided with a global shift toward the adaptive reuse of shopping center spaces through mixed-use redevelopment models that integrate residential, work, leisure, and social activities within flexible and integrated urban environments [3]. In the city of Riyadh, similar dynamics are evident with the expansion of e-commerce platforms alongside declining visitation rates to some physical retail markets. At the same time, large-scale development projects for future commercial spaces continue, exceeding 2.8 million square meters within the city alone according to Knight Frank 2024 report [4]. This context raises critical questions regarding the effective utilization of these spaces and their functional relevance amid digital transformation. It also presents a significant challenge for designers and real estate developers to redefine the functions of shopping centers in a manner that balances the demands of the digital economy with users' sensory and social experiences. This study seeks to address the following primary questions:

- How has digital transformation influenced the design of shopping centers in the city of Riyadh?
- What design and behavioral factors motivate shoppers to prefer visiting physical retail environments rather than relying on online shopping? and what aspects of the shopping experience cannot be replicated through online platforms?
- Is shopping primarily an experience or a necessity?

Literature Review

Previous research has highlighted the strong relationship between shopping behavior and the spatial and architectural configuration of retail environments. Studies comparing traditional markets and modern shopping malls consistently demonstrate that spatial form significantly influences movement patterns, social interaction, and the duration of visits. Cetin, Gadola, and

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Cheol (2011), in their study of shopping environments in Al Khobar, found that traditional markets exhibit higher pedestrian density, longer visit durations, slower movement, and stronger social interaction compared to malls, which tend to be more spatially segregated and less integrated with their surrounding urban context. [5] Similarly, Zorgane and Benidir (2022), in a case study of Constantine, Algeria, concluded that traditional markets retain their attractiveness due to affordability, product diversity, and proximity, while modern shopping malls primarily attract visitors through entertainment, comfort, and social gathering functions.[6] Other comparable behavioral distinctions were observed in Dubai, where Jahawi (2015) identified clear differences between Naif Souq and Dubai Mall, revealing that contemporary malls encourage longer stays and leisure-oriented behavior, while traditional markets remain preferred by older users due to accessibility, pricing, and social familiarity.[7] Other studies have focused on identifying the key factors influencing consumer choice of shopping centers. Kushwaha, Ubeja, and Chatterjee (2017) emphasized the importance of cleanliness, safety, interior design, accessibility, facilities, and environmental comfort in shaping consumer preferences, highlighting the growing relevance of experiential and spatial qualities.[8] At the urban and strategic level, several studies have examined the decline of shopping malls under the pressure of e-commerce and proposed adaptive reuse strategies. Cambre, Azhar, and Yucel (2023) documented increasing mall closures in the United States and argued that mixed-use redevelopment offers a viable approach to revitalizing declining retail spaces. This study emphasizes that experiential qualities, flexibility, and sensory engagement are critical to sustaining physical retail environments in the digital era.[2] More recently, digital transformation within shopping centers has gained scholarly attention. Iyer (2025) demonstrated that artificial intelligence applications in Dubai Mall significantly enhanced customer experience and operational efficiency, while also raising concerns related to privacy, ethics, and system integration.[9]

The reviewed studies show that the sustainability of shopping centers mainly depends on their ability to provide experiential, social, and culturally embedded environments that cannot be replicated through online platforms. They also highlight the growing importance of spatial configuration and experiential design in shaping consumer behavior within retail environments. However, these findings have largely been developed through international case studies, with limited investigation of shopping environments in Saudi cities. This highlights the need to examine how different retail typologies in Riyadh respond to changing consumer behavior and digital transformation.

Research Objectives

The study aims to identify the influential and attractive factors that motivate shoppers to visit shopping centers, whether traditional markets or modern malls, despite the widespread and rapidly growing adoption of e-commerce. The research seeks to analyze the physical shopping experience in the city of Riyadh by examining the aspects that cannot be substituted by digital shopping, while highlighting the underlying social and cultural dimensions embedded within this experience. In addition, the study focuses on tracing the transformations in shopping center design patterns in Riyadh through a comparative analysis of three models representing different temporal phases, examined across three main dimensions: consumer behavior, architectural design, and digital transformation.

Methodology

This research adopts *a field-based descriptive–analytical methodology*, aimed at exploring the relationship between shopping center design and shopper behavior in the city of Riyadh within the context of digital transformation. The study is conducted through the analysis of three distinct shopping environments and the direct collection of data from users. The research includes a

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comparative analysis of three shopping center models in Riyadh, each representing a different temporal stage and reflecting shifts in design approaches and the digital and economic context:

- Traditional Model: *Souq Taibah*, established in 1989
- Modern Model (Pre–E-Commerce Expansion): *Granada Mall*, established in 2005
- Contemporary Model (Post–E-Commerce Expansion): *Solitaire Mall*, established in 2024

These three models were selected based on several criteria:

1. Variation in their dates of establishment, which may reflect the influence of the digital environment on architectural design.
2. Their prominence and popularity among residents of Riyadh, as well as the diversity of commercial activities they offer.
3. Their strategic locations within the city's urban fabric.

To achieve research objectives, the study employs a mixed method approach combining qualitative and quantitative techniques, including comparative direct observation to analyze shopper behavior across the three selected models in relation to architectural and interior design elements, movement patterns, social interaction, and types of activities undertaken. This is accomplished through a questionnaire survey (n = 63) distributed electronically to a random sample of residents in Riyadh through digital media platforms. The questionnaire consisted of structured questions addressing visit motivations, attraction factors, frequency of visits, product preferences and perceptions of physical versus online shopping. The survey instrument was developed based on variables identified in previous retail environment and consumer behavior studies and was reviewed for clarity and relevance prior to distribution. In addition, semi-structured interviews were conducted with a purposive sample of female visitors (n = 12), identified as a primary user group of these environments. Each interview lasted approximately 10 minutes and was conducted in person within the shopping environments to explore user preferences, and responses to digital retail transformation. The collected qualitative data were analyzed through thematic coding to identify recurring patterns related to spatial experience, social interaction, and shopping motivations.

Case Studies Analysis

This study examines three shopping environments in Riyadh representing distinct phases in the evolution of retail architecture: a traditional market (Souq), a modern pre–e-commerce mall, and a contemporary post–e-commerce mixed-use complex.

1. Taibah Souq (1989) represents the traditional market typology, characterized by locally owned retail units and a radial spatial layout centered around a main plaza and mosque (Fig. 1&2)



Fig. 1Taibah Souq Layout, source: Riyadh maps

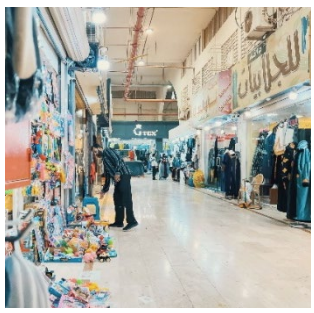


Fig. 2 Taibah souq, Source: Visit Saudi website



Fig. 3 Social interaction in Kiosks, source: Authors



Fig. 4 Umm Mut'eb's stall, source: Authors

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in addition to other carts and kiosks (Fig. 3). Field observations found Taibah Souq to exhibit a notably higher level of social interaction compared to the other case studies. This was evident through the active engagement between vendors and visitors, as sellers frequently attempted to attract customers through verbal invitations, while shoppers demonstrated a willingness to negotiate prices. This exchange contributes to a dynamic and socially driven shopping experience. However, the market lacks formal wayfinding and exhibits informal spatial practices, including the presence of vendors from productive families selling handmade products, occupying designated locations using simple display methods, such as stacked plastic crates (Fig. 4). In addition, parking congestion was observed, which may affect accessibility and overall user convenience.

2. Granada Mall (2005) reflects the modern enclosed shopping mall typology, developed prior to the widespread adoption of e-commerce while experiencing an expansion that occurred post e-commerce (Fig. 5&6). The mall combines international retail brands with dining and entertainment facilities, and it benefits from a direct pedestrian bridge connection to one of Riyadh Metro stations (Granada Station), significantly enhancing its accessibility, in addition to a sufficient amount of parking lots above and below ground. This connection was introduced as part of the mall's expansion project, which was completed in 2023. The expansion also added a cinema and a diversified retail mix, including international furniture brands. Observations indicated the lowest levels of social interaction among the other case studies, with visitors primarily engaging in individual movement and limited interaction confined to retail interiors (Fig. 7). The mall's recent expansion introduced wider corridors, natural daylight, interior screens, and additional leisure functions, reflecting a transition toward experience-oriented retail design. (Fig. 8)



Fig.5 Granada Mall layout, source: granadamall.info/



Fig. 6 Granada Mall main facade, source:



Fig. 7 Social interaction in the mall, source: Authors

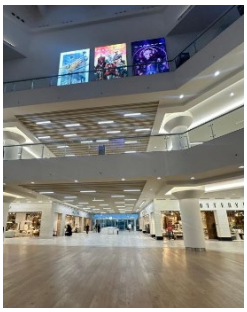


Fig. 8The expansion, source: Authors

A notable hybrid retail experience was observed at Granada Mall during the visit through a temporary pop-up exhibition for the online platform (Shein), where products were displayed for physical trial without direct purchase. This initiative illustrates the integration of digital retail platforms within physical shopping environments, highlighting emerging models that merge online and offline retail experiences to enhance user engagement. (Fig. 9, Fig. 10, Fig. 11).



Fig. 9 Pop-up in the central plaza of the mall, source: Authors



Fig. 10 Fitting rooms, source: Authors



Fig. 11 Experience of touching fabric, source: Authors

3. Solitaire Complex (2024) represents a contemporary post–e-commerce lifestyle destination integrating retail, dining, entertainment, wellness, and public spaces. The architectural design emphasizes open and flexible spaces, indoor–outdoor integration, landscape elements, and extensive digital technologies (Fig. 12, Fig. 13, Fig. 14). Retail façades employ distinctive visual strategies, and parking capacity was observed to be adequate. Field observations revealed high levels of social interaction between visitors, with most of them arriving in groups and primarily engaging in leisure and social activities rather than shopping activities. (Fig. 15)



Fig. 12 Solitaire layout, source: Benoy website



Fig. 13 Solitaire interior, source solitaireksa.com



Fig. 14 Solitaire exterior, source solitaireksa.com



Fig. 15 Social interaction & activities, source Authors

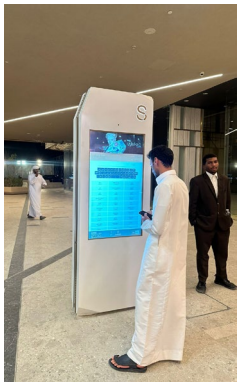


Fig. 16 Technology integration, source Authors



Fig. 17 Retail interactive facades, source Authors

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Table 1comparasion between the three case studies

	Taibah Souq	**Granada Mall**	**Solitaire Complex**
Typology	Traditional market	Enclosed shopping mall	Mixed-use lifestyle complex
Year Established	1989	2005	2024
Architectural Character	Informal, traditional outdoor environment	Organized, enclosed, indoor environment	Open, experiential, mix between indoor and outdoor
Social Interaction	High (vendor–shopper)	Low	High (visitor–visitor)
Retail Type	Local brands	International brands	Luxury / curated brands
Entertainment	None	Cinema, cafés, food court	Cinema, cafés, plazas, wellness
Digital Integration	None	Moderate	High
Photo			

Discussion and Results

The results indicate that shopping is no longer perceived solely as a functional necessity but rather as a holistic user experience, which explains the continued relevance of physical shopping environments despite the widespread adoption of e-commerce. When it comes to shopping as a purchasing activity, an electronic survey conducted among 63 residents of Riyadh (90.5% female) showed that 73% of participants prefer online shopping, while 27% favor physical shopping in markets and malls. In addition, 50% of respondents reported visiting shopping centers less than once per month, highlighting the growing dominance of digital retail and the challenge faced by physical malls.

Preferences varied by product type, with participants favoring online shopping for clothing, stationery, and electrical appliances, while preferring physical markets for furniture, jewelry, and groceries due to the need for direct inspection and quality assurance. The main motivations for visiting shopping centers were shopping, dining at cafés and restaurants, and walking, with many respondents indicating that mall visits are driven more by social and recreational purposes than by purchasing alone. The most influential design factors affecting mall visitation included effective air conditioning, availability of restaurants and cafés, cleanliness and organization, sufficient parking, and ease of movement within the space. Notably, 68.3% of participants stated that visiting shopping malls still holds value despite the availability of online shopping, citing sensory experience, social interaction, and the ability to examine products physically.

Findings from semi-structured interviews further support these results, revealing that while most participants regularly engage in online shopping, they continue to value physical shopping for immediacy, product assurance, social interaction, and leisure. Comparative analysis of the three case studies demonstrates a clear evolution in shopping center design, shifting from traditional, socially driven markets to organized enclosed malls, and finally to contemporary mixed-use developments that prioritize experience, leisure, and digital integration. These contemporary retail environments increasingly function as informal social gathering spaces, aligning with Oldenburg's concept of the "Third Place"[10] where spaces outside home and work support social interaction and leisure activities. This framework provides a useful lens for understanding how shopping centers have evolved from purely commercial facilities into experiential and socially oriented environments. This transformation also aligns with the principles of sustainable urban

development emphasized in the United Nations Sustainable Development Goal 11 (Sustainable Cities and Communities), which highlights the importance of inclusive, accessible, and socially vibrant urban spaces. In this context, shopping centers increasingly operate as multifunctional urban environments that support social interaction and public life within the contemporary city.

Recommendations

The findings of this study lead to several design-oriented recommendations for shopping centers in the context of digital transformation.

First, there is a need to enhance the experiential and social dimension in commercial design by creating a sensory and social experience that goes beyond mere selling. This can be achieved through designing comfortable and welcoming environments that include family seating areas, cafés and restaurants, wide walking paths, and open spaces that support interaction and activities. Second, greater attention should be given to the quality of the indoor environment, as the results showed that elements such as air conditioning, good lighting, and overall appearance are among the most influential factors in the decision to visit shopping malls. Accordingly, it is recommended that these elements be integrated carefully within interior design standards.

Third, the study highlights the importance of integrating technology intelligently within the architectural experience, such as interactive screens and smart wayfinding systems, in a way that supports user experience without overwhelming the physical space.

Fourth, it is recommended to allocate dedicated spaces for sensory-based retail, focusing on stores that cannot be easily replaced by digital shopping, such as furniture, jewelry, and perfumes. These product types encourage visitors to attend in person and engage in direct physical experience.

Fifth, the redevelopment of traditional markets without eliminating their identity is essential. As demonstrated in the case of Taibah Souq, popular markets hold cultural and social value. Therefore, redevelopment efforts should focus on improving organizational and service infrastructure, such as parking and shop regulation, while maintaining the popular and interactive character of these environments.

Finally, there is a need to rethink the concept of points of sale in light of digital transformation. Retail spaces can be redesigned to function as areas for display, experience, and interaction, while the actual purchasing process takes place through electronic platforms. This approach redefines the role of the market as a space for presentation and influence rather than direct selling, as observed in the online pop-up model in Granada Mall.

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Empark: A Prototype Framework for Climate-Adaptive and Comfort-Aware Urban Park Recommendation in Hot-Arid Cities

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Keywords: Smart Parks, Urban Park Recommendation, Hot-Arid Cities, Thermal Comfort, Soundscape, Accessibility, Sensory Comfort Index, Mental Health, Crowdsourced Feedback, Urban Informatics, Recommender Systems, Saudi Arabia

Abstract. Hot-arid urban environments are characterized by extreme temperatures, solar radiation, and other environmental stressors, which impact the usability of urban parks and limit the opportunities for outdoor recreational activities. The present paper introduces a mental health-informed, climate-adaptive prototype framework for urban park recommendation based on comfort factors, titled 'Empark.' The proposed framework combines five aspects of comfort: shade, noise, accessibility, greenery density, and sensory, to generate a 'Sensory Comfort Index' and 'Community Well-Being Score' based on user feedback and comments. The proposed framework is implemented as a React/TypeScript-based single-page web application with Google Maps integration and a lightweight Node/Express backend, and the scenario-based testing approach is applied to show the potential of the proposed framework to differentiate between parks based on the hot-arid environmental conditions and the comfort-based recommendation for parks. The proposed framework introduces a conceptual model, functional interface, a validation framework and a structured evaluation roadmap.

Introduction

Greenspaces in urban cities are increasingly being recognized as integral parts of the urban infrastructure. A body of literature suggests that greenspaces are essential in the urban landscape as they offer a means of psychological restoration, stress relief, and mitigation of environmental burdens such as heat, noise, and air quality. [1-3]. Moreover, recent research indicates that urban greenspaces can provide urban cooling and relief, especially within densely populated urban cities, as they moderate microclimate conditions [4-9].

Within Saudi Arabia, urban parks are greatly influenced by time, location, and environmental conditions. Extreme temperatures, solar intensity, and lack of shaded outdoor spaces can greatly reduce the utilization of urban parks, thus discouraging inhabitants from fully enjoying these spaces. Even with small greenspaces, such as pocket parks, these spaces can play important roles as microclimate refuge spaces, especially within densely populated urban cities [1, 8-11]. However, the effectiveness of these spaces depends on various comfort conditions, including perceived comfort, greenery, noise, and accessibility.

This paper presents a framework of a climate-adaptive, mental health-informed prototype of a decision support framework called Empark, which effectively translates various aspects of environmental comfort into an explainable recommendation for parks. The proposed framework

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is not offered as an "operational" tool but rather a methodological and interface prototype of a multi-factor approach to park selection, prioritizing the comfort needs of users. The proposed tool is likely to be useful for users who wish to locate parks matching their comfort criteria and planners who might benefit from the structured user feedback and insights into the performance of parks.

Empark differs from conventional tools for finding parks or rating parks, such as Google Maps, in the sense that the proposed framework is focused on multi-domain user comfort rather than the "most popular" or "closest" park. It incorporates various aspects of user comfort, such as thermal comfort, acoustic comfort, greenery, accessibility, and sensory comfort, using a single recommendation paradigm. Additionally, the proposed framework incorporates user opinions through the Sensory Comfort Index (SCI) and the Community Well-Being Score. This moves the conventional approach to a more holistic approach to climate-responsive urban park recommendations. The contributions of this paper are fourfold: an integrated comfort scoring model using evidence-informed environmental and user criteria; a user interface and interaction structure to effectively convey user comfort preferences; a prototype implementation of the proposed framework to demonstrate the effectiveness of the proposed criteria; and a structured approach to the proposed framework's validation through various tools, such as field sensing, user surveys, usability testing, and behavioral analysis [12-25].

Related Work and Research Gap

Several empirical studies have established the relationship between greenspace exposure and enhanced mental health, including reduced stress, depression, and anxiety [3, 26]. In addition, urban environmental and health research generally emphasizes the role of green infrastructure in creating a more healthy and resilient urban environment, including within the Saudi Arabian context of human-centered urban development [2, 26, 27]. At the same time, urban heat mitigation research also confirms the effectiveness of greenspaces, including parks and green-blue infrastructure, in reducing land surface temperature and improving outdoor thermal comfort, with their effectiveness depending on vegetation structure, spatial configuration, water features, and urban morphology [1, 28-30]. Moreover, recent research also indicates that park characteristics, including vegetation density and size, can influence cooling effectiveness, with remote sensing and machine learning techniques increasingly being employed to evaluate urban green infrastructure and their environmental effectiveness [31, 32]. Field and review research also indicates that even small greenspaces and shaded areas can provide meaningful localized relief, which is particularly important within hot and arid cities, with outdoor temperature strongly influencing urban spaces [1, 4-10, 33].

In terms of inclusion and accessibility, digital tools have been designed for specific issues related to public space usability. Some tools, such as Wheelmap and AccessNow, have proven the value of crowdsourcing public space accessibility information and spatial data (**Table 1**) [15, 34]. However, there is still no integration of thermal comfort, soundscape quality, or even sensory-environmental factors in these tools. On the other hand, there have been many studies on sensory-responsive environments that have emphasized the importance of reducing over stimuli in public spaces and designing supportive outdoor environments for neurodiverse individuals and other sensitive user groups [12, 13]. Platforms such as KultureCity and NeuroHub address the issue by identifying sensory-friendly venues (**Table 1**) [35, 36]. However, these platforms are still focused on venue certifications or user groups rather than climate-responsive public spaces.

Moreover, international guidelines on designing inclusive public spaces and child-friendly cities have emphasized the importance of addressing diverse user needs in public space planning and management [14, 37, 38]. Some of the advancements include urban noise monitoring, low-cost sensing technologies, and cyber-physical systems for environmental data collection [16-18, 39], as well as broader applications of IoT-based monitoring to domains such as air quality and urban environmental management [40]. These studies have proven the feasibility of multi-domain

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environmental sensing; location-based recommendation systems have also been proposed as a methodological basis for developing user decision support tools [41-43]. These systems are still focused on popularity, similarity, or spatiotemporal behavior rather than environmental comfort, inclusion, or public health-oriented recommendations.

In this context, the role of Empark is to function as an integrative prototype framework that seeks to incorporate different strands of research, which have thus far largely remained discrete from one another, such as the relationship between greenspace and mental health, urban microclimate/thermal relief, accessibility/sensory inclusion, smart environmental sensing, and recommendation logic [44-46]. Though various tools and studies have thus far offered important contributions to the understanding of the aforementioned dimensions, the current literature review suggests that the extant tools do not integrate climate-adaptive comfort, accessibility, greenspace, sensory inclusion, and user feedback within a single park-based recommendation tool [15, 42, 43]. The gap in the literature, therefore, is not the absence of tools but the absence of a tool for decision support, which seeks to integrate the aforementioned dimensions into user-based recommendations for parks while simultaneously offering planners actionable user feedback [34-36]. The tool seeks to address the gap through the Sensory Comfort Index (SCI), the Community Well-Being Score, and the interface logic for multi-factor park comfort in hot arid environments.

Table 1. Comparison of existing accessibility and sensory-inclusion tools and the gap addressed by Empark

Tool	Primary focus	Strength	Gap relative to Empark
Wheelmap	Wheelchair physical accessibility	Extensive global coverage; community-driven accessibility data	Focuses mainly on physical access; does not address thermal, acoustic, greenery, or sensory comfort dimensions [15]
AccessNow	Accessibility mapping	Crowd-sourced venue information and user-generated accessibility reports	Limited attention to climate-responsive comfort and park-specific environmental quality [34]
KultureCity	Sensory-inclusive venue certification	Strong sensory-inclusion orientation for selected venues	Certification-oriented and not designed as a park recommendation or climate-adaptive comfort tool [35]
NeuroHub	Autism-friendly place discovery	Sensory-oriented place ratings for specific user needs	Narrower user scope and limited integration with environmental comfort or planning feedback [36]

System Design and Methods

User Journey and Interface Concept. The design of the Empark prototype is centered around providing users with an interface that can offer feedback on which parks would best suit their comfort requirements. The design is centered around an interactive map that uses colors to denote different levels of comfort according to the Sensory Comfort Index (SCI), ranging from green for high comfort levels, amber for medium comfort levels, and another color for lower comfort levels. The users can also enter their comfort requirements, for example, "a quiet and shaded area with wheelchair access," and receive recommendations for different parks according to their requirements and the data provided by the prototype. Each park will have a factor-wise comfort summary, for example, "Shade 85/100, Noise 30/100," so that users can get an idea of what their choice of park is based on, providing more transparent information for users about different options available for their requirements. Moreover, users can apply filters according to their requirements

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for different types of parks and their comfort needs, provide feedback regarding their experience with different parks, allowing them to identify different concerns, for example, "excessive noise, insufficient parking, etc." **Figure 1** represents the architecture framework of the Empark prototype.

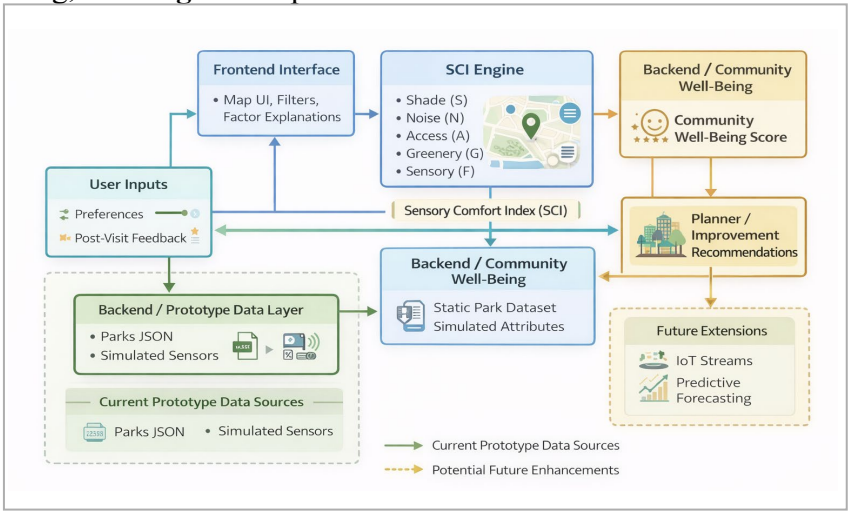


Fig. 1. *Architecture and data flow of Empark prototype.*

Sensory Comfort Index (SCI). The Empark prototype is founded on the Sensory Comfort Index (SCI), which consists of five factors, each assigned a score between 0 and 100 (**Fig. 2, left**). These factors include shade coverage (S), noise level (N), which is inversely used in the SCI calculation, accessibility score (A), greenery density (G), and sensory friendliness (F). These factors were chosen based on the recurring themes in the literature regarding the benefits of urban green spaces, moderation of microclimate, accessibility, and environments that respond to the senses [4-9, 12, 13, 15, 35, 36, 47]. The SCI for a given park i is calculated as follows:

$$SCI_i = \frac{(S_i+(100-N_i)+A_i+G_i+F_i)}{5} \quad (1)$$

The SCI is then used to categorize park comfort levels for visualization purposes. Parks are classified as high comfort (SCI ≥ 75), moderate comfort (60 ≤ SCI < 75), or low comfort (SCI < 60). At the prototype stage, the five factors have equal weight to ensure the simplicity and ease of interpretation of the SCI, which is important at the early stages of the system's development and testing.

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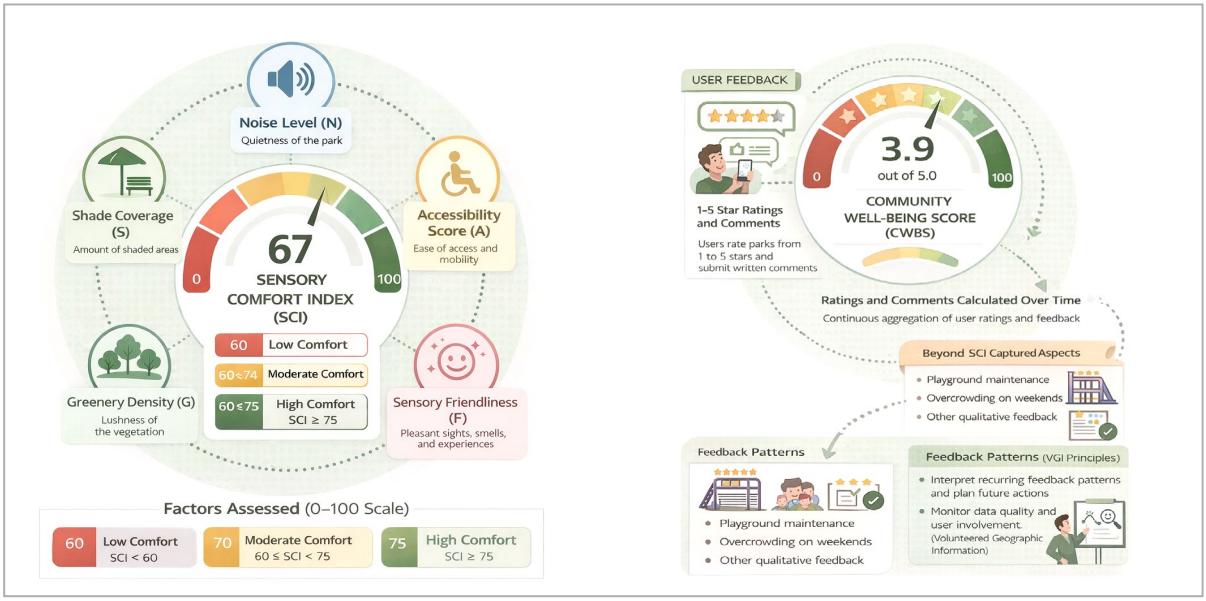


Fig. 2. *Empark framework measures. Left, Sensory Comfort Index (SCI); right, Community Well-Being Score and feedback loop.*

Community Well-Being Score and Feedback Loop. The second quantitative measure used in the Empark system is the Community Well-Being Score, which is derived from user feedback (**Fig. 2, right**). This score is calculated using ratings and comments submitted by users after visiting a park. Visitors can evaluate their experience by assigning a rating between 1 and 5 stars and optionally providing written comments describing their observations. As a result, the Community Well-Being Score for a park may differ from its Sensory Comfort Index (SCI). For example, a park might receive a relatively high SCI but still obtain a lower community well-being score due to issues not captured by the SCI. These may include factors such as poorly maintained playground equipment, overcrowding during weekends, or other experiential aspects reported by visitors. Recurring patterns in the feedback are also emphasized for further interpretation and planning of future actions. The quality of the data, given the partial involvement of users in the provision of information, is also considered based on the principles of Volunteered Geographic Information (VGI) and participatory feedback systems, such as the recognition of recurring patterns, anomalies, and the interpretation of recurring patterns in the data provided by users [21, 25]. The feedback loop also takes into consideration the co-creation paradigm, in which the experience of the users can provide insight into the shortcomings of the design from the perspective of the users, relevant to the needs of the planner and the decision-maker [20, 24].

AI and Analytics Roadmap. As stated earlier, the current prototype relies on a clear and transparent scoring method based on the SCI, which is pertinent for the current prototype, given its status as a proof of concept. However, the roadmap for the current research indicates the following possible extensions for the analytical component: the development of predictive models for estimating time-varying comfort based on weather inputs, remote sensing data, and environmental sensing; the development of context-based recommendation methods that learn from the users without compromising the interpretability of the models; and the use of natural language processing for the interpretation of the feedback from the members of the community. These extensions are based on the research on smart cities for environmental sensing, point of interest recommendation systems for smart cities, and community engagement [10, 14, 16-18, 39-

43, 48]. In the current paper, they are presented as future directions rather than as implemented features of the current prototype.

Implementation and Results

Empark is developed as a single-page web application using React 18, with TypeScript and Tailwind CSS for styling, along with Google Maps JavaScript API to support interactive park visualization **(Fig. 3)**. The system is backed by a lightweight Node.js/Express server that hosts the Empark interface and delivers a static dataset containing park information in JSON format. The data set includes comfort-related attributes for calculating the Sensory Comfort Index (SCI) and visualizing the park based on the comfort thresholds. Additionally, each park provides a factor-wise description of the comfort-related attributes for increased transparency and ease of use for the end users.

As the current development status of the proposed system is a prototype, the environmental inputs are simulated based on the static attributes of the park. Nevertheless, the architecture of the proposed system allows for the integration of IoT-based environmental sensing in the future, facilitating the integration of thermal, acoustic, and other environmental data sources. The current prototype is accessible at https://emparkapp.manus.space/.

Scenario-based testing with the current static data set indicates the performance of the Empark prototype in terms of its applicability to the hot arid urban environment, particularly with the user preference for shade and quietness during periods of high thermal stress. Under these scenarios, the ranking of the parks is based on the total shade coverage and the quietness of the park, with lower SCI values resulting in lower-ranked parks. The user can also get recommendations based on the factors that contributed to the comfort profile of the recommended park. This is achieved by the explainable recommendations provided by the prototype, as the user can view the factor-wise contribution to the comfort profile of the recommended park.

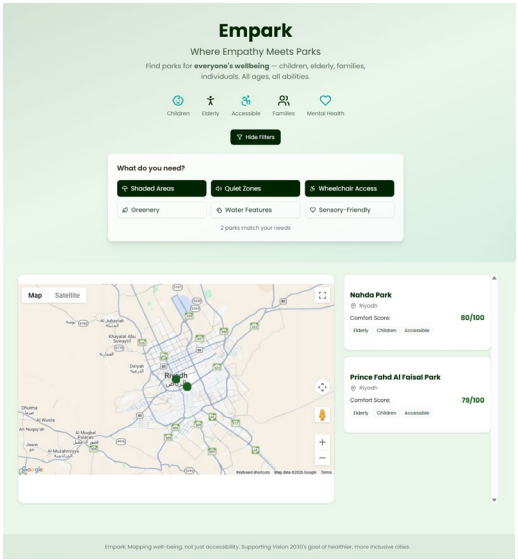


Fig. 3. *Empark Main Interface. The park comfort filters, such as shaded areas, quiet areas, and wheelchair accessibility, update Google Maps. The list of parks is also filtered based on the SCI ranking.*

Empark allows the user to set comfort filters for the parks, compare their performance using the interactive map and the ranked results list, and provide feedback for the park visited (**Fig. 4**). The prototype also provides an "Improvement Recommendations" panel for the users, which indicates

the performance of the park in terms of the comfort of the users and improvement recommendations. These findings must be recognized as a prototype-based demonstration rather than a performance assessment. At the current stage of the research, the system processes a static data set with simulated environmental attributes. Thus, there has been no field-based validation study. The current findings can be recognized as a demonstration of the feasibility of the interface logic, scoring scheme, and scenario-based recommendation behavior.

Proposed Evaluation and Validation Framework

Given the fact that the current prototype depends on simulated environmental input and the above description of the results section presents a scenario-based demonstration rather than validation, the paper does not aim to achieve empirical validation. To overcome this limitation, the research includes a future evaluation and validation framework (**Fig. 5**):

Phase 1: Usability and Interface Evaluation. The first phase of the proposed framework is based on the evaluation of the usability of the Empark interface and the ease with which the interface can be understood and utilized by the end-users. For this purpose, the usability of the system can be evaluated using the System Usability Scale (SUS) and similar tests. These tests will cover various aspects of the system, including the ease of navigation and understanding the filters, and the overall comprehension of the factor level comfort indicators [19]. The results obtained from the first phase can be useful in improving the overall interface and the presentation of the recommendations for various groups of people, including the elderly, families, and people with disabilities.

Phase 2: SCI Validation through Field Measurements and User Perception. The second phase of the proposed framework is based on the validation of the Sensory Comfort Index (SCI) by means of the results obtained by performing environmental measurements as well as the perception of the users. For this purpose, environmental measurement devices can be deployed in the parks for measuring temperature, humidity, as well as noise levels. At the same time, surveys can be conducted among the users of the parks for evaluation of perceived comfort, accessibility, as well as satisfaction with the parks [10, 14, 16-18, 23]. Through statistical analysis, it is possible to use the outcomes of the second phase of the proposed framework for evaluation of the accuracy of the proposed SCI prototype.

Phase 3: Behavioral and Well-Being Assessment. A third phase of research could involve evaluating the impact of the application of the Empark recommendation tool in terms of behavioral outcomes, as well as well-being. This could include a quasi-experimental study in which the behavior of the users of the tool is compared to non-users of the tool [22].

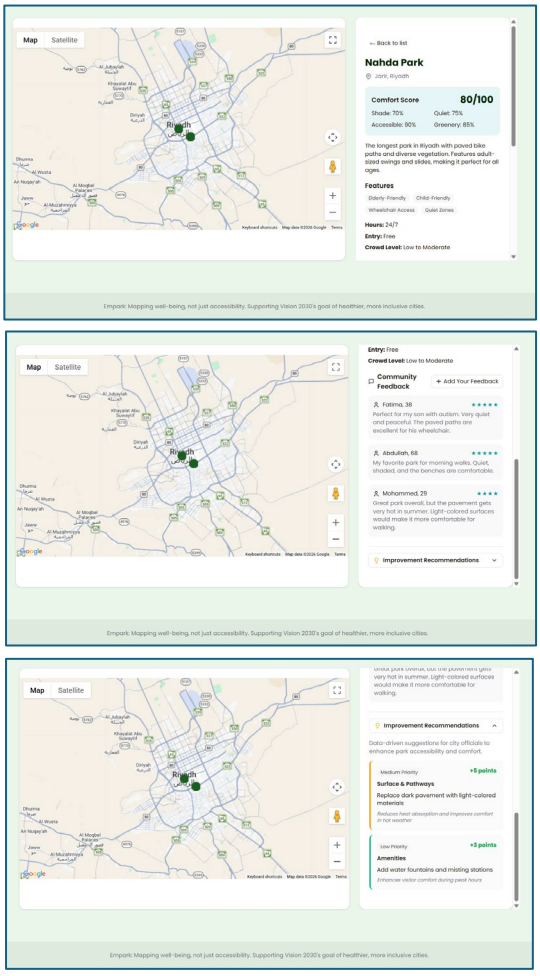


Fig. 4. *The Park Profile with Feedback. The selected park page displays the comfort score with factor-wise breakdowns (above), community feedback and ratings (middle), and an "Improvement Recommendations" panel for potential planner-facing actions (bellow).*



Fig. 5. *Proposed evaluation and validation*

Discussion

Empark prototype has demonstrated the application of the principles of environmental comfort, accessibility, and community feedback in the design of a single tool for parks in hot arid environment. Its importance is in the demonstration of how the available literature of greenspace, mental well-being, mitigation of effects of urban heat island, and inclusive design can be used in the design of an integrated tool for the selection of parks and the generation of feedback for their planning [1, 3, 28-30, 47]. One of the strengths of the Empark tool is the integration of the factors of thermal comfort, sensory experience, greenery, and accessibility in the design of the tool, as opposed to the application of any of the factors in isolation. This is particularly significant in the hot arid environment, where the usability of the green spaces is not only dependent on their availability, but also on the experience of the spaces being shaded, quiet, accessible, and usable for all. The application of the factor-based approach of the Sensory Comfort Index (SCI), in addition to the Community Well-Being Score, has made all these factors more visible.

The findings of the prototype demonstration indicate that it could be useful in facilitating the explainable filtering and ranking of parks in comfort-sensitive scenarios. However, it is important to note that the results were obtained from a proof-of-concept system and need to be understood in the context of the specific system. Moreover, the SCI is still an initial operational framework and has not been validated as a predictor of real-world comfort conditions [23]. The same limitations and considerations that have been discussed for other systems that rely on user-generated spatial feedback need to be taken into consideration [21, 25]. Despite these limitations, Empark suggests a larger potential in the creation of a more explicable and comfort-oriented urban tool that assists in connecting data, experience, and planning intervention. If this concept is further developed, it could not only be useful in facilitating more discerning choices in selecting parks, but also in facilitating a better sensitivity in terms of how parks function for different individuals.

Limitations and Future Work

There are a number of limitations that are currently associated with the use of the prototype. First, the prototype does not currently utilize live environmental sensor inputs. Instead, it utilizes simulated inputs. The Sensory Comfort Index (SCI) has not yet been validated in real-world scenarios. Secondly, it is imperative to point out that the SCI model currently utilizes equal weightings of all five factors. Although this is useful in facilitating greater transparency and simplicity in the context of the prototype, it might not be appropriate in facilitating different priorities and preferences of different user groups. Thirdly, the tool is currently dependent on a static park dataset, which is specific to hot arid urban environments in Saudi Arabia. Lastly, the framework relies on user feedback to a certain extent. It is therefore necessary to consider the issues that arise from such a situation, which is similar to the issues that arise from the research on Volunteered Geographic Information [21, 25]. Some of the developments that need to be addressed in the future revolve around the following: the validation of the SCI framework through field sensing and user comfort surveys to calibrate the SCI in a real-world setting [10, 14, 16-18, 23]; usability and interface evaluation to determine the interpretability of the recommendation system for users [19]; the refinement of the recommendation model to consider preference-sensitive weighting schemes for the interpretation of user feedback; and the exploration of the long-term consequences of providing users with comfort-aware recommendations for parks to determine whether it influences user behavior [22]. Future research could also be directed towards the application of the Empark framework for other hot-arid environments and possibly for different climates.

Conclusion

This paper introduced Empark as a framework, conceptual model and functional interface for a comfort-aware park recommendation tool in hot arid cities by utilizing the ‘Sensory Comfort Index’ and ‘Community Well-Being Score.’ The tool is implemented as a single-page web application that combines five aspects of comfort: shade, noise, accessibility, greenery density, and sensory; community feedback and improvements’ recommendations. The paper also proposed a 3-phase validation framework and structured evaluation roadmap through environmental sensing, user comfort surveys, usability studies, and the evaluation of the system’s long-term behavioral outcomes. Future development of the system could also include the incorporation of open data sources, pilot deployments with city stakeholders, and the improvement of the recommendation system through context-aware research [41-43]. In general, the planning-oriented aspect of Empark aligns with the quality-of-life goals set by the Vision 2030 of the Kingdom of Saudi Arabia. Additionally, the system’s goals contributes to the overarching goals set by the Sustainable Development Goals (SDGs) for SDG 3, SDG 11, and SDG 13, which focus on health, sustainable cities, and climate change, respectively [49-54]. The integration of environmental

comfort, inclusivity, and community feedback through the proposed framework has been able to show the potential for a promising approach to the planning and recommendation of urban spaces.

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Designing for Walking in Gulf Cities: User Perspectives from New Muwaileh Park, Sharjah

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Abstract. Walkability is a key component of sustainable urban development, yet in hot-arid regions such as the Gulf, it is constrained by a combination of environmental, infrastructural, mobility, and socio-cultural factors. While previous research has primarily focused on the physical attributes of the built environment, there is still limited understanding of how users perceive and experience these challenges in everyday situations. This study aims to explore how public space design can improve walkability in a hot-arid urban setting by analyzing users' perceptions of challenges and their proposed mitigation strategies. The research focuses on New Muwaileh Park in Sharjah, UAE, and adopts a user-centered approach based on structured, face-to-face interviews with 135 users. Open-ended responses were analyzed using thematic analysis to identify key challenge areas and user-driven recommendations. The findings reveal that walkability challenges are mainly linked to socio-cultural factors and urban form and infrastructure, while environmental conditions, traffic safety, and mobility systems have more context-specific roles. These challenges differ across user groups: women and caregivers focus on safety and usability, older adults prioritize accessibility and comfort, and perceptions vary depending on mobility activities like walking, driving, or cycling. User suggestions indicate a strong preference for design-oriented mitigation strategies, especially environmental enhancements such as greenery, shading, and better public spaces, along with improved pedestrian infrastructure and safer crossings. By connecting perceived challenges to user-driven solutions, the research offers practical insights for creating more inclusive, climate-responsive, and human-centered public spaces in rapidly urbanizing Gulf cities.

Introduction

The sustainability agenda for urban sustainability now includes walkability as a fundamental feature of sustainable development. Thus, it integrates the concepts of mobility, health, social equity, and sustainability [1]. While the concept of walkability has received considerable attention in urban design, implementing it in hot-arid regions poses challenges that limit pedestrian activity [2,3]. In urban environments characterized by extreme climatic conditions, as seen in the Gulf region, walkability is influenced not only by traditional urban form variables such as density, land-use mix, and connectivity, but also by environmental and socio-cultural factors that directly affect human comfort [4,5].

Among the most critical challenges is thermal stress, which is exacerbated by higher air temperatures, intense solar radiation, and reduced shading. This reduces outdoor thermal comfort and walking activities, particularly during daytime [1,3,6]. In this context, walking in hot-arid environments is temporally adapted, with increased activity observed in the evenings and during colder seasons, which is not associated with spatial factors, but rather environmental factors.

Furthermore, urban design and infrastructure significantly influence walkability in Gulf cities. These environments are often characterized by dispersed urban planning, low-density development, and car-oriented infrastructure, which reduce connectivity and encourage reliance

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on automobiles [2,7]. Pedestrian infrastructure is often incomplete or obstructed, lacking essential features such as continuous footpaths, adequate shading, and safe crosswalks, making walking especially difficult for vulnerable groups, such as older people and families with children [8].

These spatial constraints are closely linked to the wider conditions within the mobility system. In the United Arab Emirates (UAE), public transportation options differ across the emirates. Dubai provides more advanced public transit compared to other emirates, with a metro system, a tram network, and an extensive bus system. Meanwhile, other emirates mainly depend on buses and taxis for both intra- and inter-city transportation. Despite the availability of public transit, private motor vehicles still dominate, largely due to a deeply rooted car culture. Similar trends are observed in other developed Gulf cities, such as Riyadh [3].

Besides limiting mobility options, these factors also affect the social aspects of the walking environment. If walking is not part of regular mobility routines, then the opportunity for regular pedestrian interaction decreases, and the public space's potential for social engagement diminishes. Conversely, walkable environments can encourage frequent interaction and neighborhood cohesion through trust and density, especially when mixed land use and lively public spaces are present [9]. However, the connection between walkability and social factors is complex and influenced by density and urban design in shaping user experiences.

Given current mobility conditions and sociocultural factors, traffic and road safety issues constitute another set of barriers to walkability in Gulf cities. A car-centric urban planning approach, marked by extensive road networks and a focus on vehicular speed, further encourages high car ownership rates and an increasing dependence on motorized transportation. As a result, the frequency of walking as a daily mode of transport declines, and pedestrian presence in the urban environment becomes limited. Although not all Gulf cities experience severe traffic problems, the presence of high-speed vehicles, multiple road intersections, and limited pedestrian crossings creates an unsafe environment for walking [10]. These conditions affect safety perceptions, which are recognized as a key factor influencing walking behavior, especially for purposive walking [11]. Additionally, safety concerns tend to impact vulnerable groups such as older adults, children, and families, who are especially sensitive to road safety and infrastructure conditions [8].

In response to these challenges, research in climate-responsive design has shifted toward mitigation strategies to enhance the effectiveness of urban environments. Among the most commonly discussed design strategies in hot-arid regions are responsive public spaces, street-level greenery, shaded pedestrian corridors, and pedestrian-focused urban design. These strategies can potentially reduce heat exposure in urban environments and make them more walkable [2,12].

Public parks hold a particularly important role in this regard, given their potential to address multiple walkability barriers simultaneously. Parks serve as destinations for walking, recreation, and socializing, while also playing a key role in regulating microclimatic conditions through vegetation, shade, and the cooling effects of various landscape components [6,12,13]. Empirical research on sheltered and climate-protected pedestrian environments shows that providing weather protection, ensuring comfort, improving accessibility, and prioritizing safety can enhance pedestrians' walking experience and perceptions of walkability [12–14]. In addition, such public spaces, especially when embedded in mixed-use built environments and integrated with daily destinations, can promote pedestrian mobility while fostering social interaction and social cohesion in neighborhoods [9,15].

However, understanding the effectiveness of these strategies requires the use of physical or morphological indicators. Although these indicators remain a fundamental part of walkability research, they do not fully explain variations in walking patterns across locations, groups, and purposes [4–7]. Recent research has shown that comfort, safety, aesthetics, accessibility, and ambient social factors all influence walking in different ways. Safety and traffic conditions are

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more important for purposeful walking, while aesthetic and environmental appeal matter more for recreational walking [8,11]. These factors may differ across groups, with older people more sensitive to path quality, whereas women and children may be more sensitive to safety and the presence of others, respectively [8].

Building on the understanding of perception-based influences on walking identified in literature, this study aims to examine how public space design can encourage and support walking in a hot-arid urban environment from a user perspective. Existing research has highlighted various physical, environmental, and morphological factors related to walking. However, there remains a need for a deeper understanding of how users perceive these spaces and which design elements promote or hinder walking in daily life, especially in culturally and climatically specific settings like Gulf cities.

This study focuses on New Muwaileh Park in Sharjah, UAE, using a qualitative, user-centered interview-based approach to analyze pedestrian behavior in the neighborhood. The study aims to identify how factors such as accessibility, public transportation options, road safety, and environmental comfort influence individuals' decisions to walk, and to explore walking motivations related to health and social interaction. It also examines challenges posed by age, physical capacity, and climate conditions. By understanding users' experiences, the research seeks to identify design considerations that can promote pedestrian activity and improve the usability of public spaces in hot-arid regions.

Methodology

Study area

New Muwaileh Park is a neighborhood park within a highly urbanized mixed-use development in Sharjah, UAE. It features a mix of mid-rise residential buildings and active commercial spaces on the ground floor. Although it is a neighborhood park, it is notable as the only accessible park in its immediate surroundings. Its proximity to major urban destinations, including Al Zahia, Al Mamsha, and the University City of Sharjah, further enhances its relevance within the district. Adjacent to the park is a mosque, which adds to the area's cultural and social significance. The shaded open space between the mosque and the park serves as an informal extension of the park, particularly as a frequented area for seating, socializing, and kids' play (Fig. 1). Given the climatic conditions, park use is concentrated during the evening, with operating hours from 4:00 pm to 10:00 pm daily.



Figure 1: The open space between the park and the mosque acts as a social space, regardless of the weather.

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Data collection

Data collection methods included structured, face-to-face interviews with users of New Muwaileh Park and its surrounding streets. A total of 135 adults (18 years or older) were interviewed at various times during the mornings and evenings over a few days in January 2026. A pilot study was conducted in June 2025; however, due to a lack of pedestrian activity and respondents' recognition of weather as a challenge, it was decided to target higher pedestrian activity, which typically occurs in colder months. After verbal consent was obtained, interviews were conducted in either Arabic or English, depending on the interviewee's preference.

The interview form included questions about socio-demographic characteristics, transportation modes, and perceptions of factors related to walking, including environmental comfort, accessibility, traffic safety, access to amenities, and social interaction. Additionally, on-site observations were conducted to document the park's physical conditions, surrounding walking conditions, and social interactions.

Data analysis

The qualitative responses collected from the open-ended interview questions were analyzed using thematic analysis, following the approach by Braun and Clarke (2006) [16]. This method enables systematic identification, organization, and interpretation of recurring patterns in the qualitative data set.

The analysis was carried out in multiple steps. First, all responses were reviewed and familiarized to develop an overall understanding of the data. Second, initial codes were created by identifying recurring ideas related to perceived challenges and user suggestions. These codes were then grouped into broader themes based on conceptual similarity.

Importantly, the development of themes was guided by the analytical framework established in the literature review, ensuring consistency between theoretical ideas and empirical results. Therefore, responses were organized into key thematic groups that reflect the main aspects of walkability in hot-arid environments, including environmental conditions, urban form and infrastructure, mobility systems, socio-cultural factors, and traffic safety.

Results and discussion

The results present findings from the structured interviews and complementary qualitative inputs, organized to reflect participants' characteristics, perceived challenges, and user suggestions relating to the themes identified in the literature.

Demographics

A total of 135 participants took part in the study, with a nearly balanced gender distribution, comprising 51% female (n = 69) and 49% male (n = 66). The majority of participants were middle-aged (25-58 years), accounting for 80% of the total. This was followed by young adults (18-24 years), comprising 13%, and older people (59+ years), comprising 7%. In terms of nationality, 88% of respondents identified as non-locals, while 12% were Emirati locals. Regarding primary transportation modes, private vehicles were the most common, used by 52% of respondents. Walking was a primary or secondary mode for 29%, indicating a considerable level of pedestrian activity. Public transport use was reported by 12%, while bicycle or scooter use was reported by 6% of respondents, as shown in Table 1.

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Table 1: Basic demographics description (n=135).

ATTRIBUTE	VARIANT	COUNT	PERCENTAGE
GENDER	*Male*	*66*	*51%*
	Female	*69*	*49%*
AGE	*18-24*	*18*	*13%*
	25-58	*108*	*80%*
	59+	*9*	*7%*
NATIONALITY	*Local*	*16*	*12%*
	Non-local	*119*	*88%*
TRANSPORTATION MODE	*Private vehicle*	*81*	*52%*
	Public transit	*19*	*12%*
	Bike/ Scooter	*10*	*6%*
	Walking	*45*	*29%*
	Others	*2*	*1%*

Perceived challenges

Challenges deducted from the open-ended questions were grouped into five themes: environmental conditions (climatic conditions, air and noise pollution, and green spaces); urban form and infrastructure (urban planning, connectivity, and street conditions); mobility systems (public transportation availability and infrastructure supporting different modes of mobility); socio-cultural factors (cultural and special needs for vulnerable groups); and traffic safety.

When asked to identify challenges facing respondents, the most frequently mentioned theme was socio-cultural factors (54%), followed by urban form and infrastructure (40%). Environmental conditions were less frequent (18%), while traffic safety (14%) and mobility systems (10%) appeared more selectively, as shown in Table 2.

The gender pattern was especially clear. Women made up the majority of substantive challenge responses and were more likely than men to mention both urban form and infrastructure (46.9% versus 27.8%) and traffic safety (18.8% versus 5.6%). Their responses often connected walking difficulties to care-related mobility issues, including stroller access, narrow sidewalks, limited places to rest children, and concerns about crossing streets safely with kids. Men also most often mentioned socio-cultural factors, but their responses more frequently focused on crowding, fatigue, weather, odor, or general discomfort. This indicates that women view walkability more through everyday care and usability, while men tend to see it as a matter of general comfort and inconvenience.

Age also shaped how challenges were interpreted. Young respondents most frequently raised socio-cultural factors (75%), including exhaustion, low motivation to go out, crowding, and concern about scooter use on local roads. Middle-aged respondents, who formed the bulk of the sample, reported the widest range of challenges and were the only group to meaningfully register all five theme types. Their responses combined infrastructure concerns with daily-life pressures, especially walking with children, limited time, and the difficulty of moving between residential buildings and the park. Older respondents provided fewer responses, but their comments focused on infrastructure and socio-cultural constraints, particularly the lack of paths suitable for slower walkers, limited support for people with disabilities, and discomfort in noisy or crowded conditions. Although the number of older respondents was small, their responses point to accessibility and pace as central dimensions of walkability in later life.

The patterns also varied by transport mode. Respondents who used private vehicles most often cited socio-cultural factors (54.8%) and infrastructure (35.5%), but they also accounted for the majority of environmental and traffic-related complaints. Their responses frequently combined heat, paid parking, and insufficient pedestrian space. Respondents who reported walking were

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proportionally the most likely to mention traffic safety (23.5%) and environmental discomfort (23.5%), indicating that direct exposure to streets, crossings, and weather heightened awareness of immediate physical risk. Public-transport users produced fewer challenge responses overall. But when they did respond, they linked walking to the extra effort of reaching transit and the lack of attractive public transport options. Bike and scooter users were the group most strongly associated with infrastructure concerns (60%), particularly designated bicycle parking and the absence of dedicated lanes. Overall, these differences show that respondents interpreted walkability through their everyday mobility practice: walkers noticed crossing risk and exposure, cyclists noticed missing facilities, and car-dependent users revealed the structural conditions that keep walking secondary.

Table 2: Challenge themes: within-group mention rates.

GROUP	ENVIRONMENTAL CONDITIONS	URBAN FORM & INFRASTRUCTURE	MOBILITY SYSTEMS	SOCIO-CULTURAL	TRAFFIC SAFETY
OVERALL	***18.0%***	***40.0%***	***10.0%***	***54.0%***	***14.0%***
FEMALE	*15.6%*	*46.9%*	*9.4%*	*56.3%*	*18.8%*
MALE	*22.2%*	*27.8%*	*11.1%*	*50.0%*	*5.6%*
YOUNG (18-24)	*12.5%*	*25.0%*	*0.0%*	*75.0%*	*12.5%*
MIDDLE AGED (25-58)	*21.1%*	*42.1%*	*13.2%*	*47.4%*	*15.8%*
ELDERLY (59+)	*0.0%*	*50.0%*	*0.0%*	*75.0%*	*0.0%*
PRIVATE VEHICLE	*22.6%*	*35.5%*	*9.7%*	*54.8%*	*16.1%*
WALKING	*23.5%*	*35.3%*	*5.9%*	*58.8%*	*23.5%*
PUBLIC TRANSIT	*22.2%*	*33.3%*	*11.1%*	*55.6%*	*0.0%*
BIKE/ SCOOTER	0.0%	60.0%	*0.0%*	*40.0%*	*20.0%*

Users' suggestions as mitigation priorities

Forty-one coded suggestions were identified across the open-ended recommendation questions. In contrast to the challenge responses, suggestions mainly focused on environmental improvements (17 mentions; 41.5%) and urban form and infrastructure (14 mentions; 34.1%), followed by traffic safety (10 mentions; 24.4%) and both mobility systems and socio-cultural measures (8 mentions each; 19.5%). The most common recommendations included adding more greenery and nearby parks, improving cleanliness and maintenance, enhancing sidewalks and walking or cycling lanes, providing more benches and child-friendly facilities, increasing safety at crossings and controlling speeds, and strengthening bus or metro services.

These priorities also varied between groups. Women most often suggested environmental improvements (46.2%) and infrastructure changes (30.8%), focusing on more greenery, cleaner pavements, better-maintained walkways, and environments that support children and strollers. Men offered suggestions more evenly across infrastructure, traffic safety, and mobility systems, emphasizing walking lanes, pedestrian bridges, cycling or e-scooter facilities, signals, speed reduction, and public transportation. Age-based differences in suggestions were minimal because nearly all responses (39 out of 41) came from middle-aged adults, indicating that this group was most actively identifying improvement priorities. Among walkers, infrastructure and traffic safety were the primary themes of suggestions (38.5% each), reinforcing the idea that regular walkers seek both better path quality and safer crossings. Public-transport users focused their suggestions on mobility systems (50.0%), especially bus stops and the potential for rail transit in Sharjah.

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Private-vehicle users generated the most suggestions overall, highlighting greenery, neighborhood parks, and child-sensitive safety measures.

The findings regarding the most attractive elements also support this, with greenery identified as the most attractive (55%), followed by children's playgrounds, seating areas (24% each), and, finally, the availability of shade (19%). Other elements included the availability of exercise machines and Wi-Fi (3%) (Fig. 2).



Figure 2: Summary of the question "What elements do you find most attractive?"

Conclusion

This study explored walkability in a hot-arid urban setting using a user-centered, perception-based approach, focusing on how environmental, infrastructural, mobility, socio-cultural, and safety factors influence walking behavior around New Muwaileh Park in Sharjah. By aligning qualitative results with a thematic framework from the literature, the study offers a more integrated understanding of walkability as both a physical and experiential phenomenon.

The findings show that walkability challenges are not experienced equally but are shaped by users' daily mobility habits and socio-demographic traits. Socio-cultural factors along with urban design and infrastructure stand out as the main barriers, suggesting that walkability in Gulf cities is influenced as much by behavioral patterns and daily routines as by physical layout. While environmental issues like heat remain significant, they are often understood through lived experience rather than as standalone obstacles. Similarly, challenges related to traffic safety and mobility systems are not universally prominent but become more noticeable among users directly affected, especially regular walkers and families.

The analysis also spotlights distinct differences among user groups. Women and caregivers prioritized usability, safety, and child-related mobility needs, while older respondents concentrated on accessibility, pace, and comfort. The mode of transport further influenced perceptions: walkers were more affected by immediate environmental and safety conditions, cyclists worried about infrastructure gaps, and car users focused on broader structural issues like parking, distance, and the lack of alternatives. These variations emphasize the need to view walkability as a user-specific and context-dependent experience rather than a uniform city feature.

The overall results have several implications for the design and planning of hot-arid urban environments.

- First, climate-responsiveness strategies, such as increased greenery, continuous shade, seating areas, and water features, should be prioritized to improve outdoor thermal comfort and extend walking times beyond the evenings.
- Second, walking infrastructure must be inclusive, featuring continuous, accessible walking areas to accommodate older adults, children, and people with physical limitations.

- Third, traffic safety and improved connectivity for crossing and public transportation must be prioritized to enable walking as an active mode of transportation rather than merely a recreational activity.
- Fourth, urban spaces must be designed to accommodate a variety of social activities, including family gatherings, socializing, and solitary activity, while being sensitive to contextual factors such as mosques.

By incorporating user perception into walkability analysis, this study enhances a deeper understanding of climate-responsive urban design in the Gulf region. It emphasizes the need to go beyond solely physical or morphological factors and include behavioral, social, and experiential aspects. The results provide practical guidance for planners and designers aiming to boost walkability through context-aware, user-centered strategies that integrate environmental mitigation with everyday urban life.

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Evolutionary-Inspired Design Choices to Mitigate Between Our Stable Ancient Past and Everchanging Environments: A Case for Modifiable Cities, Buildings, and Communities

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Abstract. The framework of the Environment of Evolutionary Adaptedness (EEA) and evolutionary medicine (EM) has offered principles grounded in the design of human bodies to initiate thinking about our relationships to our surroundings for health-related outcomes. Despite this general call, architectural methods have not yet developed a major connection to the developing literature of EM. Modern architecture often ignores the biological imperatives ingrained in our species, frequently creating "mismatch conditions"—such as poor circadian lighting and sedentary-focused layouts—that exacerbate chronic illness and disability. As climate change introduces extreme thermal stress and ecological instability, the built environment must be reimagined not merely as shelter, but as a corrective interface that narrows the "functional gap" between human physiology and a hostile biosphere. This paper argues for a framework of "Pro-Adaptive Niche Construction" in architectural design, with particular attention to thermal mismatch mitigation, sensory coherence, and inclusive design. Drawing on the author's prior work in evolutionary medicine [1, 2, 3] and on building science research addressing overheating and adaptive housing [4, 5], the paper develops the case for modifiable, adaptable cities, buildings, and communities that serve as evolutionary interfaces for all bodies—particularly those at the physiological "edges" of capability. It further introduces the concept of inherited adaptability across scales—from room to building to neighborhood to city—as an evolutionary design principle. The argument concludes that evolutionary literacy, combined with adaptive building performance evaluation and multi-scale design flexibility, is essential for architecture that genuinely supports biological life in the Anthropocene.

1. INTRODUCTION

Contemporary cities are increasingly at odds with the bodies that inhabit them. The gap between the environments in which Homo sapiens evolved - characterised by natural light cycles, thermal variability, multisensory landscapes, and varied physical demands - and the sealed, artificially conditioned, and predominantly sedentary spaces of modern urban life has grown to a degree that poses significant risks to human health. Evolutionary medicine (EM) has long made this argument for clinical settings [1, 3], but the translation of its insights into architectural and urban design has remained underdeveloped.

The concept of the Environment of Evolutionary Adaptedness (EEA) refers to the ancestral conditions under which key human physiological and psychological systems were selected. Our thermoregulatory mechanisms, immune responses, circadian rhythms, and sensory integration capacities were calibrated over hundreds of thousands of years of Pleistocene living. Contemporary architecture, by contrast, is typically designed around the average, able-bodied occupant operating under stable climatic conditions - a model that is becoming increasingly

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untenable in the context of accelerating climate change and growing awareness of human biological diversity.

This paper builds on the author's prior theoretical work in evolutionary medicine [1, 2, 3], which applied concepts from the Extended Evolutionary Synthesis (EES); especially niche construction theory, to reframe how we understand disease, disability, and human function. It brings these frameworks into dialogue with architectural and building science research, particularly work on overheating risk, adaptive housing design, and building performance evaluation [4, 5], and with established theories of architectural adaptability [11, 12, 13], to develop a coherent argument for modifiable environments at multiple scales: from the room to the building to the community to the city. The paper proceeds as follows. Section 2 outlines the theoretical foundations in evolutionary medicine and niche construction theory. Section 3 addresses thermal mismatch as a key design problem. Section 4 develops the framework of Pro-Adaptive Niche Construction. Section 5 examines the scales of modifiability, building, community, and urban, and introduces the concept of inherited adaptability. Section 6 builds the case for modifiable cities as a planning vision. Section 7 addresses biophilic urbanism and sensory coherence. Section 8 concludes with implications for practice.

2. EVOLUTIONARY MEDICINE, MISMATCH, AND THE BUILT ENVIRONMENT

2.1 From Biostatistics to Niche Construction

Evolutionary medicine arose as a discipline from the recognition that many chronic diseases of modernity, obesity, type 2 diabetes, cardiovascular disease, depression, myopia, are not merely genetic failures but products of "evolutionary mismatch": the discordance between ancestral selective environments and contemporary conditions [3]. Classical accounts of disease in EM have relied on evolutionary functional frameworks, where dysfunction is defined relative to proper functions selected in ancestral environments.

The author's prior work [1] argued that such accounts need to be enriched by insights from disability studies and new developments in evolutionary biology, particularly the Extended Evolutionary Synthesis (EES). Where standard Modern Synthesis models prioritize gene-frequency change as the mechanism of adaptation, the EES incorporates niche construction, developmental plasticity, and epigenetic inheritance as equally important evolutionary processes [1, 2]. Niche construction; the capacity of organisms to modify their own selective environments, is particularly relevant for architecture, since buildings and cities are, at their most fundamental, constructed niches. In earlier work on extending evolutionary medicine [2], the author argued that the distinction between "Darwinizing" a phenomenon (applying evolutionary logic) and genuinely integrating new evolutionary mechanisms is crucial. Applying EM insights to architecture must therefore go beyond simple analogy. It must engage with the mechanisms by which built environments actually alter human developmental trajectories, physiological regulation, and long-term health outcomes, not merely invoke the language of evolution as rhetorical support for naturalistic design preferences.

2.2 Disability, Individual Variation, and the Edges of Capability

A second theoretical contribution from the author's work in the philosophy of medicine [1] is the argument that naturalistic accounts of disease and disability have historically marginalised the individual. Reference classes in biostatistical accounts tend to average out the variation that disability studies scholars argue is central to understanding health and function. By incorporating niche conformance and construction into the biostatistical framework, it becomes possible to represent individual life histories and capacity profiles in a more nuanced way.

This insight has direct architectural implications. If the reference class for "the user" in building design is a statistical average, typically a non-disabled adult operating under temperate conditions, then design systematically underserves those at the physiological edges of human variation: people

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with mobility impairments, autonomic dysregulation, sensory processing differences, or compromised thermoregulation. The architecture of inclusion is not a special category; it is the baseline for evolutionary adequacy.

3. THERMAL MISMATCH: THE OVERHEATING PROBLEM IN EVOLUTIONARY PERSPECTIVE

3.1 The Biological Baseline

The human body evolved sophisticated thermoregulatory mechanisms in the context of sub-Saharan Africa and later Pleistocene environments characterised by significant diurnal temperature variation. Beyond the survivable thermal band, particularly in sustained heat above approximately 35°C wet-bulb temperature, human thermoregulation begins to fail, with potentially fatal consequences for vulnerable populations.

Modern architecture has responded to this challenge primarily through mechanical air conditioning: a technological fix that seals buildings against the thermal environment and maintains indoor conditions within the comfort zone through energy-intensive refrigeration. This approach has three significant problems from an EM perspective. First, it creates a thermally homogeneous environment that eliminates the mild thermal variability supporting circadian regulation, metabolic health, and immune function. Second, it is entirely dependent on continuous electrical supply, making thermally vulnerable occupants critically exposed during a power failure in a heat wave. Third, it contributes to the urban heat island (UHI) effect by exhausting heat into the urban canyon, intensifying the very problem it is designed to manage at the building scale.

3.2 Evidence from Building Science: Overheating in Low-Energy Housing

Building science research has documented a paradox: the same design strategies intended to reduce heating energy demand; high insulation, airtightness, reduced thermal mass, often increase overheating risk in temperate and warm climates. Toledo's research into overheating in highly insulated English houses [4] demonstrated that the design process frequently fails to assess summer thermal performance adequately, and that occupants of energy-efficient homes may face conditions during heat waves that exceed adaptive comfort thresholds, particularly when they lack the capacity to open windows effectively or adjust their thermal environment.

Post-occupancy evaluation (POE) studies in this area [4, 5] reveal a fundamental disconnect between modelled and actual building performance: buildings that appear thermally adequate in design-stage simulations may perform poorly during real heat events, particularly for occupants with limited behavioral or physiological adaptive capacity. Toledo's Adaptive Housing research programme [5] specifically addresses the need for low-energy housing to be redesigned for climate resilience: incorporating passive cooling strategies (cross-ventilation, thermal mass, external shading), occupant-controlled adaptive features, and performance monitoring that can detect and respond to emerging overheating risk.

4. PRO-ADAPTIVE NICHE CONSTRUCTION: A DESIGN FRAMEWORK

Drawing on the theoretical resources of evolutionary medicine and the empirical evidence from building science, the author proposes the framework of "Pro-Adaptive Niche Construction" (PANC) as an organising principle for architectural design in the Anthropocene. PANC is defined as the intentional modification of the built environment to reduce the functional gap between human physiological capacity, especially at the edges of biological variation, and the demands imposed by a changing climate.

PANC has four core design principles: **Thermal buffering without thermal imprisonment.** Buildings should moderate extreme thermal conditions without eliminating mild thermal variability that supports biological regulation. Passive cooling strategies: night-time ventilation, thermal mass, external shading, evaporative elements, should be prioritised over mechanical

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solutions that create thermal monocultures and fail under grid disruption. **Modifiability and occupant agency.** Buildings designed as fixed thermal envelopes deny occupants the adaptive behaviours that are central to human thermoregulatory strategy. PANC buildings should be modifiable: equipped with operable elements, adjustable shading, and zoned thermal environments that allow occupants to exercise behavioural thermoregulation. **Sensory coherence and biological richness.** Evolutionary medicine suggests that neuro-atypicality and sensory disabilities are often amplified by the "sensory smog" of modern urbanism. Design choices that incorporate biophilic urbanism, the integration of diverse flora and natural water cycles, serve a dual purpose: they provide the psychological "Old Friends" stimuli required for immune and mental health regulation while simultaneously creating urban cooling sinks. **Design for the edges.** The central lesson of disability studies [1] for architecture is that designing for the full range of human capability produces environments that function better for everyone. A building that remains thermally tolerable without air conditioning during a power failure is not merely accessible, it is resilient.

5. SCALES OF MODIFIABILITY: BUILDINGS, COMMUNITIES, AND ARCHITECTURAL UNITS

While the PANC framework establishes the design logic, its practical implementation requires careful attention to the scale at which modifiability is designed. Buildings, communities, and urban fabrics are not equivalent units; they operate on different temporal, spatial, and social logics. Crucially, modifications made at one scale "inherit" constraints and affordances from the scales above and below, a relationship that maps directly onto the evolutionary concept of niche inheritance within niche construction theory [1, 2, 10].

5.1 The Building Scale: Shearing Layers and Biological Analogues

The foundational theory of building-scale modifiability is the concept of "shearing layers", originally proposed by British architect Frank Duffy and later elaborated by Stewart Brand in his seminal work *How Buildings Learn* [11]. Brand identified six nested layers of a building, each changing at a different pace: Site (permanent), Structure (50+ years), Skin (20–30 years), Services (7–15 years), Space Plan (3–10 years), and Stuff (daily to monthly). The core insight is that layers which change at different rates must be designed to be "loose" from one another: entangling fast-changing layers with slow-changing ones produces buildings that are rigid, expensive to adapt, and prone to premature obsolescence.

This layered model has a compelling biological analogue within evolutionary medicine. Just as the EES identifies multiple timescales of evolutionary change, genetic, epigenetic, developmental, and cultural, Brand's shearing layers identify multiple timescales of built-environment change [2, 11]. Niche construction theory would frame each layer as a partially heritable modification of the constructed environment: the structure inherited by successive occupants, the services modified to reflect technological change, the space plan adjusted to reflect the needs of particular individuals or households. The key evolutionary insight is that modifiability at faster layers: services, space plan, stuff, amplifies the adaptive value of investment in slow layers - structure and site - by extending the range of conditions those slow investments can accommodate.

Schmidt and Austin's systematic treatment of adaptable architecture [12] identifies seven specific strategies through which building-scale modifiability can be designed: versatility (supporting multiple uses in a single space), convertibility (enabling shifts between different use types), expandability (allowing physical growth), scalability, movability, refitability (easy replacement of technical components), and recyclability (component recovery at end of life). These strategies are not merely economic or environmental goods; from a PANC perspective, they are the means by which buildings maintain their function as adaptive niches across the changing biological and climatic conditions that their occupants will face over a multi-decade life span.

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Of particular importance for thermal performance is *refitability*: the ease with which building services: particularly ventilation, shading, and heating/cooling systems, can be replaced or reconfigured as climate conditions change or as occupant needs shift. Toledo's research [4, 5] demonstrates that many low-energy buildings in temperate climates were designed with services that cannot be reconfigured for passive cooling without structural intervention. This is precisely the kind of shearing-layer entanglement that Brand [11] identified as the primary source of building obsolescence and that PANC argues constitutes a biological risk for thermally vulnerable occupants.

5.2 The Community Scale: Collective Adaptation and Shared Adaptive Resources

The community or neighbourhood scale represents the intermediate level between the individual building and the city. At this scale, the logic of modifiability shifts from individual occupant agency to collective adaptive capacity, the ability of a defined community of buildings and residents to respond together to changing conditions. Research on housing adaptability [13] has demonstrated that adaptability at the building scale is not sufficient if the surrounding community infrastructure is itself rigid: residents of adaptable homes who cannot access shade, cooling refuges, or green space through the public realm are still thermally trapped during extreme heat events.

The community scale introduces two forms of modifiability that are absent at the building scale. The first is *infrastructural modularity*: the capacity to add, remove, or reconfigure shared elements; street trees, permeable surfaces, shared courtyard spaces, communal cooling facilities, green corridors, in response to changing thermal and ecological conditions. The second is *social modifiability*: the capacity of community structures to redistribute adaptive resources toward those most in need. The cooperative provisioning of shade, water, cooling, and social contact during heat events is a form of niche construction that is irreducibly collective; it cannot be designed at the building scale alone.

From a niche construction perspective [1, 2], community-scale modifiability is the primary mechanism by which the adaptive benefits of individual building modifications are aggregated and shared. A single building with a green roof contributes minimally to urban cooling; a neighbourhood where a significant proportion of buildings carry green roofs, interconnected by tree-lined streets and distributed water features, constitutes a thermally distinct microclimate that provides adaptive benefits to all its residents, including those in buildings that cannot themselves be modified. This is the community-scale equivalent of the ecological concept of niche inheritance: adaptive modifications by some members of a community become part of the shared constructed environment that shapes the physiological conditions of all members.

5.3 Intermediate Architectural Units: The Block, the Courtyard, and the Street

Between the building and the community lie intermediate architectural units, the urban block, the courtyard, the shared access way, the street, that mediate the relationship between private and public adaptive resources. These units are particularly significant because they are the scale at which many traditional architectural responses to thermal stress operated before the advent of mechanical air conditioning. The courtyard house forms of the Arabian Peninsula, the narrow shaded streets of Mediterranean and Middle Eastern urban morphologies, and the wind-tower (barjeel) systems of Gulf architecture all represent evolved responses to high thermal stress that operate at the intermediate scale, between the individual building and the public street [9].

The systematic review of building adaptability by Frontiers in Built Environment [14] highlights that adaptability strategies spanning these intermediate scales: including modularity, flexibility, convertibility, and upgradability are most effective when they are embedded in the urban morphology itself: when block layouts allow for through-ventilation, when street orientations create thermally differentiated shade patterns across the day, and when plot layouts

allow individual buildings to expand or contract without disrupting the adaptive properties of the surrounding fabric. This is the "inheritance" of adaptability across scales: buildings that inherit a favourable thermal morphology from their block and street context require less active intervention to maintain comfortable conditions than buildings that inherit an unfavourable one.

The PANC framework proposes that these intermediate architectural units should be explicitly designed as adaptive infrastructure; not as residual spaces between buildings, but as the primary carriers of community-scale thermal and ecological services. This requires a revision of planning and design standards that currently treat block interiors, courtyards, and shared access ways primarily as circulation and service infrastructure, rather than as the biological commons of the urban niche.

5.4 Inherited Adaptability: Niche Construction Across Temporal Scales

The concept of inheritance is central to evolutionary theory, and its application to the built environment reveals a dimension of the modifiability agenda that is frequently overlooked in architectural discourse. In biological systems, niche construction produces heritable ecological traces: the modifications an organism makes to its environment can persist across generations, altering the selective conditions experienced by its descendants [2, 10]. The equivalent in the built environment is the inheritance of physical form, infrastructure, and regulatory frameworks by successive generations of occupants, developers, and planners.

Brand's pace-layer model [11] makes this explicit: the Site layer is essentially permanent on human timescales and is therefore inherited unconditionally by all future occupants. The Structure layer is inherited for 50 or more years. The Services layer is inherited for a decade or more. Each layer of the building constrains and enables the adaptive options available to future occupants, in much the same way that the evolutionary legacy of earlier niche-constructing generations shapes the adaptive challenges and opportunities of their descendants.

This temporal inheritance has direct implications for the PANC design agenda. Buildings designed today will be occupied through a period of significant climate change: the IPCC projects continued increases in the frequency and intensity of heat waves through at least 2050 under all but the most optimistic emissions scenarios. Buildings whose structural and service layers are designed today with modifiability as a criterion will transmit greater adaptive capacity to their future occupants than buildings optimised solely for current conditions. Conversely, buildings that entangle their thermal control systems with their structural systems - embedding mechanical cooling in sealed facades and fixed air-handling systems - will transmit adaptive constraints to their future occupants, constraining their options for passive adaptation in the way that an evolutionary dead-end constrains a lineage's adaptive options.

Schmidt and Austin [12] introduce the concept of "adaptive value" to capture this temporal dimension: the present-value contribution of design choices that increase the range of conditions a building can accommodate over its life. From an evolutionary medicine perspective, adaptive value is not merely an economic concept; it is a biological one. Buildings with high adaptive value are better positioned to maintain their function as constructed niches that support human physiological function across the range of conditions that climate change will produce. Buildings with low adaptive value may become, within decades, the thermal traps and sensory wastelands that the PANC framework identifies as primary drivers of chronic mismatch disease.

A complementary perspective emerges from the housing adaptability literature [13], which distinguishes between adaptability as designed into the physical fabric of a building ("future-proofing") and adaptability as exercised by occupants through behavioural and social mechanisms ("coping strategies"). The most resilient buildings and communities are those where both forms of adaptability are available: where the physical fabric supports a range of occupant-controlled adjustments, and where the social infrastructure supports collective responses to conditions that

exceed individual capacity. This is the multi-scale, multi-mechanism adaptive system that the PANC framework proposes as the appropriate model for architecture in the Anthropocene.

6. THE CASE FOR MODIFIABLE CITIES

6.1 From Adaptive Buildings to Adaptive Urban Systems

The PANC framework, if applied only at the scale of individual buildings, will be insufficient. The evolutionary mismatch problem is systemic: it arises from the organisation of urban life as much as from the properties of individual structures. Cities concentrate population into thermally amplified environments (the UHI effect), separate residents from restorative natural environments, and impose temporal rhythms that chronically disrupt circadian physiology. Addressing evolutionary mismatch requires modifiable cities: urban systems designed for adaptability at multiple scales and over multiple time horizons.

Building on Toledo's research framework of adaptive housing and building performance evaluation [4, 5], the concept of the modifiable city can be articulated around three interconnected dimensions: **Thermal modifiability.** The urban thermal environment should be treated as an adaptive system that can be modulated in response to changing climate conditions. Green roofs and walls, urban forests, cool pavement materials, and distributed water features can collectively reduce urban surface temperatures and create accessible cooling environments. Critically, these interventions must be distributed equitably across urban neighbourhoods: thermal vulnerability and green space deprivation are strongly correlated with socioeconomic marginalisation. **Structural modifiability.** The physical fabric of cities should be designed and regulated for adaptive reuse and modification over time. Building standards should assess performance over the building's anticipated life under projected climate scenarios, rather than at a single design-stage snapshot [5, 12]. **Social and behavioural modifiability.** The capacity of urban residents to engage in adaptive behaviour, moving between thermally differentiated spaces, accessing green areas, adjusting activity patterns during heat events, depends on the social infrastructure of the city as much as its physical infrastructure. The cooperative behaviours that supported survival in the EEA must be consciously scaffolded into urban design.

6.2 Modifiability as Evolutionary Strategy: Lessons from Niche Construction Theory

Niche construction theory [1, 2] suggests that organisms actively modify their selective environments, and that these modifications can have heritable effects that alter the direction and pace of subsequent evolution. Human beings are the most extreme niche constructors on Earth: our cities, agricultural systems, and technological infrastructures constitute constructed niches of extraordinary complexity and power. The modifiable city concept is, in effect, an application of niche construction thinking to urban design: it proposes that cities should be designed not as static artifacts optimised for a fixed set of conditions, but as dynamically modifiable niches capable of responding to the changing relationship between human physiological needs and environmental conditions. Just as the EES identifies developmental plasticity as a key mechanism of evolutionary response to environmental change [2], modifiable cities provide the behavioural and structural plasticity through which urban populations can respond to climate change at a pace that biological evolution cannot match. Resilience in this evolutionary sense means not merely the restoration of prior function, but the expansion of adaptive capacity, the ability to maintain viable function across a wider range of conditions.

7. BIOPHILIC URBANISM AND THE OLD FRIENDS HYPOTHESIS

The "Old Friends" hypothesis proposes that many chronic inflammatory and psychiatric conditions of modernity are partly attributable to the severing of evolutionarily ancient relationships between human immune and nervous systems and the microbial, botanical, and ecological environments in which they were calibrated [3]. The microbiome of the soil, the pollen and volatile organic

compounds of diverse plant communities, the acoustic signatures of natural water and wind: these are not merely aesthetic amenities but biologically active stimuli that regulate stress responses, immune function, and attention restoration.

Biophilic urbanism, the systematic integration of natural elements into the built environment, has been growing in practice and evidence base. Green roofs, living walls, urban forests, rain gardens, and biodiverse green corridors contribute measurable effects on urban temperature, air quality, stormwater management, and biodiversity [8]. Within the PANC framework, they serve an additional function: they are the means by which the Old Friends stimuli are reintroduced into the constructed niche of the city, at the building, community, and urban scales simultaneously.

For individuals with sensory processing differences, neurodiverse conditions, or conditions of heightened stress and anxiety, access to biophilic environments has been shown to have particularly significant therapeutic effects. This supports the argument that designing biophilic urban environments is an accessibility issue as much as an environmental one. The modifiable city, designed around PANC principles, places the restoration of sensory and ecological coherence at the center of urban planning' not as an afterthought or an amenity for those who can afford urban green space, but as a fundamental requirement of an inclusive urban biosphere.

8. DISCUSSION AND CONCLUSION

This paper argued for the integration of evolutionary medicine principles with architectural and urban design practice across multiple scales, proposing the framework of Pro-Adaptive Niche Construction as a guide for designing buildings, communities, and cities that genuinely support human biological flourishing in the context of accelerating climate change. The argument rests on four theoretical pillars: the author's work in the philosophy of evolutionary medicine [1, 2, 3], which provides the conceptual foundations for understanding the built environment as a constructed niche; building science research on overheating, adaptive housing, and building performance evaluation [4, 5], which provides the empirical evidence base for the thermal modifiability agenda; established architectural theory on building adaptability and shearing layers [11, 12, 13], which provides the design framework for multi-scale modifiability; and the disability studies insight that designing for the physiological edges of human capability produces more resilient and inclusive environments for all [1]. The concept of inherited adaptability, drawn from the parallel between niche construction theory's emphasis on heritable ecological legacies and Brand's pace-layer model of buildings as layered temporal systems [11] represents this paper's central theoretical contribution. Buildings, communities, and urban fabrics do not merely serve their present occupants; they transmit physiological affordances and constraints to future occupants across multiple generations. In the context of climate change, the adaptive value of built environments, their capacity to support human biological function across a wide range of future conditions, is a public good of the highest order. Design decisions made today that reduce adaptive value will impose biological costs on future inhabitants in the same way that ecological decisions that reduce biodiversity impose costs on future ecosystems. Several challenges attend the realisation of this vision. Economic and regulatory frameworks governing urban development are poorly designed for adaptive or modifiable urbanism: they favour standardised solutions, fixed performance metrics, and lowest upfront cost [12]. The equitable distribution of adaptive infrastructure requires deliberate policy intervention. The interdisciplinary knowledge required to design PANC environments, spanning evolutionary biology, building physics, environmental psychology, disability studies, and urban planning, exceeds the training of any single profession.

These challenges are not arguments against the vision. They are arguments for the urgency of pursuing it. The functional gap between our Pleistocene-evolved bodies and the 21st-century climate is not narrowing; it is widening. Architecture and urban design are among the most powerful tools available to human societies for managing this gap. The framework proposed here, evolutionary literacy combined with adaptive design practice at the scales of room, building, block,

community, and city, represents a necessary step toward environments that function as adaptive membranes supporting biological life, rather than sealed boxes accelerating its deterioration.

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Integrating User Needs into Evidence-Based Green Space Redesign Using a Decision Matrix Approach

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Abstract. Residential green spaces are essential for urban livability, mental health, and social interaction. However, studies show that 40 to 60% of neighborhood green spaces are underused because their design does not meet users' social and behavioral needs. In the Gulf region, more than 55% of residents find neighborhood parks inadequate for family activities. This research aims to address the gap between post occupancy evaluation findings and actual design improvements using POE and user surveys. The study examines user behavior and needs in parks within the rapidly growing Al Falah District in Riyadh by creating a user centered. The research proposes a User-Centered Decision Matrix (UCDM) that links user needs with design interventions and measurable performance indicators to support evidence-based green space redesign.

1.Introduction

Residential green spaces leverage mental health, social interaction, and urban livability [1]. However, studies reveal that 40 to 60% of neighborhood parks are underused if their design does not meet users' behavioral needs [2]. In Riyadh, 55% of residents view parks as insufficient for family or culturally relevant activities [3]. Post-occupancy evaluations (POEs) are infrequently translated into design changes, which creates a continuous gap between research and practice [4], [5]. This study seeks to close this gap by developing a user-centered decision matrix (UCDM) that uses POE and survey data to create actionable design strategies. The Al-Falah District case study demonstrates the framework's use in rapidly growing Riyadh neighborhoods that have less green space than the WHO recommends [1],[6].

2.Litareture Review

Recent studies highlight the key role of residential green spaces in promoting well-being, social interaction, and urban livability [7]. User satisfaction and park use are strongly affected by factors like accessibility, perceived safety, thermal comfort, and spatial quality [8]. In hot climates, a lack of shade, seating, and adaptation to the climate often results in underuse and a "behavioral mismatch" between design and actual user needs [9] post-occupancy evaluation (POE) has been widely used to check the performance of urban open spaces and to understand user behavior [4], [10]. However, many studies show that POE findings seldom lead to real design changes [8]. Decision-support tools like multi-criteria analysis and participatory frameworks help prioritize design actions but often do not incorporate user feedback or spatial evaluation results [11],[12].

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Therefore, a clear gap exists in converting user needs and evaluation results into practical design strategies. This gap motivates the development of the User-Centered Decision Matrix (UCDM).

3. Methodology

The study area selected for this research was Al-Falah District in Riyadh, which was chosen due to its rapid growth, and its participation in the Humanizing Neighborhoods Initiative (Homoud & Jarrar, 2024). The availability of green space is below the 9 m² per person standard set by the WHO [1],[6]. (Fig.1)

3.1 Research Design: a mixed-method approach was used, which included: POE: Assessing spatial quality, thermal comfort, safety, accessibility, and activity patterns [4],[5] User Surveys: Gathering demographics, visitation frequency, comfort needs, activity preferences, and satisfaction [3]

3.2 Data Collection and Analysis: POE: Rating spatial and environmental conditions on a scale of 1 to 5 scale, Survey: Ranking user priorities and identifying perceived shortcomings, Need Prioritization: Combining POE and survey results using the principles of multi-criteria decision analysis [7].

3.3 Survey Components: The survey components shown (Table 1) align with Ledraa & Aldegheishem and Alymani. [3],[8].

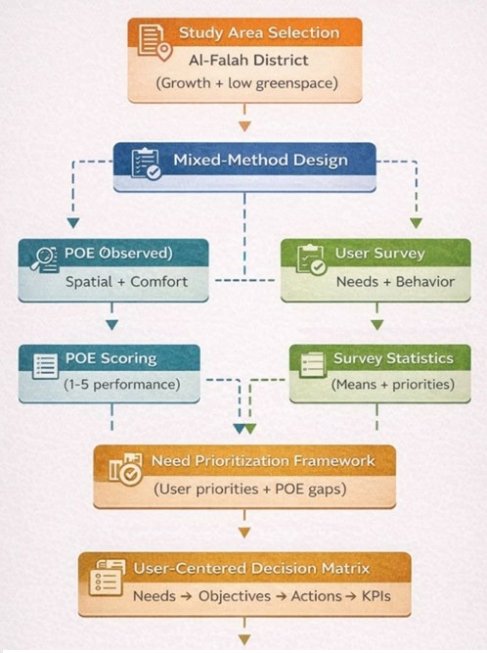


Fig.1 Methodology Workflow for Developing the UCDM for Green Spaces

Table 1: Design of Survey Questionnaire

Section	Survey Question	Objective	Type of Question
1. Demographics	What is your age group?	Identify demographic categories for analysis	Multiple choice
	What is your gender?	Understand demographic distribution	Multiple choice
	How many people live in your household?	Assess household size and family structure	Numeric/categorical
	How long have you lived in Al-Falah District?	Capture residency duration as a factor in park use	Multiple choice
2. Visit Frequency & Behavior	How often do you visit neighborhood parks?	Measure frequency of engagement	Multiple choice
	What is your main purpose for visiting the park?	Identify primary behavioral motivations	Multiple choice
	What time of day do you typically visit?	Link usage patterns with microclimate & comfort factors	Multiple choice
3. Comfort Perceptions	How would you rate the amount of shade in the park?	Assess thermal comfort quality	Likert scale
	How would you rate seating comfort and availability?	Evaluate seating adequacy	Likert scale
	How safe do you feel during evening hours?	Measure perceived safety (lighting, visibility)	Likert scale
4. Accessibility & Safety	Are Park entrances and paths easy to access?	Understand accessibility barriers	Multiple choice
	Are the walking paths well lit at night?	Evaluate lighting adequacy	Multiple choice
	Is the park easy to navigate for elderly or disabled family members?	Assess inclusivity	Multiple choice
5. Social Cultural Needs	Are there enough family-oriented spaces (picnic areas, family seating)?	Identify social infrastructure needs	Likert scale
	Do Park spaces accommodate group gatherings?	Evaluate cultural alignment for social use	Likert scale
6. Satisfaction Assessment	Overall, how satisfied are you with the park's design and features?	Assess global satisfaction	Likert scale
	Which park features do you use most often?	Link satisfaction with actual usage patterns	Multiple choice
	Which features do you avoid and why?	Identify barriers to use	Open-ended
	Select your top 3 needs for improving the park.	Determine user-prioritized design needs	Multiple choice ranking

7. Priority Needs for Improvement	What is the *most important* improvement to you personally?	Identify the highest-priority intervention	Single-choice ranking
	Additional comments or suggestions	Capture rich qualitative perceptions	Open-ended

4.Results

The selected neighborhood park in Al-Falah District is one of several small parks found throughout the area's residential landscape (Fig.2). Al-Falah has multiple small, similarly sized parks that fit within its superblock pattern. These parks usually occupy a single neighborhood plot, are surrounded by local streets, and feature a mix of grassy areas, a limited number of trees, some shade structures, and basic seating.

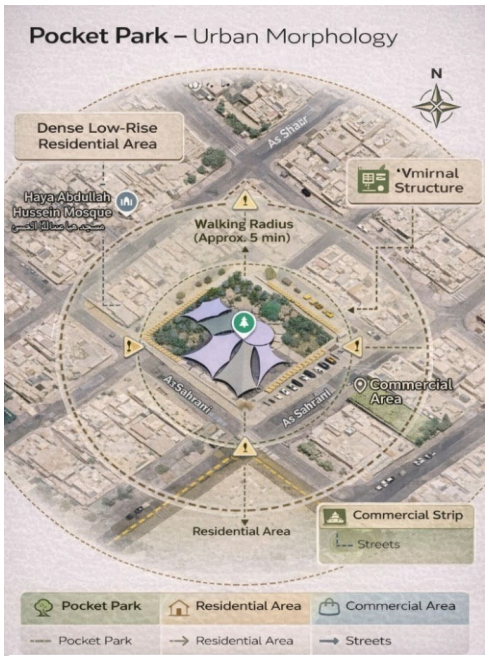


Fig. 2: Selected neighborhood park at Alfalah district

4.1 Spatial Condition and Environmental Performance (POE Findings): The POE showed a clear gap between the site's structural quality and its environmental conditions. The way the spaces are arranged supports movement and visibility, but contradicts climate adaptation, and zoning limits the user experience and extended stay (Fig.3,4).

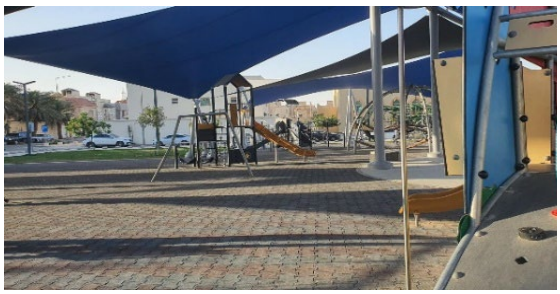


***Fig**. 3: Shaded areas are still exposed to intense heat and direct sunlight for most of the day.*



***Fig**. 4: The garden design did not adequately consider climatic conditions.*

4.1.1 Path Quality and Circulation Performance: The pedestrian network shows spatial continuity, clarity, and has enough width. The physical accessibility standards are partially met, especially in terms of slopes, width, and smooth surfaces. However, there is not enough shading, which makes it hard to use during the day. The materials on the surface trap heat, which limits users from staying out for long during the hottest times (Fig.5,6).



***Fig**. 5: Walkway paths oriented toward the north are unshaded.*

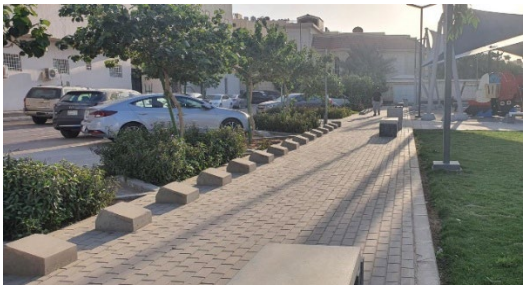


***Fig**. 6: Walkway paths toward the east have widths that do not allow more than two persons*

4.1.2 Shading and Thermal Comfort: The site has limited canopy coverage and does not have fixed shading structures. This leads to high solar exposure in seating and circulation areas. This situation results in user dissatisfaction regarding comfort and how long they stay. The absence of shade decreases thermal comfort and lowers social interaction, activity variety, and occupancy during the day. (Fig.7,8,9).



***Fig**. 7: Shaded areas in the garden are limited.*



***Fig**. 8: Children's play areas are not adequately shaded.*



***Fig**. 9: Seating areas are unshaded.*
.

4.1.3. Seating Configuration and Social Functionality: Seating elements are found throughout the site, but their placement and surroundings limit their effectiveness. Benches are spread out instead of grouped together, and many are in areas without shade. The orientation of the seating does not always encourage direct interaction, which reduces chances for socializing. Observations of how long people use the seating show that most people stay for a short time. (Fig.10,11,12).



***Fig**. 10: The seating design is uncomfortable*

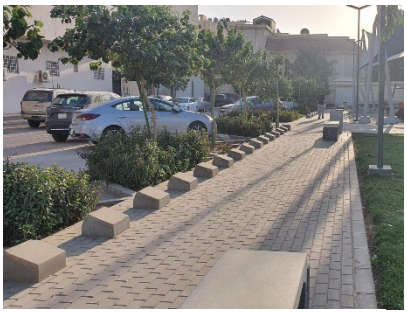


***Fig**. 11: Benches only exist along the walkway and are*



***Fig**. 12: Open waste bins are placed next to the seating areas.*

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4.1.4 Safety and Visibility: The open design of the park allows for clear sightlines and natural observation, which helps people feel safer. However, some environmental factors make it uncomfortable for users at certain times. This can reduce the number of people present, which affects the level of natural observation. Thus, Safety performance can be categorized as visually strong but environmentally compromised, (Fig13,14,15,16).



***Fig**. 13: The play areas is directly exposed to the*



***Fig**. 14: The barriers along the walkway paths do not provide safety or separation from the roadway.*

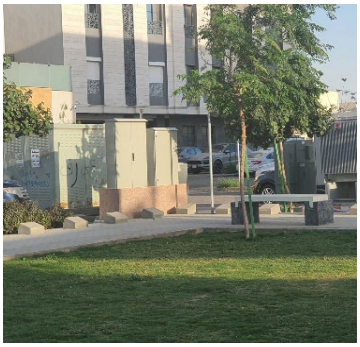
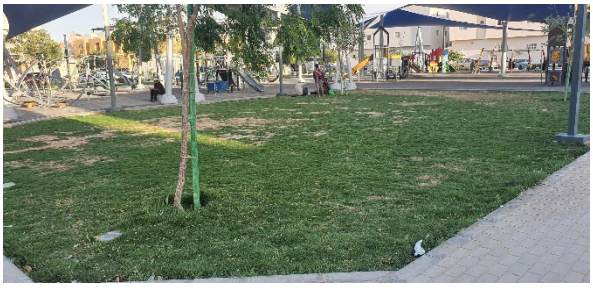


***Fig**. 15: Electrical rooms are directly adjacent to the garden and are not isolated to ensure user safety.*



***Fig**. 16: lighting allows clear visibility and provides safety*

4.1.5 Activity Zoning and Spatial Legibility: Functional zoning within the site is not clearly defined. Circulation, gathering, and passive recreation areas lack clear spatial variations. The absence of defined activity nodes reduces the hierarchy of spaces. This leads to the underuse of outer areas and restricts a variety of activities. The site currently operates primarily as a transitional or short-stay environment rather than a destination space (Fig.17,18).



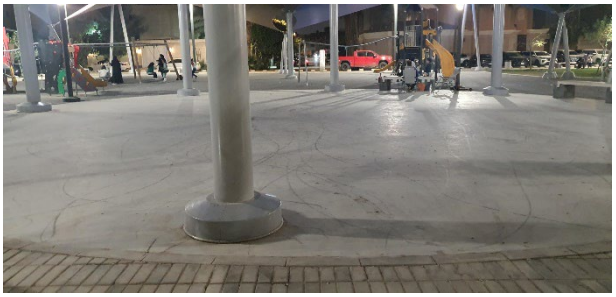


***Fig (1**7,18): green areas and open spaces are functionally underutilized.*

4.1.6 High- and Low-Performing Zones: High-performing areas are concentrated in visually central zones near to primary circulation routes. These areas benefit from openness and accessibility. Conversely, low-performing zones are characterized by:

- High solar exposure
- Limited seating comfort
- Weak identity
- Peripheral spatial positioning

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4.2 User Behavior Patterns (Based on Analysis of Survey) : Survey findings confirm that site usage is primarily climate-responsive rather than structurally constrained.

4.2.1 Temporal Occupancy Patterns: Evening use represents the dominant visitation period (~50%), (Fig.19), while morning, afternoon, and late-night visits each account for smaller shares. This distribution reflects thermal sensitivity, with occupancy shifting toward cooler hours. Reduced daytime summer use highlights that environmental comfort is the main factor influencing behavior over time.

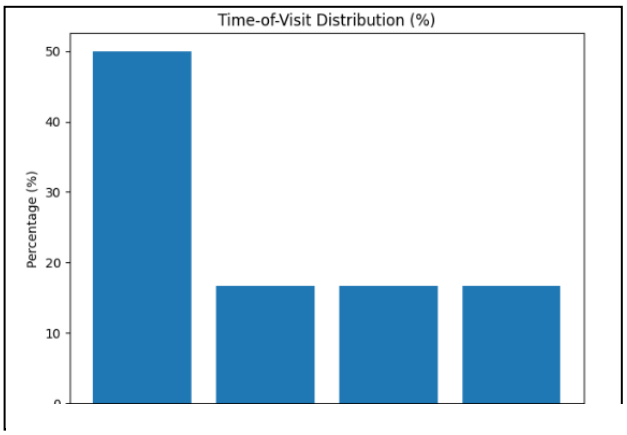


Fig. 19: Temporal Occupancy Patterns

4.2.2 Activity Profile: User activities show a mostly passive-use pattern. The most common behaviors are sitting for long periods, walking for short durations, and informal social interactions with family. There are few organized recreational activities and programs for youth, which indicate a lack of clear purpose and a low range of activities.

4.2.3 Performance Gaps: Importance–Satisfaction Matrix: The Importance–Satisfaction analysis identifies seating as the critical intervention zone (high importance, low satisfaction). Shade demonstrates moderate alignment between importance and performance, while safety registers comparatively higher satisfaction relative to perceived importance. These findings indicate that spatial performance inefficiencies are concentrated in environmental comfort provisions rather than security or accessibility (Fig. 20).

4.2.4 Underutilized Zones: Peripheral hardscape areas and exposed seating clusters show consistently low use. Spatial correlation with unshaded conditions indicates that this underuse is due to environmental factors rather than access related. This highlights the importance of climatic adaptation to improve how people use space.

4.3 User Needs and Preferences: Survey-based priority distribution confirms that environmental comfort remains the main factor influencing satisfaction. Respondents expressed demand for clearly defined family areas, children's spaces, flexible multi-use zones, and supportive seating layouts. Their preference for different spatial zones shows a need for more defined functions. Comfort-related factors rank highest in priority. Providing shade and improving seating quality emerge as the most critical interventions, followed by reducing heat and improving evening lighting.Users prefer clustered seating, semi-private family areas, and shaded communal spots, (Fig. 21).

4.3.1 Priority Hierarchy: Percentage-based ranking confirms a needs hierarchy led by shade and seating improvements, followed by spatial zoning clarity. Environmental retrofitting is therefore expected to have the highest immediate performance gains, especially in extending usable hours and changing occupancy patterns.

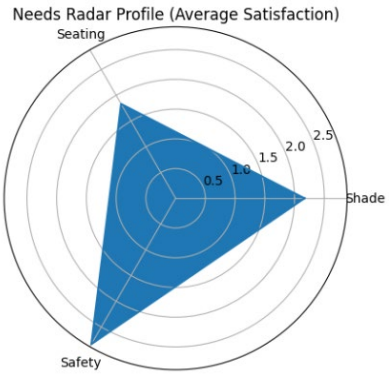


Fig. 20: Radar chart showing average satisfaction levels

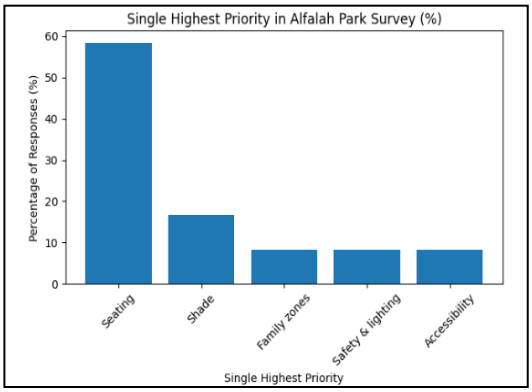


Fig. 21: Single Highest Priority

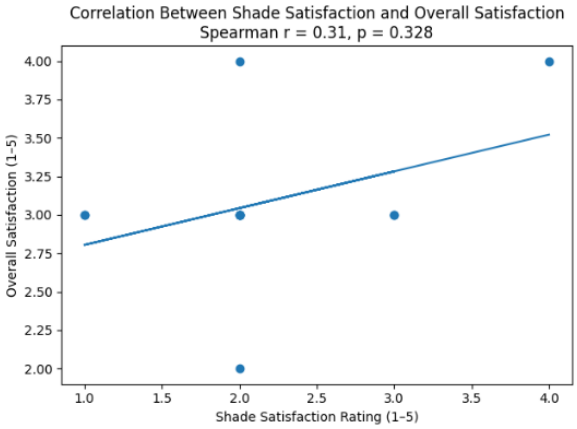


***Fig. 22**: Correlation between shade satisfaction and overall satisfaction*

A Spearman correlation analysis was conducted to examine the relationship between shade satisfaction and overall park satisfaction (Fig.22). Results indicate a positive but moderate association (r = 0.31), suggesting that improved shading may be associated with higher perceived performance. The study findings thus reveal a consistent pattern: environmental comfort deficits undermine social and functional performance. To operate these findings beyond descriptive evaluation, a structured practical process was required. This led to the design of USDM.

5. Development of the User-Centered Decision Matrix

The design of the UCDM was based on a systematic structure, starting with reframing the User-expressed needs into measurable design objectives as follows:

- The need for shade was operationalized as increasing thermal comfort performance.
- The need for family gathering areas was reframed as strengthening sociability and spatial inclusivity.
- The need for clearer activity zones was translated into enhancing spatial clarity and hierarchy.

Then this was followed by pairing each design objective with physical interventions as follows:

- Thermal comfort → Tree canopy expansion, pergolas, tensile shading systems
- Staying duration → Clustered ergonomic seating in shaded nodes
- Sociability → Semi-enclosed gathering pockets
- Spatial clarity → Zoning through paving differentiation and landscape buffers
- Safety enhancement → Layered lighting strategies

Interventions were selected based on feasibility, climatic relevance, and user priority ranking. Finally, each intervention was associated with KPIs to ensure measurability and accountability.

Thus, This Matrix establishes a feedback loop between user perception, spatial intervention, and measurable performance outcomes (Table 2).

Table 2: Actual user-centered decision matrix points (based on POE and Survey analysis

Observed Gap (POE + Survey Evidence)	Design Objective	Spatial / Technical Intervention	KPI (Measurable Indicator)
1. Insufficient Shade for Thermal Comfort: Only 35% of seating is shaded at peak hours	Increase thermal comfort	Add 3–4 pergolas + 8–10 large-canopy native trees; reposition benches under shade	≥70% shaded seating; ΔUTCI/PET −5–10 K during peak
2. Poor Night Visibility & Safety: Dark segments on the north path	Improve safety & extend evening use	Install LED poles @ 20–25 m spacing; trim shrubs to maintain clear sightlines	≥15 lux on main paths; perceived safety score +1.0
3. Family & Social Gathering Spaces Undersized	Support group and family-based use	Expand shaded family pads (picnic tables + stroller circulation); introduce semi-private clusters	Family zone occupancy +25%; average stay duration +20%
4. Accessibility Gaps (South West Corner): Poor stroller/wheelchair access	Ensure inclusive access	Add curb ramps (≤5% slope) + tactile paving at crossings; smooth path transitions	100% compliant entry ramps; tactile coverage at major nodes
5. Isolated Seating Reducing Sociability	Strengthening social interaction	Reconfigure benches into clusters (4–6 seats per node); orient face-to-face	Seating occupancy +30%; group-use frequency increase
6. Underused Peripheral Hardscape Zones	Activate low-performing areas	Introduce shaded micro-activity nodes (fitness element / play feature / shaded bench pocket)	Peripheral occupancy +20%; reduced spatial vacancy rate
7. Weak Activity Zoning & Spatial Legibility	Improve spatial hierarchy and clarity	Use paving differentiation + low planting buffers to define zones	User-reported clarity scores +1.0; activity diversity index +15%
8. Limited Green Coverage (Heat Island Effect)	Enhance Environmental resilience	Increase canopy cover to ≥40% of site area; introduce bioswale planting strips	Surface temperature −3–5°C; canopy coverage ≥40%
9. Short Duration of Stay (Heat-Driven Exit)	Extend stay duration	Combine shade + misting (seasonal) + water feature cooling	Avg. stay duration +25%; daytime occupancy +15%
10. Limited Youth Engagement Spaces	Diversifying activity profile	Add a small flexible play/fitness zone near a visible central area	Youth activity frequency +20%; activity diversity score +15%

6. Discussion

6.1 Cultural and Climatic Embeddedness

Public-space use in Riyadh is shaped by extreme heat and family-oriented social norms. The preference for shaded seating, clustered family zones, and evening use aligns with research showing that thermal comfort is the primary driver of outdoor activity in hot-arid climates [13], [14]. Shade has been shown to increase duration of stay [15], and public spaces often function as extensions of domestic life, where dispersed seating limits group interaction [16]. The observed patterns therefore reflect both environmental and cultural conditions.

6.2 Explaining the Design–User Gap

Environmental-behavior theory explains the mismatch between design intent and user needs: environments prioritizing form over behavioral affordances underperform [19]. Key misalignments include limited shade and extensive hardscape, which reduce comfort despite strong evidence supporting microclimatic mitigation [14], [16]. Weak programmatic clarity—unclear zoning and mixed circulation—lowers spatial legibility [17]. Socially, the layout does not support group use, highlighting the absence of user feedback in the design process [22].

6.3 The Decision Matrix and Closing the POE–Design Gap

This study contributes a User-Centered Decision Matrix that translates POE findings into actionable design criteria. It (1) converts user perceptions into measurable goals, such as improved thermal comfort hours [23]; (2) links interventions to performance indicators like canopy coverage or occupancy; and (3) supports iterative design through benchmark-based reassessment. The matrix reframes POE from an evaluation tool into a design-refinement mechanism.

6.4 Implications for Practice

The matrix supports integrating user-focused and climate-responsive principles into municipal and design workflows (Fig. 23). Embedding POE within governance and professional processes can improve public-space performance in hot-arid cities.

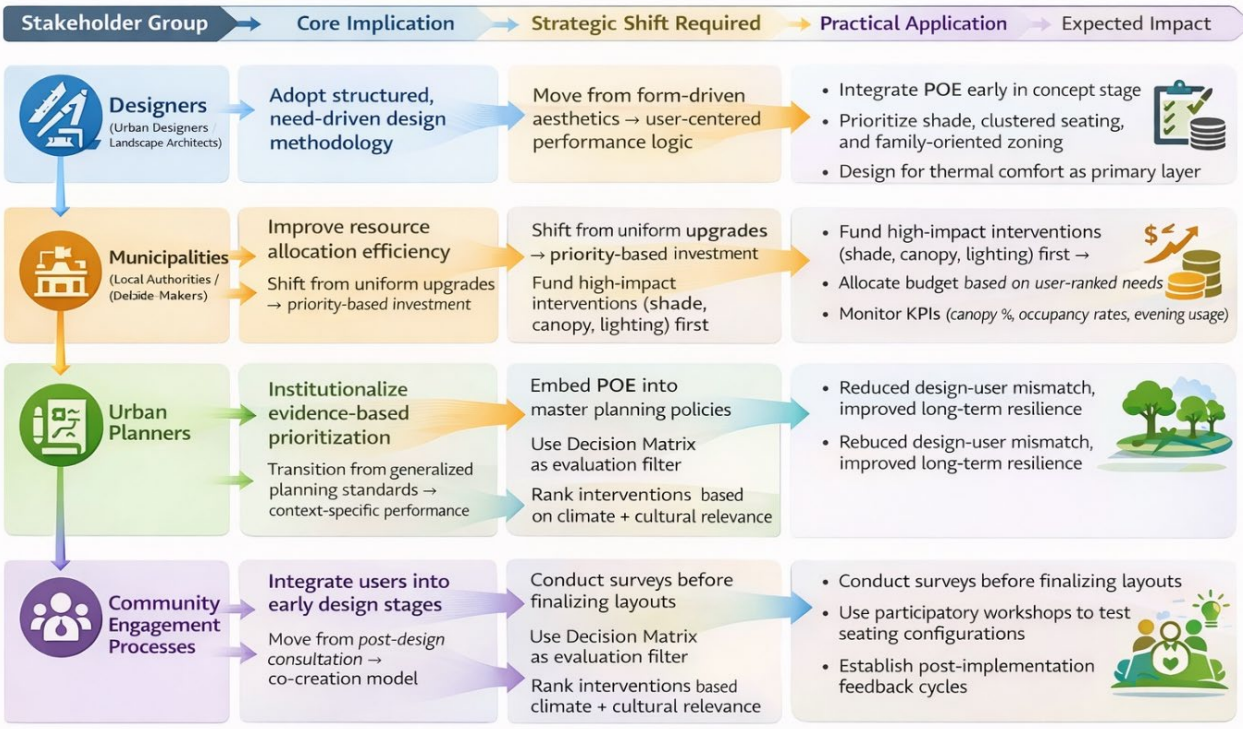


Fig. 23 Practical Implications Framework: Translating POE Findings into Professional Action

7. Conclusion

This study shows that in hot-arid cities, environmental adaptability—especially thermal mitigation and socially supportive layouts—is central to effective public-space performance. The case study revealed that high heat exposure, dispersed seating, and weak spatial organization limit use and social engagement. By converting POE findings into a User-Centered Decision Matrix, the research links user needs to measurable, evidence-based design actions. The matrix offers a practical and replicable tool for climate-responsive green-space planning in Gulf cities. The accompanying stakeholder framework clarifies how designers, planners, municipalities, and communities can integrate POE into decision-making, supporting a shift toward user-driven and climate-responsive urban design.

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Public Space Activation as a Strategic Framework for Sustainable Urban River Recovery: A Comparative Case Study of Zarqa and Vinalopó

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Keywords: Urban River Recovery, Public Space Activation, Zarqa River, Vinalopó River, Water-Scarce Urbanism, Socio-Spatial Resilience, Historic Urban Landscape, Political Ecology, Urban Stream Syndrome, Blue-Green Infrastructure, River Urbanism

Abstract. The Zarqa River in Jordan represents a degraded urban waterway. Attempts at remediation have been technically fragmented and politically dispersed, consistently failing to reconnect the river to urban life. This paper argues that such failure is not merely environmental; it is spatial and cultural. Drawing on a decade of fieldwork across Jordan and Spain, this research advances public space activation as the missing strategic layer in urban river recovery frameworks. Through systematic comparison with the Vinalopó River in Elche, Spain, where landscape-led interventions transformed a hostile concrete channel into a celebrated civic connector, the study demonstrates that sustainable recovery requires the simultaneous integration of three interdependent pillars: ecological restoration, spatial integration, and cultural continuity. Public space activation is positioned not as an aesthetic supplement to technical projects, but as the structural mechanism through which environmental recovery becomes socially legible and durable. The paper offers a transferable framework applicable to water-scarce, rapidly urbanising contexts where rivers remain trapped in remediation cycles without civic reintegration.

1. Introduction

Urban rivers are not passive features of the landscape; they are, as Swyngedouw [18] argues, socio-natural assemblages, shaped by political economies, hydraulic engineering decisions, and the everyday practices of urban life. When rivers are degraded, the loss is never merely ecological. In water-scarce regions, this damage is compounded by the scarcity imperative: rivers become controlled resources rather than living systems, managed for extraction and flood control rather than civic or ecological value.

The Zarqa River in Jordan is an instructive case of this dynamic taken to its limit. Once the most productive freshwater source for the Amman-Zarqa basin, the river now constitutes what Jordan's Ministry of Environment has described as one of the country's principal "environmental black spots". More than 52% of Jordan's industrial plants are located within the basin; untreated wastewater from overburdened sewage infrastructure enters the river continuously; and the communities that once depended on it for agriculture and recreation now regard it with fear and disgust (Alshawabka [5]). Despite decades of international funding, from USAID, the EU, the World Bank, and Germany's GIZ, restoration interventions have remained narrowly technical, cycling through wastewater plant upgrades without addressing the river's spatial disconnection from urban life.

The Vinalopó River in Elche, Spain, presents a fundamentally different trajectory. Channelised in the 1970s to manage flood risk, the river became a 40-metre-wide concrete barrier physically dividing the city's historic core from its expanding suburbs. What transformed the Vinalopó was not further engineering, but design: the Braided Valley project (Grupo Aranea, 2009-2013)

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introduced pedestrian bridges, carved pathways, native vegetation, and recreational amenities into the channel, converting an infrastructural void into a celebrated civic spine. The project received the European Prize for Urban Public Space in 2014 CCCB [9], not for ecological sophistication but for its success in reintegrating the river into daily urban experience.

This paper argues that public space functions as the structural interface between ecological process and social life, and that without it, even the most technically ambitious restoration efforts will fail to secure durable resilience. The comparative case study analysis draws on the case studies of Jordan and Spain, and a qualitative assessment of policy documents, design outcomes, and community perception data.

Research Question: *How can public space activation function as a strategic framework for sustainable urban river recovery in water-scarce, rapidly urbanising contexts, and what transferable lessons does Zarqa derive from Vinalopó?*

2. Theoretical Framing

2.1 The Limits of Technical Remediation

Four decades of river restoration research reveal a persistent pattern: engineering-led interventions consistently underperform. Bernhardt & Palmer [8] synthesised over 37,000 stream restoration projects in the US and found that the majority improved channel stability without measurably enhancing ecological function or community engagement. The reason, they argued, is structural: restoration projects tend to treat rivers as isolated problems rather than as components of urban socio-ecological systems. Walsh et al. [19] identified this failure mode as the "urban stream syndrome", a constellation of hydrological, biological, and geomorphological pathologies that cannot be addressed through single-sector technical interventions.

Water-scarce contexts amplify these limitations. Abdulla and Al-Omari [1] demonstrated that in semi-arid catchments like the Zarqa basin, climate variability compounds pollution and over-extraction, making conventional restoration targets, stable base flows, riparian vegetation, fish populations, effectively unreachable without first addressing the governance and spatial conditions that sustain degradation. Wohl [21] further argues that river connectivity, longitudinal, lateral, and vertical, is the fundamental prerequisite for ecological resilience, and that channelisation systematically eliminates it. In the Zarqa, every dimension of connectivity has been compromised: longitudinally by industrial abstraction, laterally by concrete reinforcement and encroachment, and vertically by aquifer depletion.

2.2 Nature-Based Solutions and the Social Dimension

The emergence of nature-based solutions (NBS) and blue-green infrastructure has opened important new ground by insisting on the co-production of environmental and social benefits Kabisch et al. [13]. However, NBS frameworks often remain insufficiently attentive to the morphological and cultural dimensions of urban rivers. Hohensinner et al. [12] argue that successful hydrogeomorphic interventions must work within, and creatively against, the structural constraints imposed by prior engineering decisions. This is precisely the insight Grupo Aranea [6] exploited in Elche: rather than removing the concrete channel, they used its geometry as a design scaffold. The UNESCO [18] Recommendation on the Historic Urban Landscape provides a further conceptual resource. By expanding heritage management beyond monument preservation to encompass layered socio-ecological systems, HUL creates normative space for treating degraded rivers as recoverable cultural assets. Deacon [10] argues that HUL's practical value lies in its insistence on the simultaneity of natural and cultural values, an insistence directly relevant to rivers

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like the Zarqa and Vinalopó, whose degradation has stripped away both ecological and historical meaning.

3. The Zarqa River: A Crisis of Governance, Pollution, and Spatial Abandonment

3.1 Accumulation of Damage

The Zarqa River rises northeast of Amman and flows approximately 105 kilometres before entering King Talal Reservoir and eventually the Jordan River system. Its basin encompasses Jordan's two most populous cities and houses over half the country's industrial infrastructure, tanneries, petroleum refineries, metal works, abattoirs, pharmaceutical plants, and hundreds of smaller manufacturing operations [4]. Al-Omari et al. [4] identify five primary pollution pathways: industrial discharge (heavy metals including chromium, nickel, and cadmium from tanneries and metalworks); wastewater treatment plant effluent overflow during peak demand; direct sewage inflows from informal settlements and leaking sewer infrastructure; solid waste dumping on riverbanks; and agricultural runoff from fields irrigated with reclaimed water. During summer months, when base flow drops to 2-3 million cubic metres per month, treated and untreated wastewater constitute virtually the entire river flow [4]. Fish populations have been extirpated. Two amphibian species, the Southern banded newt and Eastern spadefoot, are considered locally extinct [4]. The river emits strong odours across wide areas, particularly in summer, and episodic algal blooms have been documented at King Talal Reservoir.



Figure 1. *Polluted Zarqa River in Jordan (Source: Alkayed, 2019)*

3.2 Governance Fragmentation and Institutional Failure

The Zarqa's degradation cannot be explained by technical incapacity alone; it reflects a structural governance failure. Water allocation is controlled by the Ministry of Water and Irrigation; pollution regulation by the Ministry of Environment; solid waste management by municipalities; and land use planning by the Ministry of Municipal Affairs. There is no integrated basin-level authority, no coordinated restoration mandate, and no mechanism for pooling the financial and technical capacities of these separate bodies (Alshawabka [5]). International donors, including USAID, the EU's Euro-Mediterranean programme, and Germany's GIZ, have provided recurring grants of $50-60 million per cycle, but as Jordan's Ministry of Irrigation acknowledged to Gulf News [11], the bulk of this funding has consistently been redirected toward expanding wastewater treatment capacity rather than restoring the river itself.

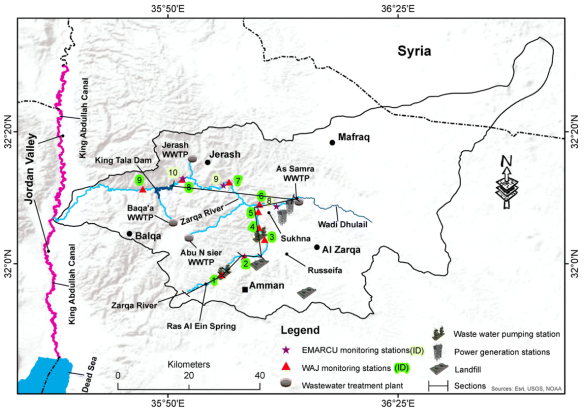


Figure 2. *Map of Zarqa River Basin, showing monitoring stations and pollution sources (Source: Al-Omari et al. 2019)*

The consequence is a remediation trap: each intervention addresses a downstream symptom without dismantling the upstream conditions that reproduce degradation. Jordan's Ministry of Environment conducted a field survey of 349 facilities along the river corridor and produced an action matrix assigning pollution reduction responsibilities, but enforcement remains weak and coordination across ministries minimal Zawya [22]. The 2023 Zarqa River Basin Restoration and Development Program, supported by the Korea Green Growth Trust Fund, represents the most ambitious attempt yet to break this cycle. Its four-pillar framework addresses pollution source identification, sustainable water resource management, ecological restoration, and green economic development WBGKGGTF [20]. As of early 2026, however, the programme remains in baseline study and stakeholder consultation phases.

3.3 The Missing Socio-Spatial Dimension

What the 2023 programme still does not adequately address, and what decades of prior intervention have systematically overlooked, is the socio-spatial abandonment of the Zarqa corridor. In the Jannah neighbourhood and adjacent riverside areas, the riverbank is not a civic amenity but a liability: land values have collapsed Alshawabka [5], residents avoid the waterfront, and younger generations have no experiential connection to the river Abed and Aljibarat [2]. Swaiss & Rababeh's [17] survey of community perceptions confirmed that residents regard the Zarqa primarily as a health hazard and governance failure; positive cultural associations have largely dissolved. Without accessible riverfront spaces, residents have no stake in recovery; without public investment in spatial quality, there is no constituency for the ecological restoration that spatial activation requires.

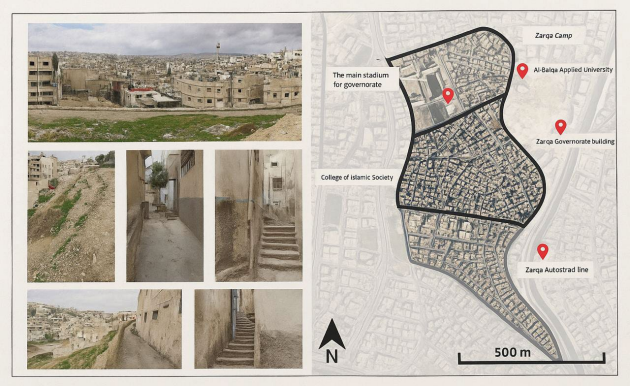


Figure 3. *Jannah's neighbourhood: map and selected views (adapted from Abed & Aljibarat, 2023)*

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4. The Vinalopó River: From Infrastructural Barrier to Civic Connector

4.1 The Channelisation Legacy

The Vinalopó River flows southward through the province of Alicante before reaching the Mediterranean near Santa Pola. In Elche, the river is inseparable from the Palmeral, the World Heritage Arab-engineered palm grove, dating to the 10th century, which the river historically irrigated. The relationship between the Vinalopó and the Palmeral constitutes one of Spain's most distinctive urban-ecological heritage assemblages CCCB [9]. However, severe floods in 1941 and 1970 prompted authorities to channelise the river through the city. The resulting concrete structure, averaging 40m in width and 5m in depth, lined with riprap, physically severed the city in two, creating a psychological and spatial barrier that divided the historic centre from newer southern suburbs and made the Palmeral effectively peripheral Aranea [6].



Figure 4. *Aerial view of Vinalopó River post-restoration, showing integrated public paths (Source: Aranea, 2014)*

4.2 The Braided Valley Intervention

By the 1990s, public dissatisfaction with the sterile channel had become a civic mobilisation. Local artists began painting murals on the concrete walls, a spontaneous spatial reclamation that preceded formal design by two decades. Over-extraction of groundwater and a semi-arid climate reduce it to a trickle; its flow declines from about 0.85 m^3/s near the source to 0.38 m^3/s downstream and dry spells predominate. Civil society organisations demanded ecological restoration and public access. In 2009 the city of Elche launched a competition with 140 entries, to transform the dry channel into a park. Grupo Aranea's proposal was selected [6]. The winning Braided Valley proposal envisioned interlaced paths and bridges that mimic braided channels and weave across the riverbed.



Figure 5. *Vinalopó before restoration, depicting channelized void with graffiti (Source: Molina, 2025)*

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The design premise was disciplined and counterintuitive: retain the concrete channel rather than attempting costly removal, and subvert its infrastructure logic through spatial creativity. The intervention introduced a series of sinuous pedestrian bridges with varying curvatures and materials, reconnecting previously isolated neighbourhoods. Pathways were carved into the concrete embankments, allowing residents to descend into the channel. The channel floor was redesigned with flood-tolerant lawns, play areas, and sports facilities. Construction proceeded in phases between 2009 and 2013, beginning at the historic centre where disconnection was most acute, before extending upstream and downstream CCCB [9]. The project received the European Prize for Urban Public Space in 2014, commended explicitly for transforming a "neglected infrastructural void" into an urban connector.

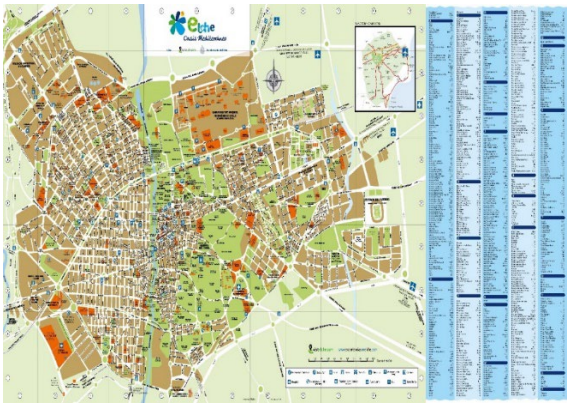


Figure 6. *Public space and cultural route integration along the Vinalopó River, Elche (VisitElche official city map, Spain)*

4.3 Outcomes and Limitations

Post-occupancy assessments reveal substantial socio-spatial gains. Pedestrian counts across the channel increased dramatically following completion. Crime rates in adjacent neighbourhoods declined. Residents report heightened civic pride and a renewed sense of identity linked to the river (Swaiss & Rababeh [17]). The Palmeral gained new visitors drawn through the channel pathway. These outcomes validate the central claim that spatial accessibility and cultural reconnection can transform public perception and behaviour even in the absence of comprehensive ecological restoration. The river remains hydrologically intermittent and continues to receive upstream pollution; true ecological restoration, constructed wetlands, habitat islands, floodplain reactivation, was not incorporated into the design. Maintenance costs are high: graffiti management and vegetation upkeep demand sustained municipal expenditure. Critics have argued that the project's spatial ambition was not matched by watershed-level ecological strategy (Hohensinner et al. [12]).

5. Comparative Analysis: Divergent Trajectories, Shared Lessons

5.1 The Structural Divergence

The Zarqa and Vinalopó cases represent not merely different stages along a common recovery trajectory, but fundamentally different understandings of what urban river recovery is for. In Zarqa, recovery has been framed as a pollution problem: a technical condition requiring regulatory enforcement, infrastructure investment, and industrial compliance. In Elche, recovery was framed as a spatial problem: a condition of urban disconnection requiring design intervention that could restore civic relationships damaged by engineering. Neither framing is complete, but the Vinalopó framing has generated tangible socio-spatial resilience; the Zarqa framing has not.

From a morphological perspective, both rivers demonstrate how channel form shapes recovery potential. The Vinalopó's concrete channel, though ecologically impoverished, provided a stable

geometrical framework within which pedestrian design could operate. Grupo Aranea's genius was to recognise this constraint as a resource rather than an obstacle. In Zarqa, the morphological challenge is more severe: the river corridor is fragmented by industrial zones, informal settlements, and riprap-lined embankments with minimal vertical differentiation. The absence of continuous accessible edges limits the design strategies available. This does not foreclose spatial activation but does require a phased approach: environmental stabilisation must create minimum thresholds of safety and legibility before design-led interventions can be realistically planned.

5.2 Cultural Narratives and Civic Ownership

Cultural continuity emerges from both cases as a determinant of recovery durability that technical frameworks systematically underestimate. In Elche, the Vinalopó's historic connection to the Palmeral heritage landscape provided a narrative resource that the Braided Valley project consciously activated. The design's success in generating civic pride was not incidental to its spatial qualities; it was enabled by the prior existence of a cultural story worth reconnecting to. In Zarqa, that narrative foundation has been substantially eroded. Residents in their seventies can still recall fishing and picnicking on the river Gulf News [11]; younger generations have no positive experiential reference. Rebuilding those associations requires not only spatial design but also community programming, heritage interpretation, and long-term public engagement, dimensions absent from the current restoration framework. The UNESCO HUL Recommendation (2011) provides a policy instrument for requiring this cultural dimension in recovery planning. Deacon [10] argues that HUL's most transformative potential lies precisely in its insistence on layered social meaning as a conservation value. For the Zarqa, operationalising HUL would mean treating community memory, riverside agricultural heritage, and the traditional relationship between the river and Zarqa City's neighbourhoods as assets to be recovered alongside water quality and riparian vegetation.

6. Towards a Strategic Framework: Three Interdependent Pillars

The comparative analysis supports a three-pillar model of sustainable urban river recovery in which public space activation operates as the integrating mechanism across ecological, spatial, and cultural dimensions. This is not a sequential model, it is a simultaneous one. The critical insight from both cases is that sequencing ('first fix the ecology, then design the space') reliably fails because ecological recovery processes require social support, monitoring, and investment that only civic engagement can sustain over the long term.

6.1 Ecological Restoration

The ecological pillar encompasses pollution abatement, riparian vegetation restoration, hydrological connectivity enhancement, and floodplain reactivation where morphological conditions permit. For the Zarqa, this means, in the immediate term, reducing industrial discharge through enforcement rather than voluntary compliance, upgrading the As Samra wastewater treatment plant to tertiary standards, and eliminating direct sewage inflows from informal settlement areas. In the medium term, strategic floodplain reactivation at the Zarqa's upper reaches (where channelisation is less severe) could restore lateral hydrological connectivity and begin rebuilding riparian habitat. The Vinalopó case demonstrates that full hydrological restoration is not a prerequisite for socio-spatial recovery, but it also demonstrates that without ecological improvement, socio-spatial gains remain fragile.

6.2 Spatial Integration

Spatial integration requires the creation of continuous, accessible, and safe riverfront environments that reconnect the river corridor to the surrounding urban fabric. For the Zarqa, this cannot happen without first achieving minimum ecological thresholds, odour reduction, visible pollution elimination, and basic safety, but planning for spatial integration should begin now, not after

remediation is declared complete. The Vinalopó model offers specific transferable tactics: working within existing channel geometry rather than removing it; prioritising pedestrian connectivity over vehicular access; designing for flood resilience; and phasing construction to deliver visible improvements in high-use areas first. Key design moves for Zarqa would include: accessible riverbank pathways in the Jannah neighbourhood; one or two focal public spaces near the city centre to generate civic interest; and illuminated routes to enable evening use.

7. Conclusions

This paper has argued that the Zarqa River's recovery failure is not primarily a technical problem, and cannot be solved by technical means alone. The river is trapped in a remediation cycle because the strategic framework guiding intervention is too narrow: it addresses pollution without addressing disconnection, and it improves water quality without creating the civic conditions that give communities a stake in the river's future. The Vinalopó River's transformation demonstrates that spatial creativity and cultural reconnection can generate genuine socio-ecological resilience even in the presence of ongoing ecological limitations, and that public space activation is the mechanism through which environmental recovery becomes durable.

Three conclusions follow for research and practice. First, sustainable urban river recovery requires the simultaneous pursuit of ecological restoration, spatial integration, and cultural continuity, not their sequential ordering. Second, public space activation functions as the strategic interface between these dimensions, making ecological processes socially legible and creating the civic ownership without which long-term maintenance and protection of restored corridors is impossible. Third, in heavily degraded contexts like the Zarqa, minimum ecological thresholds must precede full spatial design, but planning for spatial integration should proceed in parallel with remediation from the outset. In terms of limitations, this analysis is based on comparative case studies and fieldwork, which may introduce limitations related to scope, data comparability across countries, and reliance on secondary policy documents for certain claims.

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Adaptive Reuse as Heritage-Led Urban Regeneration: A Qualitative Case Study Analysis of Diriyah and AlUla Old Town

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Keywords: Adaptive Reuse, Heritage-Led Regeneration, Cultural Continuity, Comparative Case Study, Qualitative Analysis

Abstract Historic urban sites are increasingly challenged by rapid modern development, which can diminish their relevance within contemporary cities. In Saudi Arabia, adaptive reuse has emerged as a strategic approach to revitalize these sites and reintegrate them into active urban life. This study examines adaptive reuse as a heritage-led urban regeneration strategy through a qualitative comparative case study of Diriyah and AlUla Old Town. The research focuses on adaptive reuse interventions within the historic urban fabric of these two sites. Data sources include academic literature, UNESCO documentation, conservation management plans, and official development authority publications. Using document analysis and cross-case thematic comparison, the study evaluates how conservation strategies are implemented and how new functions are integrated within historic structures. The findings demonstrate that adaptive reuse in both cases preserve historic urban morphology while introducing cultural and tourism-oriented programming. They also show that conservation strategies maintain material authenticity and spatial continuity while accommodating contemporary infrastructure. Finally, the study reveals that adaptive reuse repositions heritage districts from static monuments into active and accessible components of contemporary urban life. The study highlights how adaptive reuse functions not only as a conservation approach but as a structured mechanism for heritage-led urban regeneration in the Saudi context.

Introduction

Historic urban sites play a critical role in shaping cultural identity, collective memory, and the character of cities. However, rapid urban development has increasingly challenged the ability of historic districts to remain relevant and functional within contemporary urban life. While preservation efforts have traditionally focused on maintaining physical fabric, such approaches can limit the capacity of heritage sites to respond to evolving social needs and urban change.

Adaptive reuse has emerged as an approach that responds to this challenge by integrating heritage conservation with contemporary functions. Rather than preserving historic sites as static monuments, adaptive reuse allows existing structures and urban areas to accommodate new social, cultural, and economic activities while retaining their historical significance [1]. It is also widely recognized for its contribution to sustainability, as extending the life cycle of existing buildings reduces the environmental impact associated with demolition and new construction [2].

In Saudi Arabia, heritage-led development has gained increasing attention as part of broader cultural and urban initiatives. Projects such as Diriyah and AlUla Old Town reflect a shift toward reactivating historic urban areas as living environments that support cultural continuity and contemporary urban activities [3].

This paper examines how adaptive reuse is applied in selected Saudi heritage sites and explores its role in supporting cultural continuity while accommodating modern urban functions. Using a

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qualitative comparative case study approach supported by literature review and document analysis, the study identifies key strategies through which historic urban areas are revived and reactivated, and assesses their contribution to sustainable and culturally responsive urban development. The study is guided by the following research question: How does adaptive reuse function as a heritage-led urban regeneration strategy in Diriyah and AlUla Old Town? To address this question, the analysis focuses on the adaptive reuse strategies implemented within each site and the spatial and urban impacts of these interventions.

Methodology

This study adopts a qualitative comparative case study approach to examine adaptive reuse as a heritage-led urban regeneration strategy. Diriyah (At-Turaif District) and AlUla Old Town were selected due to their heritage significance, structured governance models through the Diriyah Gate Development Authority (DGDA) and the Royal Commission for AlUla (RCU), distinct historic urban typologies, and advanced stages of redevelopment. These criteria allow for a comparative analysis of implemented adaptive reuse strategies within two major Saudi heritage projects.

The study draws on multiple data sources, including academic literature on adaptive reuse and heritage-led regeneration, UNESCO nomination and management documents, official planning frameworks, and publications from DGDA and RCU. These documents provide insight into conservation strategies, planning approaches, and redevelopment frameworks guiding both projects.

The analysis involved reviewing and organizing the material around key themes derived from the research question, including adaptive reuse strategies, conservation approaches, integration of contemporary infrastructure, and urban activation. Each case was examined individually before comparing shared patterns and contextual differences across both sites.

The analysis is based on multiple documentary sources, which helps ensure consistency and reliability. However, the study relies on publicly available materials and does not include interviews or quantitative data. The findings therefore focus on spatial and strategic aspects of adaptive reuse.

Theoretical Background: Heritage, Identity, and Adaptive Reuse

Architectural heritage is commonly understood as the physical expression of cultural values, historical continuity, and collective memory embedded within the built environment. Beyond individual monuments, heritage includes historic urban areas, traditional settlements, and everyday buildings that reflect social practices, local knowledge, and spatial traditions. This broader understanding emphasizes heritage as a living system rather than a collection of isolated objects, particularly within urban contexts, heritage contributes to a sense of place and identity by linking present communities with their historical and cultural roots [4]. As cities evolve, the challenge lies not only in preserving physical fabric but also in sustaining the cultural meanings and social relevance associated with historic environments.

The concept of identity in architecture is closely connected to heritage, as built forms often serve as expressions of local culture, climate, and ways of life [5]. Architectural identity is shaped through materials, construction techniques, spatial organization, and relationships between buildings and public space. In historic urban settings, identity emerges from the continuity of these elements over time. However, rapid modernization and globalization have introduced new architectural forms and functions that may conflict with traditional urban character. This tension has intensified the need for approaches that allow heritage environments to adapt while maintaining their distinctive identity, rather than freezing them in a particular historical moment.

Adaptive reuse has emerged as a key strategy in addressing this challenge. Unlike preservation or restoration approaches that aim to maintain buildings in a fixed historical state, adaptive reuse allows historic structures and urban areas to be modified for new uses while retaining their cultural

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and architectural significance [1,6]. By introducing contemporary functions into existing fabric, adaptive reuse enables heritage sites to remain active and relevant within modern urban life. This approach acknowledges that change is an inherent part of urban evolution and that heritage can accommodate transformation without losing its value.

In addition to its cultural role, adaptive reuse is widely recognized for its contribution to sustainability. Reusing existing buildings reduces the need for demolition and new construction, thereby conserving material resources and minimizing environmental impact [2]. Socially, adaptive reuse supports community engagement by reactivating historic areas as spaces for cultural, educational, and economic activities. Economically, it can stimulate urban regeneration by attracting tourism, investment, and public life to previously underutilized heritage districts. Together, these dimensions show that adaptive reuse links heritage conservation with sustainable urban development.

Within this theoretical framework, adaptive reuse can be understood as a process that transforms heritage from static preservation into a dynamic urban system. Rather than isolating historic sites from contemporary life, adaptive reuse integrates them into ongoing urban processes, allowing heritage to function as a living component of the city. This perspective provides the conceptual foundation for analyzing how adaptive reuse is applied in selected Saudi heritage sites and how it contributes to cultural continuity and urban vitality.

Adaptive Reuse in Saudi Heritage Sites

Adaptive reuse has become a central strategy in the revitalization of heritage sites in Saudi Arabia, particularly within historic urban areas that hold cultural, social, and symbolic significance. Rather than isolating heritage sites as preserved artifacts, recent approaches emphasize their reintegration into contemporary urban life through new functions and programs. This section examines how adaptive reuse has been applied in selected Saudi heritage sites, focusing on the relationship between conservation, transformation, and urban activation. Through case study analysis, the section explores how historic fabric is preserved while accommodating contemporary cultural, social, and economic uses.

Case study: Diriyah. *Historical and urban context*. Diriyah is one of the most significant heritage sites in Saudi Arabia, known as the birthplace of the first Saudi state and a key reference for Najdi architectural and urban traditions. The historic district is characterized by earthen architecture, compact urban fabric, courtyard-based buildings, and narrow streets that respond to local climatic conditions. These features reflect traditional Najdi construction methods and social organization, where architecture was closely linked to environmental adaptation and community life [7]. Due to its historical importance and architectural coherence, Diriyah, specifically the At-Turaif district, has been designated as a UNESCO World Heritage Site, reinforcing its role as a cultural landmark at both national and international levels [8]. In Diriyah, redevelopment interventions can be broadly categorized into three types: conservation, adaptive reuse, and new-build insertion. Conservation focuses on stabilizing and preserving historic fabric without substantially altering its function. Adaptive reuse involves retaining historic structures while introducing new cultural or public uses. New-build insertions refer to contemporary buildings added to support tourism infrastructure and visitor services while remaining physically distinct from the protected historic core. Distinguishing these approaches clarifies how heritage preservation and urban regeneration operate simultaneously within the redevelopment of At-Turaif.

Adaptive reuse strategies. Recent conservation and redevelopment initiatives in Diriyah have focused on preserving the historic urban fabric while introducing new cultural, educational, and tourism-related functions. Adaptive reuse strategies prioritize the conservation of original building materials, construction techniques, and spatial configurations, particularly the use of mud-brick architecture and courtyard typologies [9]. At the same time, selected structures have been

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repurposed to accommodate museums, cultural venues, public gathering spaces, and visitor facilities. Contemporary interventions are carefully integrated to support modern requirements while maintaining visual and material continuity with the historic context.

Case-evidence anchors. To clarify how adaptive reuse operates in practice, several specific interventions within At-Turaif can be identified. Salwa Palace represents a conservation-led intervention. Historically functioning as the political and administrative center of the First Saudi State, the mud-brick complex underwent structural stabilization and restoration to preserve its original fabric and spatial organization. While primarily a conservation project, it now operates as an interpretive heritage site with curated exhibition programming, enabling contemporary cultural engagement without significant alteration of the original structure.

In contrast, the House of Al Saud Museum, In contrast, the House of Al Saud Museum illustrates adaptive reuse. Originally a residential courtyard building within the Najdi urban fabric, the structure has been repurposed as a thematic museum presenting the history of the Saudi state. The intervention retained the building's material authenticity and spatial configuration while introducing exhibition functions within the preserved structure.

Similarly, several traditional Najdi courtyard houses have been converted into military and social history exhibition spaces. These projects demonstrate adaptive reuse in which historic residential structures are functionally transformed into cultural venues while maintaining their architectural integrity and original spatial organization [8–10].

Alongside conservation and adaptive reuse, new-build developments surrounding the historic core provide visitor facilities, hospitality functions, and tourism infrastructure. These contemporary additions are intentionally located outside the protected heritage fabric, allowing modern development to support the historic district without altering its original urban morphology.

Impact on heritage and urban life. Through adaptive reuse, Diriyah has been transformed from a largely inactive historic district into an active cultural destination. The introduction of new uses has increased public accessibility and engagement, allowing the site to function as a living urban environment rather than a preserved ruin. This transformation supports cultural continuity by maintaining the site's historical identity while enabling contemporary social and economic activities [10]. In addition, the reuse of existing structures contributes to sustainability by reducing demolition, conserving materials, and reinforcing heritage-led urban regeneration as a long-term development strategy.



Fig. 1. Historic urban fabric and earthen architecture of Diriyah (source: UNESCO World Heritage Centre).

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Case study: AlUla Old Town. *Historical and urban context*. AlUla Old Town is one of the most significant historic settlements in Saudi Arabia, shaped by centuries of continuous habitation linked to agriculture, trade, and pilgrimage routes. The settlement developed as a compact and inward-oriented urban fabric composed of closely clustered stone and mud-brick buildings connected by narrow alleyways and shared courtyards. This dense Configuration provided environmental protection from extreme climatic conditions while reinforcing social cohesion and communal life. The spatial organization of the settlement reflects traditional building practices that responded directly to local climate, materials, and social structures [11].

Over time, AlUla Old Town experienced gradual abandonment as residents relocated to newly developed areas outside the historic core. As a result, the settlement faced deterioration and loss of function despite its strong cultural and architectural value. Recent conservation initiatives have sought to address this condition by repositioning the Old Town as an active cultural environment rather than a static archaeological site.

Adaptive reuse strategies. Adaptive reuse interventions in AlUla Old Town emphasize minimal intervention and careful conservation of existing fabric while introducing new uses that support cultural engagement and tourism. Restoration efforts focus on stabilizing historic structures, preserving original materials, and maintaining the spatial integrity of the settlement [12]. Rather than extensive reconstruction, adaptive reuse strategies prioritize reversible and lightweight interventions that respect the fragile historic fabric.

A key example of adaptive reuse within the AlUla heritage landscape is the transformation of historic structures in the Al-Jadidah district into contemporary cultural venues. Former residential and storage buildings have been restored and repurposed as art galleries, cultural exhibition spaces, and creative studios, forming the Al-Jadidah Arts District. These interventions retain the original stone construction and spatial configuration while introducing new cultural programming that activates the historic environment [12]. Additional interventions include the creation of guided visitor circulation routes and discreet lighting installations throughout the Old Town. These improvements enhance accessibility and safety while remaining reversible and visually minimal, ensuring that new infrastructure can be removed without permanently altering the historic fabric [12].

These interventions follow conservation principles emphasizing minimal physical alteration and reversibility, These interventions follow conservation principles emphasizing minimal physical alteration and reversibility, ensuring that contemporary additions can be removed without permanently altering the historic fabric.

Impact on heritage and urban life. The revitalization of AlUla Old Town has significantly increased visitor activity, requiring careful management of circulation and carrying capacity. The Royal Commission for AlUla manages visitor flows through guided routes, controlled event programming, and phased restoration strategies designed to balance tourism with long-term conservation of the fragile historic fabric. Through adaptive reuse, AlUla Old Town has been transformed into a living cultural environment that reconnects heritage with contemporary urban life. The reactivation of the settlement has increased public access and engagement, enabling visitors and local communities to experience the site as an active place rather than a preserved ruin. This approach reinforces cultural continuity by sustaining traditional spatial relationships and architectural identity while accommodating new cultural and economic activities [13].

From a sustainability perspective, the reuse of existing structures minimizes material consumption and environmental impact, aligning heritage conservation with sustainable urban development goals. By positioning AlUla Old Town as a cultural destination rooted in its historic landscape, adaptive reuse contributes to long-term urban vitality and supports broader efforts toward heritage-led regeneration in Saudi Arabia.

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Fig. 2. Public space activation in AlUla Old Town (Source: Royal Commission for AlUla).

Discussion: Heritage as a Living Urban System

Table 1. Cross-case comparison of adaptive reuse and conservation approaches in Diriyah and AlUla Old Town.

Dimension	Diriyah	AlUla Old Town
Historic urban form	Monumental Najdi mud-brick settlement organized around palaces and courtyard compounds	Dense cluster of stone and mud-brick courtyard houses forming an oasis settlement
Pre-regeneration condition	Historic district preserved but largely inactive as a heritage site	Abandoned historic settlement with deteriorating residential fabric
Adaptive reuse strategy	Conversion of historic structures into museums and interpretive heritage attractions	Reuse of restored courtyard houses as artisan workshops, cultural venues, and exhibition spaces
Conservation approach	Structural stabilization and restoration of monumental heritage buildings	Minimal intervention and reversible restoration techniques

The comparison highlights how both sites employ adaptive reuse to reactivate historic environments while adopting different conservation approaches. In Diriyah, regeneration focuses on the restoration and interpretation of monumental heritage structures, while in AlUla Old Town the strategy emphasizes minimal intervention and the reuse of residential buildings for cultural activities. These differences reflect how adaptive reuse strategies respond to distinct urban conditions and conservation priorities.

The case studies of Diriyah and AlUla Old Town demonstrate shared adaptive reuse strategies despite their distinct historical, spatial, and urban contexts. In both cases, heritage revival is achieved through a careful balance between the conservation of historic fabric and the introduction

of new cultural, social, and tourism-oriented functions. Rather than replacing existing structures, adaptive reuse strategies prioritize the retention of material authenticity, spatial organization, and overall urban morphology, allowing historic environments to accommodate contemporary uses without compromising their character.

A central finding from both case studies is the shift from static preservation toward active urban integration. Historic districts are no longer treated solely as protected or museum-like sites but are repositioned as accessible, functional components of the contemporary city. Through adaptive reuse, these areas are transformed into spaces for public life, cultural activities, and everyday use. This transition supports cultural continuity by enabling heritage sites to evolve over time while preserving their architectural identity and historical significance.

Within the Saudi context, adaptive reuse also plays a significant role in advancing sustainability objectives. The reuse of existing buildings reduces the demand for demolition and new construction, thereby conserving material resources and limiting environmental impact. Simultaneously, the activation of heritage sites enhances public accessibility and encourages social interaction. From an economic perspective, heritage-led regeneration stimulates tourism, cultural industries, and investment, contributing to long-term urban vitality and reinforcing the role of heritage as a driver of development rather than a constraint.

The comparative analysis suggests several practical lessons for heritage-led regeneration initiatives. First, adaptive reuse strategies should prioritize the preservation of historic spatial organization while introducing new cultural or educational functions that sustain public engagement. Second, redevelopment should clearly distinguish between conservation of heritage structures and new-build infrastructure to avoid altering historic urban morphology. Third, minimal intervention and reversible design strategies, as demonstrated in AlUla Old Town, are particularly effective for fragile heritage environments. Finally, effective visitor management and governance frameworks are essential to balance tourism growth with long-term conservation of historic sites.

Despite these benefits, adaptive reuse presents practical and managerial challenges. Adapting historic buildings for new uses requires careful design to avoid damaging original materials and spatial qualities. Increased visitation and public activity may also place pressure on fragile structures, underscoring the need for continuous maintenance, monitoring, and adaptive management strategies. Managing these factors is necessary to balance functional activation with long-term conservation.

Overall, the findings suggest that adaptive reuse provides an effective framework for heritage-led urban development in Saudi Arabia. By integrating conservation with contemporary use, adaptive reuse allows historic urban sites to function as living systems rather than isolated traces of the past. The experiences of Diriyah and AlUla Old Town illustrate how heritage revival can strengthen cultural identity, enhance urban vitality, and support sustainability, offering valuable insights for future heritage conservation and urban regeneration initiatives in the region.

Conclusion

This paper examined adaptive reuse as a strategy for heritage-led urban regeneration in Saudi Arabia through a qualitative analysis of Diriyah and AlUla Old Town. The findings show that adaptive reuse enables historic urban environments to accommodate contemporary cultural, social, and economic functions while maintaining architectural authenticity and spatial identity. In both cases, regeneration strategies combine the conservation of historic fabric with the introduction of new cultural programming, transforming heritage sites from static monuments into active and accessible urban environments.

Adaptive reuse also contributes to sustainability by extending the life cycle of historic structures and reducing the need for demolition and new construction [2]. At the same time, the activation of

heritage areas supports cultural engagement, tourism, and economic activity, reinforcing the role of heritage as a driver of urban regeneration rather than a constraint [5].

This study has several limitations. The analysis focuses on two case studies, Diriyah and AlUla Old Town, which do not represent the full diversity of heritage sites in Saudi Arabia. In addition, the research relies primarily on publicly available documents and secondary sources and does not include primary data such as interviews or detailed field measurements. Future research could expand the analysis by incorporating additional case studies and primary data to further examine the long-term impacts of adaptive reuse strategies.

Overall, the cases of Diriyah and AlUla Old Town illustrate how adaptive reuse can support cultural continuity while allowing historic environments to evolve in response to contemporary urban needs [13].

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AI, IoT & Digital Innovations in the Built Environment

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Smart Home Strategies for Aging in Place: Spatial and Technological Planning for Elderly Well-being in Saudi Arabia

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Keywords: Smart Home Design, Aging in Place, Elderly-Friendly Architecture, Healthcare-Integrated Housing, Vision 2030 Saudi Arabia

Abstract. As Saudi Arabia experiences a significant demographic shift toward an aging population, there is an urgent need to develop residential environments that support aging in place. This study proposes a strategic framework for planning senior-friendly smart homes by integrating healthcare technologies with culturally responsive architectural design. Through a comprehensive literature review and contextual analysis, four core planning dimensions—life, health, security, and community—were identified as critical to elderly well-being. Each category encompasses specific spatial elements, hardware applications, and software services tailored to the physical, psychological, and social needs of older adults. The findings underscore the gap between existing smart home technologies and their integration into spatial design. This paper contributes to the formulation of inclusive housing models that align with Saudi Arabia's Vision 2030 goals, emphasizing healthcare transformation, digital innovation, and social inclusivity. The proposed model provides actionable insights for policymakers, architects, and healthcare planners aiming to enhance the quality of life for the elderly.

1. Introduction

Saudi Arabia is undergoing a significant demographic transformation, marked by a steadily increasing proportion of older adults [1]. As of 2023, individuals aged 60 and above constitute approximately 5.6% to 6.9% of the total population, surpassing the number of children under five years old—a trend indicative of the nation's shift towards an aging society [2]. Projections estimate that by 2050, around 25% of Saudi Arabia's population will be aged 60 or older, underscoring the urgency for age-inclusive planning and services [3].

This demographic shift is accompanied by a rising prevalence of chronic conditions among the elderly. A recent nationwide study revealed that over 52% of older adults in Saudi Arabia suffer from two or more chronic diseases, including hypertension, diabetes, and cardiovascular ailments [4]. Additionally, mental health concerns are notable, with 17.7% of the elderly population at risk of depression and anxiety. Lifestyle factors such as low physical activity (only 20.1% engage sufficiently) and poor dietary habits (only 11.1% meet recommended fruit and vegetable intake) further exacerbate health challenges (Figure 1) [5].

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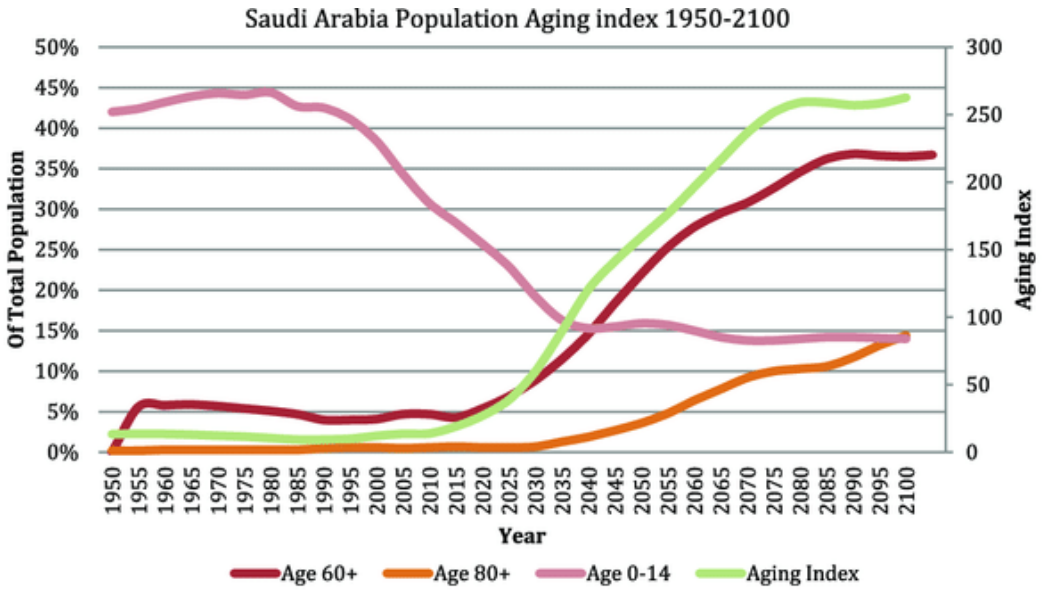


Figure 1. Saudi Arabia's population Aging Index 1950-2100

In response to these challenges, Saudi Arabia's Vision 2030 outlines comprehensive reforms aimed at enhancing healthcare services, promoting preventive care, and integrating digital health technologies [6]. Key objectives include expanding access to quality care, promoting preventive health solutions, and leveraging technology for better outcomes [7].

Smart home technologies emerge as a promising solution to support the health and well-being of the elderly [8]. These technologies enable continuous health monitoring, facilitate daily living activities, and enhance safety [9]. For instance, the integration of wearable devices like the Neda' emergency response band and Sanad health monitoring band with intelligent home systems allows for real-time health tracking, emergency alerts, and seamless communication with healthcare providers [10].

This study aims to establish a foundational framework for designing senior-friendly smart residential environments in Saudi Arabia. By synthesizing insights from smart home technology, gerontological health needs, and architectural design innovation, the research aspires to inform future housing models that enhance the quality of life for the aging population. The study particularly addresses how smart housing can serve as a proactive platform for daily health management, thereby aligning with Saudi Arabia's Vision 2030 objectives to enhance healthcare delivery and social infrastructure for all citizens.

2. Literature Review

The integration of healthcare services into residential environments has become an increasingly significant area of study in light of global demographic transitions toward aging populations [11]. In Saudi Arabia, the rising proportion of elderly citizens—projected to exceed 25% by 2050—has intensified the need to design housing environments that facilitate aging in place through technology-enhanced care [12]. While considerable research has been conducted on the deployment of smart health technologies, relatively few studies have focused on translating these innovations into spatial planning strategies that respond to the preferences and lifestyles of elderly residents within the local context (Table 1) [13].

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Table 1. Previous Studies on Smart Home in Saudi Arabia/GCC

Authors	Title	Contents
Maswadi et al. (2022)	Factors Influencing the Elderly's Behavioral Intention to Use Smart Home Technologies in Saudi Arabia	Investigated determinants affecting Saudi seniors' adoption of smart home technologies. Key factors include cultural influence, technology awareness, and perceived usefulness. The study emphasizes the need for culturally tailored smart home solutions to enhance adoption rates.
Arar et al. (2020)	Analysis of Smart Home Technology Acceptance and Preference for Elderly in Dubai, UAE	Analyzed preferences and needs of elderly users in the UAE regarding smart home technologies. Findings highlight the importance of features like automatic fall detection, lifestyle monitoring, and environmental controls, with a strong preference for user-friendly interfaces.
Kwakye (2024)	Unraveling the Privacy Paradox: Smart Home IoT Adoption Dynamics in Saudi Arabia	Explores the tension between privacy concerns and the adoption of IoT-based smart home technologies among Saudi users. Despite cultural reservations, many users adopt these technologies due to perceived benefits, indicating a complex interplay between privacy and utility.
Alharbi et al. (2023)	Smart Homes for Seniors: How Technology is Creating Safer Living Spaces in Saudi Arabia	Discusses the implementation of smart home technologies like the SANAD and NEDA Bands to enhance safety and independence for Saudi seniors. Features include fall detection, medication reminders, and integration with emergency services, aligning with Vision 2030 healthcare goals.
Uraif (2024)	Developing Healthcare Infrastructure in Saudi Arabia Using Smart Technologies: Challenges and Opportunities	Examines the integration of smart technologies into Saudi Arabia's healthcare infrastructure. Highlights opportunities for improving elderly care through smart home solutions, while addressing challenges like technological readiness and user acceptance.

Recent research in the Kingdom highlights a growing awareness of smart home technologies among older adults, yet adoption remains limited due to concerns over ease of use, privacy, and cultural alignment [14]. A notable study by Maswadi et al. (2022) explored the behavioral intentions of elderly Saudi residents in adopting smart home systems and identified trust, cultural congruence, and technological self-efficacy as key determinants [15]. These findings suggest that while technological solutions exist, their integration into the lived environment must be mediated by user-centered design practices that accommodate cultural and religious norms [16].

Furthermore, literature from neighboring Gulf countries reveals a set of recurring priorities among elderly residents, including fall detection systems, lifestyle monitoring, air quality regulation, and intuitive lighting and temperature controls [17]. These studies emphasize the need for architectural frameworks that do not treat smart technology as an add-on but instead embed it within the physical and spatial configuration of the home [18]. Despite the promising direction of these studies, the current body of research in Saudi Arabia has yet to offer comprehensive spatial models that synthesize architectural planning with healthcare-oriented technological systems in ways that are both functional and culturally appropriate [19].

Therefore, this study aims to address this critical gap by analyzing previous user preference surveys and literature to propose an integrated smart home space model for the elderly. This model seeks to combine adaptive spatial strategies with embedded healthcare technologies to create age-friendly living environments that align with Saudi Arabia’s Vision 2030 and its goals for sustainable and inclusive urban development.

2.1 Characteristics of the Elderly in Saudi Arabia

Designing residential environments that prioritize safety, convenience, and healthcare responsiveness for the elderly requires a nuanced understanding of the physiological, psychological, and social transformations that accompany aging [20]. In the Saudi Arabian context, the elderly population—those aged 60 and above—accounted for approximately 5.6% to 6.9% of the total population as of 2022, with this figure expected to rise to nearly 23% by 2050 [21]. This demographic transition is accompanied by a significant increase in chronic health conditions, with more than half of the elderly population managing two or more illnesses such as hypertension, type 2 diabetes, or cardiovascular diseases [22]. Mobility impairments are also

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prevalent, largely due to age-related muscular degeneration and a national obesity rate of over 67% among older adults, which heightens the risk of falls and home injuries (Table 2).

Table 2. Physical, Psychological, and Social Characteristics of the Elderly

Category	Contents
Physical	Decreased height and weight, decreased bone strength and muscle mass, changes in posture, decreased ability to regulate body temperature, increased fatigue, and increased risk of respiratory diseases.
Psychological	Decreased sense organs of sight, hearing, smell, and taste, decreased cognitive ability, decreased emotional stability, and strong attachment to objects.
Social	Loss of social status and dignity, loss of economic ability, reduced range of activities, loneliness, changes in life cycle

Psychologically, aging individuals in the Kingdom face elevated risks of mental health challenges, particularly depression and anxiety, which affect nearly 17.7% of the elderly population [23]. These conditions are often intensified by reduced physical activity, limited social engagement, and the fragmentation of traditional family structures [24]. Although the extended family has historically provided emotional and logistical support to aging members, increasing urbanization and the shift toward nuclear households have begun to erode these informal caregiving arrangements [25]. Despite this, cultural and religious values continue to place strong emphasis on familial responsibility for elder care, which must be considered when designing residential environments intended to support dignified and independent aging [26].

The integration of smart home systems in elderly housing must therefore be informed by these complex interrelations. Spaces must account for reduced physical mobility and sensory function, ensure emotional well-being through environmental comfort and cognitive stimulation, and respect cultural norms such as privacy, religious routines, and family interaction [27]. An effective residential model must be more than technologically advanced—it must be empathetically attuned to the lived realities of Saudi Arabia's elderly citizens.

3. Methodology

This study employs a qualitative, exploratory methodology aimed at deriving spatial planning elements for senior-friendly smart homes that prioritize daily healthcare support. The initial phase involved an extensive literature review of high-impact peer-reviewed journals indexed in Scopus, focusing on aging-in-place strategies, health-oriented residential design, and smart home technologies. International precedents from advanced aging societies—such as Japan, the Netherlands, and South Korea—were analyzed to extract architectural and technological components conducive to elderly care. These included the integration of unobtrusive health-monitoring devices, responsive environmental controls, and spatial zoning strategies that reduce physical and cognitive load for aging residents.

In the second phase, the findings were contextualized for the Saudi Arabian setting by incorporating local demographic trends, lifestyle preferences, and cultural considerations. Regional data on elderly health profiles, mobility challenges, and privacy requirements were collected from national health surveys, Ministry of Health reports, and Vision 2030 documentation. Design elements such as spatial accessibility, thermal comfort, indoor air quality, and religious space integration (e.g., provision for prayer areas) were emphasized. User expectations and behavioral patterns among the Saudi elderly were also reviewed through secondary analysis of prior user-centered studies.

The third phase of the methodology focused on developing a conceptual smart home spatial model that reflects the insights gathered. The proposed layout includes core residential zones—bedroom, living area, kitchen, and bathroom—interfaced with smart healthcare technologies such as motion sensors, environmental monitoring systems, and telemedicine connectivity. Special attention was given to ensuring barrier-free circulation, modular adaptability, and real-time

emergency response capabilities. This model serves as a prototype for future simulation testing and stakeholder validation, forming the basis for practical implementation within Saudi Arabia's aging-in-place policies and healthcare transformation framework.

4. Analysis

4.1. Senior-friendly Residential Space

Based on a synthesis of previous research, the essential characteristics of senior-friendly residential spaces can be broadly categorized into four interrelated dimensions: life, health, security, and community. These categories reflect the holistic needs of elderly residents and provide a foundational framework for designing environments that support aging in place. The "life" category emphasizes spatial accessibility, ergonomic design, and ease of daily living activities. The "health" dimension focuses on the integration of smart technologies for real-time health monitoring, indoor environmental quality, and accessibility to healthcare services. "Security" addresses both physical safety—such as fall prevention and emergency response systems—and digital privacy protections. Finally, the "community" category considers opportunities for social interaction, mental well-being, and cultural or religious engagement, which are particularly significant in the Saudi Arabian context where familial and community ties are integral to elderly well-being. These four categories are summarized in Table 3 below.

Table 3. Key Characteristics of Senior-Friendly Residential Space Design

Category	Contents
Life	Barrier-free design, accessible circulation, ergonomic furniture layout, user-friendly interfaces for lighting, temperature, and appliance control.
Health	Integration of healthcare technologies (e.g., telemedicine, wearable devices), indoor air quality monitoring, thermal comfort, and proximity to medical services.
Security	Fall detection systems, smart surveillance, emergency alert systems, reinforced door and window security, and secure data management of health records.
Community	Design for social engagement (e.g., shared lounges or prayer areas), mental wellness support, access to communal spaces, and cultural continuity through architecture.

4.2. Smart Healthcare

When designing residential spaces with a healthcare perspective, it is imperative to enhance features that support the safety and health management of elderly individuals, ensuring the maintenance of their well-being and a sustained quality of life. In Saudi Arabia, the elderly population—those aged 60 and above—constitutes approximately 7% of the total populace, with projections indicating a rise to nearly 23% by 2050. This demographic shift underscores the urgency for residential environments that cater to the unique needs of older adults.

The integration of smart healthcare technologies into residential design emerges as a pivotal strategy to address these needs. Smart homes equipped with advanced IT solutions can overcome spatial limitations, providing continuous health monitoring and personalized care. For instance, Me'kaaz, a Saudi-based health tech company, has developed wearable devices like the SANAD and NEDA Bands, which, when integrated with intelligent home systems, offer features such as fall detection, medication reminders, and real-time health status updates.

These innovations align with Saudi Arabia's Vision 2030, which aims to enhance the quality of life for all citizens, including the elderly. By creating environments that are convenient and accessible for older adults, we inherently design spaces that are beneficial for all age groups. This inclusive approach ensures that residential spaces are not only technologically advanced but also empathetically attuned to the lived realities of Saudi Arabia's aging population.

4.3. Senior-Friendly Smart Home Space Planning Elements

Based on the preceding literature review, this study identifies core planning elements for senior-friendly smart home environments, categorized into four primary domains: life, health, security,

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and community. These categories serve as a comprehensive framework for spatial design that supports aging in place. The specific components and considerations within each domain are detailed in Table 4.

Table 4. Senior-friendly Smart Home Planning Elements

Category	Hardware	Software	
		Service	Contents
Life	Furniture plan, Floor plan, Bathroom and toilet plans, Entrance plan, Lighting plan	Behavior Sensor	Understanding the current status of residents based on their daily behavior
		Helper Service	Providing daily life support services
		Door Sensor	Built-in sensors in doors and windows (automatic and batch opening and closing function)
		Mat Sensor	Install sensors on the floor to detect movement and falls of residents
Health	Space utilization plan Circulation plan Ventilation and ventilation plan	Automatic ventilation system	Continuous management of temperature, humidity, odor, noise, etc. in living spaces
		Human body detection sensor	Obtaining the elderly's vital signs through sensors installed along the wall
		Location detection sensor	Detect the location of residents and prepare for emergency situations
Security	CPTED Plan Disaster Prevention Plan, Parking Plan Entrance Plan, Emergency Plan	Automatic call service	Daily life messages and alerts for dangerous situations and automatic contact network service
		Behavior recognition sensor	Alerts and automatic reporting of emergency situations
		Location detection sensor	Providing location information to prevent intrusion by outsiders or disappearance of elderly people
Community	Public space plan Auxiliary facility plan External space plan	Smart health device	Installation of exercise equipment and health checkup equipment for the elderly in public spaces
		Location detection sensor	Detects user location in public spaces to prepare for emergencies

5. Discussion

The findings of this study offer critical insights into the spatial and technological requirements necessary to support Saudi Arabia's rapidly aging population. The categorization of smart residential space planning into four domains—life, health, security, and community—demonstrates a comprehensive approach to enhancing quality of life through intelligent design. Unlike conventional housing strategies that treat healthcare integration as an afterthought, this framework emphasizes proactive design where smart technologies are embedded into the spatial structure from the outset. This is particularly relevant given the projected demographic shift, with over 23% of Saudi Arabia's population expected to be aged 60 and above by 2050.

The results highlight a clear divergence between the availability of smart home technologies and their actual implementation within residential architecture for elderly users in the Kingdom. Although tools such as the SANAD and NEDA Bands offer sophisticated health tracking and emergency response features, their impact remains limited without corresponding architectural interventions such as barrier-free layouts, sensor-responsive zones, and ambient monitoring systems embedded into the built environment. This gap underscores the need for a more integrated model of housing development that aligns smart IT solutions with spatial design principles grounded in user-centered and culturally attuned planning.

Moreover, the study draws attention to the broader social and cultural implications of smart home adoption among elderly Saudi citizens. The traditional reliance on extended family support is gradually shifting due to urbanization and evolving family dynamics. As such, senior-friendly smart homes must serve not only as functional residences but also as socio-technological ecosystems that address emotional well-being, privacy, and religious practices. Designing for this intersection of tradition and innovation requires interdisciplinary collaboration among architects,

gerontologists, health professionals, and IT specialists. The proposed framework can inform future housing policies and development programs under Vision 2030, where inclusivity, healthcare transformation, and digital advancement are national priorities.

6. Conclusion

This study examined the planning principles of senior-friendly smart home environments within the context of Saudi Arabia's shifting demographic landscape. With the elderly population expected to surpass 23% by 2050, the urgency for housing models that support aging in place has never been more pronounced. Through a comprehensive review of literature, user preference analysis, and contextual adaptation, the study identified four foundational categories—life, health, security, and community—as critical dimensions for designing intelligent residential environments for older adults.

The proposed framework emphasizes the integration of smart technologies with architectural planning to deliver continuous healthcare, spatial accessibility, and socio-cultural alignment. By embedding intelligent systems such as wearable health monitors, motion sensors, fall detection networks, and telehealth platforms within barrier-free layouts and culturally appropriate spaces, the model enables proactive and dignified aging. Moreover, the planning elements outlined in this study provide practical design criteria that align with Saudi Arabia's Vision 2030 objectives, particularly those related to healthcare transformation, social inclusion, and smart urban development.

Ultimately, this research contributes a strategic model for age-inclusive housing development that bridges architecture, technology, and gerontology. It underscores the necessity of interdisciplinary collaboration and policy support to operationalize smart aging-in-place environments across Saudi Arabia. Future research should focus on empirical validation through user simulations, pilot implementations, and stakeholder feedback to further refine and implement the model in real-world housing projects.

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Strategic Transformation of Saudi Arabia's Smart Cities: Integrating Fourth Industrial Revolution Technologies, Governance Reform, and Private Sector Empowerment

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Keywords: Smart City Competitiveness, Fourth Industrial Revolution (4IR), Urban Governance Reform, Public-Private Partnerships (PPP), Vision 2030 Saudi Arabia

Abstract. This study critically explores strategies to enhance the global competitiveness of Saudi Arabia's smart cities within the framework of Vision 2030. The research identifies prevailing trends, governance challenges, and strategic gaps by employing text mining analysis of 412 smart city-related articles and conducting in-depth interviews with key stakeholders. The findings highlight that despite the Kingdom's advancements in flagship smart city projects, existing models remain predominantly infrastructure-led and public sector-driven, with limited integration of Fourth Industrial Revolution (4IR) technologies, private sector engagement, and citizen-centric governance. The study proposes a multi-dimensional policy roadmap emphasizing systemic technology integration, the establishment of a centralized smart city authority, lifecycle-oriented financing mechanisms, and enhanced private sector-led international market expansion. Moreover, the paper advocates for dynamic legal and regulatory reforms to foster an agile, innovation-driven, and inclusive urban ecosystem. This ensures Saudi Arabia's positioning as a global leader in the rapidly evolving smart city landscape.

1. Introduction

Smart cities increasingly emerge as strategic frameworks integrating advanced information and communication technologies (ICT) with urban infrastructure to create efficient, sustainable, and resilient urban environments [1]. Globally, the smart city market is forecasted to exceed USD 1.03 trillion by 2028, reflecting a compound annual growth rate (CAGR) of over 12% [2]. While East Asian nations such as South Korea pioneered the integration of ICT into urban development through initiatives like U-City since the mid-2000s, the Middle East, particularly Saudi Arabia, is currently positioning itself as a leading innovator in smart urbanism through its Vision 2030 agenda [3].

The government has committed to transforming its urban centers into globally competitive smart cities in Saudi Arabia as part of its broader economic diversification strategy [4]. Mega projects such as NEOM, the Line, and Qiddiya exemplify the ambition to create technologically advanced, livable, and sustainable cities from the ground up. The Kingdom has enacted the National Smart City Strategy (2020) to systematically guide these developments, which outlines the strategic objectives, technological roadmaps, and regulatory frameworks necessary to accelerate smart city transformation across key urban areas [5]. This strategy emphasizes four pillars: digital infrastructure enhancement, data governance and security, sustainable urban services, and citizen-centric innovation ecosystems [6]. Unlike the Korean model which emphasized early-stage infrastructure-centric developments in the first phase (2009–2013) and

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expanded towards industry activation and global market entry in the second phase (2014–2018), Saudi Arabia's smart city agenda is framed within a rapid leapfrogging model that simultaneously addresses infrastructure, industry activation, sustainable living, and global positioning from the outset [7]. This difference reflects the Kingdom's unique urban dynamics, including rapid urbanization, extreme climatic conditions, and ambitious net-zero targets by 2060 [8]. However, despite significant progress, Saudi Arabia's smart city policy framework faces critical challenges adapting to the rapidly evolving global technological environment, including artificial intelligence integration, the metaverse economy, and fourth industrial revolution applications in urban governance [9]. Furthermore, as global urban development models transition towards citizen-centric, data-driven, and resilient urban ecosystems, the existing frameworks within Saudi Arabia require agile adaptation to ensure their long-term global competitiveness and responsiveness to emerging societal demands [10].

This study aims to propose future-oriented policy recommendations for Saudi Arabia's smart cities by critically examining international best practices, identifying gaps within the current national strategies, and conducting in-depth interviews with local and international smart city experts. By addressing these aspects, the study seeks to strengthen the Kingdom’s position as a global leader in the smart city sector while ensuring alignment with sustainability, inclusivity, and digital resilience objectives.

2. Literature Review

2.1. Review of International Smart City Cases

The global advancement of smart city initiatives has accelerated significantly since the onset of the Fourth Industrial Revolution, characterized by the convergence of physical and digital systems [11]. The global smart city market is projected to reach approximately USD 1.1 trillion by 2026, growing at a compound annual growth rate (CAGR) of 12.1%, fueled by emerging technologies such as artificial intelligence (AI), the Internet of Things (IoT), and blockchain [12]. Frost & Sullivan (2024) further identifies smart transportation, smart energy systems, and predictive public safety services as critical domains propelling the evolution of smart city ecosystems (Table 1).

Table 1. Smart City Market Segment Growth Rate by Sector (2014-2024)

Rank	Category	Increase Rate (Percent)
1	Smart Energy	19.6%
2	Smart Transportation	14.8%
3	Smart Security	14.0%
4	Smart Government	12.4%
5	Smart Building	8.9%
6	Smart Healthcare	6.9%

Diverse national strategies for smart cities reflect variations in socioeconomic contexts, governance models, and urban challenges [13]. In rapidly urbanizing nations such as India and China, smart city initiatives have been positioned to address urban stressors, including traffic congestion, socio-spatial inequality, and crime prevention [14]. India's Smart Cities Mission, launched in 2015, targets 100 cities, focusing on retrofitting, redevelopment, and greenfield projects, embedding ICT to enhance urban services and governance efficiency [15]. In contrast, China's strategy, under the ambitious "New Smart City" framework, has shifted from initial large-scale, infrastructure-heavy developments supported by central government financing to a more entrepreneurial, innovation-led model aligning with the national "Internet Plus" policy, aiming to create sustainable economic opportunities through digital industry integration [16]. China's commitment of CNY 1 trillion toward constructing 500 smart cities by 2020 has catalyzed urban digital transformation, particularly addressing challenges of rapid urbanization, income disparity, and environmental degradation (Table 2).

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Table 2. Smart City Market Segment Growth Rate by Sector (2014-2024)

Country	Policy & Project
U.S.	- Announcement of strategy to expand R&D investment in smart cities to solve urban problems - Policy: Promoting four major smart city strategies, including private technology cooperation, regional model development, and climate change response - Project: Implementing R&D projects related to transportation issues, climate change, and economic growth with a total scale of 160 million dollars
EU	- Promoting smart city policies by focusing on areas such as energy and transportation, led by the European Commission - Policy: Promoting the implementation plan for the Smart City and Community Innovation Partnership Strategy - Project: Barcelona Smart City Project, Crossroads Project in Copenhagen, Denmark, etc.
U.K.	- Smart city project to be promoted in earnest with the National Technology Strategy Committee at the center - Policy: Announcement of the Information Economy Strategy to revitalize the ICT industry and the Smart London Plan to solve London's urban problems - Project: We are promoting the construction of a regionally tailored smart city in cooperation with global IT companies such as IBM and Intel.
China	- Promoting a nationwide smart city policy to improve urban management efficiency under the name of Wisdom City - Policy: Adoption of smart city policy as a solution to the problem of increasing urban population and regional disparity - Project: Announced a plan to build about 500 smart cities in 2015, with an investment of 1 trillion yuan by 2025
France	- Establishment of nine specialized clusters for smart city expansion - Policy: Promoting the introduction of smart cities as an alternative for energy saving - Project: Building a data platform for an eco-friendly smart city, etc.

Conversely, advanced economies such as Europe, North America, and Japan have adopted smart city strategies as adaptive responses to urban aging, energy inefficiency, and climate change resilience [17]. For instance, Singapore's Smart Nation initiative illustrates an exemplary governance-driven approach, where a centralized Smart Nation and Digital Government Office (SNDGO) oversees cross-ministerial smart city initiatives, thereby ensuring administrative efficiency, eliminating redundancies, and prioritizing citizen-centric services such as e-healthcare, transport, and housing [18]. Complementing this, the Infocomm Media 2025 strategy underscores infrastructural investments in high-speed networks, national sensor grids, and open data platforms [19].

In Europe, the city of Barcelona has emerged as a benchmark for public-private partnership-led smart city development, leveraging collaborations with global technology leaders, including Cisco, IBM, and local startups [20]. This model fosters technological innovation while ensuring solutions remain accessible and experiential for citizens. Barcelona's approach demonstrates the effectiveness of nurturing a startup-driven ecosystem that stimulates the local economy while contributing to global smart city innovations.

For Saudi Arabia, these global cases offer critical lessons. Given the Kingdom's unique socioeconomic conditions—such as its youthful population, extreme environmental conditions, and rapid urban expansion—Saudi Arabia's smart city trajectory, spearheaded by Vision 2030, must strategically integrate these global best practices while customizing them to the local context [21]. Mega-projects such as NEOM, envisioned as the world's most technologically advanced and sustainable city, showcase the Kingdom's ambition to leapfrog traditional urban models by embracing an integrated, citizen-focused, and innovation-driven approach from inception. However, as identified in recent studies, Saudi Arabia's current smart city policy framework still lacks agile mechanisms for inter-ministerial coordination, private sector stimulation, and citizen engagement compared to the Singapore or Barcelona models. Therefore, fostering a robust innovation ecosystem through PPPs, enabling regulatory flexibility, and promoting local entrepreneurial participation will be critical for the Kingdom to achieve globally competitive and socially inclusive smart cities that align with Vision 2030 and the UN SDG 11 targets for sustainable cities and communities.

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4. Analysis: Sectoral Trends Review for Smart City Competitiveness in Saudi Arabia

4.1. Survey of Emerging Smart City Trends and Issues

To secure the global competitiveness of Saudi Arabia's emerging smart cities, it is essential to critically examine prevailing trends, challenges, and strategic directions observed in the smart city discourse globally and domestically [22]. This study undertook an extensive trend analysis by employing advanced text mining techniques to systematically extract and interpret patterns within 412 digital news articles, white papers, and policy documents related to smart cities from January 2018 to April 2025. This approach offers evidence-based insights to optimize Saudi Arabia's smart city policy, ensuring alignment with the rapidly shifting global landscape.

Text mining, underpinned by natural language processing (NLP) and big data analytics, enables the systematic exploration of large, unstructured datasets to identify semantic patterns, emerging themes, and relational networks within textual content [23]. In the Fourth Industrial Revolution era, such analytical methods have proven instrumental across sectors, including urban governance, energy systems, and infrastructure planning [24]. This methodological approach ensures the extraction of actionable knowledge from the vast volumes of digital discourse shaping smart city narratives globally and within the Gulf region.

The collected articles, primarily sourced from leading English and Arabic language outlets, academic policy platforms, and think tanks, were meticulously cleansed to exclude advertisements, multimedia, and unrelated data, focusing exclusively on core textual elements. From the refined dataset, 28,745 terms were extracted, with the top 30 most frequent keywords relevant to smart cities identified after filtering out non-specific or redundant terms. Table 3 summarizes the keyword frequency analysis.

Table 3. Frequency of Keywords appearing in Smart City-related Articles

Rank	Keyword	Frequency	Relevance to Saudi Arabia's Smart City Strategy
1	Artificial Intelligence (AI)	1,245	NEOM's cognitive city ambitions and AI-driven governance
2	Fourth Industrial Revolution	1,113	Central driver for digital economy transformation under Vision 2030
3	Internet of Things (IoT)	986	Key infrastructure for hyper-connected urban services
4	Digital Governance	945	Supports transparent, efficient, citizen-centric public services
5	Transportation	823	Priority sector in Riyadh and NEOM for integrated smart mobility
6	Cybersecurity	778	Vital for ensuring data security and trust in smart city platforms
7	Citizen Engagement	702	Aligns with Vision 2030's focus on participatory governance
8	Energy Resilience	685	Essential for sustainable energy transitions in arid environments
9	Smart Services	653	Reflects the demand for personalized e-services in Saudi Arabia
10	Green Economy	621	Supports Saudi Green Initiative and net-zero ambitions
11	Data Platforms	593	Backbone for open data and predictive urban management
12	Safety & Crime Prevention	568	Saudi Arabia's urban security strategy and smart surveillance
13	Business Innovation	552	Focus on attracting global startups and digital entrepreneurs
14	Disaster Management	519	Critical for climate resilience and emergency response
15	Smart Welfare & Health	501	Supports national priorities in digital health and social services

The predominant keywords included artificial intelligence, digital governance, green economy, transportation, cybersecurity, citizen engagement, energy resilience, and sustainable urban planning. Notably, terms associated with the Fourth Industrial Revolution—such as hyper-connectivity, AI integration, and IoT platforms—dominated the discourse, reflecting a global convergence around these technologies as foundational enablers of smart urban ecosystems. This finding underscores the imperative for Saudi Arabia's smart city strategies to embrace emerging technologies as ancillary components and central pillars of future city development.

Furthermore, the rise of citizen-centric service models, digital welfare platforms, and participatory governance emerged as critical discourse areas. This shift reflects an evolving recognition that technologically advanced cities must prioritize inclusivity, equity, and user experience to achieve long-term societal acceptance and legitimacy. This aligns closely with Vision 2030's emphasis on enhancing quality of life, public service efficiency, and participatory

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digital governance mechanisms within the Saudi context. The findings of this analysis suggest that Saudi Arabia's smart city competitiveness will hinge not only on large-scale infrastructure investments but also on the agile integration of Fourth Industrial Revolution technologies, proactive positioning in global smart city markets, and the development of citizen-centered, resilient, and adaptive governance frameworks. These insights provide a strategic baseline for policy refinement and capacity-building endeavors to ensure Saudi Arabia's smart cities evolve into globally benchmarked models of future urban living.

4.2. Expert Interviews on Challenges and Strategies for Advancing Smart Cities in Saudi Arabia

Building upon the preceding trend analysis and planning review, this study conducted in-depth interviews with key stakeholders in smart city projects across Saudi Arabia [25]. The objective was to contextualize and enrich the keyword-based findings through practitioner insights, focusing on the institutional, managerial, and operational challenges faced in the local implementation of smart city initiatives [26]. Between 20 September and 15 October 2024, structured interviews were conducted with eight professionals, comprising four senior officials from municipal smart city units and four project managers from private sector consortia involved in government-led smart city initiatives. The public sector participants were selected based on their recent (within the last two years) or current involvement in smart city planning or execution, while private sector participants represented leading firms collaborating with national research bodies or participating in public-private partnerships (PPPs) for flagship projects such as NEOM, the Red Sea Project, and Qiddiya (Table 4).

Table 4. In-depth Interviews with Local Government Officials

Category	Requirements				
	Response to the 4th Industrial Revolution	Strengthening the Business Management System	Strengthening information distribution and utilization	Improving legal systems/guidelines	Strengthening financial resources
City A	○	●	◑	◑	●
City B	◑	●	●	◑	◑
City C	○	●	○	●	●
City D	◑	●	●	●	●

●: High, ◑: Medium, ○: Low

The interview findings, summarized in Table 4, reveal critical systemic barriers that hinder the practical realization and scaling of smart city projects in Saudi Arabia. A recurring theme identified by municipal officials was the inadequacy of the current project governance and management frameworks. Given the inherently interdisciplinary nature of smart cities—encompassing sectors such as energy, mobility, safety, and public services—respondents emphasized the urgent need for centralized project coordination mechanisms capable of integrating multi-sectoral programs under a unified management structure. Municipal smart city departments are often limited to small teams with constrained authority, resulting in fragmented project execution and weak interdepartmental collaboration. This mirrors findings from global smart city studies that emphasize the importance of cross-sectoral coordination and institutional agility. Further, the short-term, project-based funding structures prevailing in Saudi Arabia were highlighted as a critical challenge. Most smart city initiatives, especially those supported by national programs, are funded through limited-term grants or pilot schemes. Participants argued that this hampers the sustainability and scalability of such projects, resulting in premature project termination or underutilized infrastructure. The interviewees advocated for establishing long-term, stable funding mechanisms at the national policy level, complemented by clear guidelines for lifecycle management of smart city assets, ensuring continuity and return on investment over extended periods. This observation aligns with

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global best practices, where cities such as Singapore and Barcelona have institutionalized dedicated smart city budgets and long-term investment frameworks. Additionally, both public and private sector experts raised concerns regarding the operational capacity deficits at the local government level, particularly in managing, operating, and upgrading smart city systems post-deployment. Due to the prevalent 'handover model'—where technology solutions are transferred to local authorities following initial deployment by national agencies or private consortia—municipalities often lack the technical expertise and resources to ensure adequate system maintenance and citizen engagement. This frequently leads to infrastructure degradation, system obsolescence, and public dissatisfaction. Participants strongly recommended formally integrating smart city operations and governance standards into Saudi Arabia's legal and regulatory frameworks to address these shortcomings, supported by capacity-building programs for local government officials and operators.

4.3. Strategic Directions for Enhancing the Global Competitiveness of Saudi Smart Cities

Drawing upon the preceding analyses of trends, stakeholder interviews, and global case studies, this section proposes strategic directions for enhancing the competitiveness of Saudi Arabia's smart cities. The proposed strategies address key domains, including technology integration, institutional governance, financial mechanisms, international market expansion, and legal frameworks, ensuring alignment with Saudi Vision 2030 and emerging global standards.

1) Technological Convergence and Responsiveness to the Fourth Industrial Revolution

The Fourth Industrial Revolution (4IR), characterized by AI, IoT, blockchain, and quantum technologies, fundamentally reshapes urban paradigms worldwide. For Saudi Arabia to sustain its position as a leader in smart city innovation, it is imperative to adopt a technology convergence model, identifying strategic tipping points where 4IR technologies can be synergistically integrated into core urban services and management systems. While many existing technologies—such as autonomous mobility, smart grids, and digital health platforms—are mature enough to enhance urban services and governance efficiency, the Kingdom must adopt a rigorous evaluation framework that assesses emerging technologies' applicability, usability, and socio-economic effectiveness before deployment. This approach will mitigate the risks associated with premature adoption while ensuring that smart cities remain at the frontier of technological innovation.

2) Establishment of a Centralized Smart City Governance Authority

Reflecting the demands voiced by both public and private sector stakeholders, the establishment of an independent Smart City Authority, modeled after the Singapore Smart Nation Office, is recommended. This entity should be able to coordinate inter-ministerial initiatives, oversee project integration, monitor KPIs, and ensure coherence between national, regional, and municipal plans. Additionally, to overcome the constraints of fragmented project management and short-term funding cycles, it is necessary to transition toward long-term, lifecycle-oriented funding mechanisms, supported by alignment with the national fiscal strategy. Such reforms will ensure sustainable financing for smart city projects and facilitate efficient resource management, allowing for mid- to long-term evaluation, renewal, and optimization of ongoing initiatives.

3) Empowering Private Sector-led International Expansion

Saudi Arabia's smart city strategies have traditionally emphasized government-led megaprojects; however, empowering the private sector to drive international smart city expansion is crucial for global competitiveness. Learning from Japan's Industrial Structure Vision, Saudi Arabia must establish comprehensive export support frameworks, providing localized market intelligence, regulatory consulting, and co-financing mechanisms to enable Saudi companies to penetrate

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emerging markets across Africa, Southeast Asia, and the Middle East. This transition requires a shift from event-driven, short-term public diplomacy projects toward sustained, package-type expansions led by private sector consortia, with the government providing enabling environments, financial guarantees, and strategic diplomatic support to facilitate long-term profitability and localization in target markets.

4) Legal and Regulatory Innovation to Support Smart City Ecosystem Evolution

Finally, Saudi Arabia's legal and regulatory frameworks must be modernized to ensure flexibility and responsiveness to emerging technologies, global market shifts, and evolving societal demands. This includes codifying standards for PPP participation in smart city operation and maintenance phases, establishing robust data governance protocols, and introducing dynamic regulatory sandboxes to encourage innovation while safeguarding public interests. Moreover, legal provisions should explicitly support the participation of private firms in post-construction operations, enabling technology lifecycle commercialization and ensuring that smart city systems remain functional, adaptive, and citizen-oriented long after their initial deployment. These proposed strategies collectively aim to transition Saudi Arabia's smart city model from a predominantly infrastructure-led, public-sector-driven paradigm toward a more agile, market-oriented, citizen-centered urban innovation ecosystem, positioning the Kingdom as a global reference point in the rapidly evolving smart city domain.

5. Discussion

This study provides critical insights into the strategic gaps and governance challenges facing Saudi Arabia's smart cities. Although the Kingdom has advanced significant projects such as NEOM and Qiddiya, its current model remains heavily infrastructure-driven and top-down, making it less responsive to global shifts toward citizen-centric, data-driven urban ecosystems. The text mining analysis revealed that while Fourth Industrial Revolution technologies like AI, IoT, and digital governance dominate global discourse, their integration in Saudi Arabia remains limited to isolated pilots rather than system-wide applications.

Furthermore, in-depth interviews exposed structural weaknesses, notably the lack of centralized coordination, sustainable financing, and operational expertise at the local level. Additionally, the study identified the need for stronger private sector empowerment and structured support for international smart city market expansion, drawing lessons from Japan's export strategies. Finally, the research underscores the urgency for regulatory reforms that enable innovation, lifecycle commercialization, and agile urban governance aligned with Vision 2030.

6. Conclusion

This study critically examined Saudi Arabia's smart city trajectory by analyzing global trends, reviewing strategic planning frameworks, and conducting in-depth interviews with key stakeholders. The findings reveal that while the Kingdom has successfully launched flagship smart city projects aligned with Vision 2030, the current framework remains largely infrastructure-centric and predominantly driven by the public sector. Although successful in catalyzing initial developments, this model presents limitations in ensuring long-term adaptability, citizen-centricity, and market competitiveness in the face of rapid technological advancements and evolving urban governance paradigms.

The research underscores the necessity for Saudi Arabia to adopt a multi-dimensional strategy that prioritizes integrating Fourth Industrial Revolution technologies into all layers of urban management, while concurrently strengthening institutional governance through establishing a centralized, cross-sectoral smart city authority. Furthermore, the study recommends the development of stable, lifecycle-oriented funding mechanisms, shifting away from short-term, project-based financing models, to support sustainable urban transformation and effective resource

management. Fostering an innovation-driven, market-oriented ecosystem requires empowering the private sector to lead international smart city market expansion, supported by structured public-private export strategies, localization consulting, and targeted financial instruments. Lastly, the evolution of Saudi Arabia's legal and regulatory frameworks toward greater flexibility and responsiveness is imperative to accommodate disruptive technologies, enable PPPs across all project phases, and facilitate the lifecycle commercialization of smart city technologies.

For Saudi Arabia to position itself as a global benchmark in smart city development, a systemic transition toward a citizen-centric, innovation-driven, and globally connected urban ecosystem is essential. This will require agile governance, robust private sector participation, sustainable financing, and forward-looking regulatory reform, ensuring the Kingdom's smart cities are technologically advanced, inclusive, resilient, and globally competitive.

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Spiritual Architecture in Urban Atmospheres: Designing Inclusive Spaces for Inner Connection Through Data-Driven Guidelines

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Keywords: Urban Sanctuary, Spiritual Architecture, Non-Denominational Design, Sensory Rest, Symbolic Neutrality, Mixed-Methods Research, Urban Stress

Abstract. Rapid urban growth in India's metropolitan areas has led to an increasing sense of Urban Spiritual Disconnect - a condition where high-pressure environments and existing public or sacred spaces fail to provide inclusive areas for self reflection. This research addresses this deficiency by developing an evidence-based design framework for spiritual architecture. Using a Mixed-Methods Triangulation Approach, the study merges qualitative insights from five Universal Spiritual Factors (F1 F5), identified through architectural case studies, with quantitative feedback from a user perception survey (N = 55). The results emphasize the urgent need for a new architectural typology and establish a hierarchy of user-driven design priorities. The paper concludes by introducing five core data-derived Design Guidelines, intended as a prescriptive foundation for creating adaptable Urban Sanctuary spaces focused on Sensory Regulation and Symbolic Neutrality. The study's key contribution lies in shifting spiritual architecture from subjective artistic expression toward a measurable, performance-driven discipline.

Introduction

Modern urban life in the 21st century is characterized by constant motion, density, and sensory overload [6]. In metropolitan centers such as Bengaluru, this condition manifests as psychological fatigue and an increasing demand for spaces that allow cognitive pause and emotional recovery [2]. Such environments are no longer indulgences but essential elements for sustaining individual and social equilibrium.

The Urban Spiritual Disconnect: The research defines the *Urban Spiritual Disconnect* as a widening gap in the city's ability to offer spaces for introspection. While the psychological demand for withdrawal grows, existing architectural typologies have proven insufficient.

Limitations of Existing Typologies: Existing spaces traditionally associated with quietude and contemplation are structurally failing to serve the modern urban populace:

Public Parks and Gardens: Though publicly accessible, these spaces have become heavily exposed to visual and auditory disturbances, diminishing their effectiveness for sensory relaxation [5].

Religious Architecture: While spiritually significant, these environments often restrict participation due to their denominational nature. In diverse urban societies, such exclusivity discourages individuals seeking universal mental restoration [8].

This dual limitation demonstrates the need for a new Urban Sanctuary typology - a non-religious spatial framework designed purely around human physiological and psychological needs.

Research Aim and Question: *Research Aim :* To empirically determine and define design parameters that enable spiritual reflection in dense metropolitan environments and translate these findings into a universally accessible Urban Sanctuary typology.

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Research Question: How can architectural design objectively establish and validate universal, non denominational principles that facilitate contemplation and restoration in high-stress urban contexts?

Theoretical Framework and F1-F5 Development

This study is grounded in the notion that spiritual experience arises as a phenomenological response to controlled sensory stimuli, supported by environmental psychology and neuro-architecture research [1].

The Concept of the Spiritual Micro-Dose: Given that extended retreats are impractical for most urban dwellers, the concept of the Spiritual Micro Dose is introduced - a short yet impactful moment of restoration embedded seamlessly into everyday life. This notion validates the need for compact, high performance sanctuaries focused on sensory transformation.

The Universal Spiritual Factors(F1-F5): Synthesizing insights from architectural theory [4] and sensory science [3], five universal architectural levers (F1-F5) were formulated to operationalize restorative design:

F1 - Focused Light (Visual): Strategic control of light through apertures or slits to direct attention inward and reduce visual clutter.

F2 - Material Grounding / Sublime Scale (Physical): Restrained material palettes and simple geometry to evoke permanence and humility.

F3 - Temporal Pacing (Sequential Experience): Gradual spatial transitions that decelerate movement and support psychological detachment.

F4 - Sensory Rest (Acoustic Regulation): Architectural and acoustic strategies (e.g., water features, thick envelopes) to reduce noise and restore attention.

F5 - Symbolic Neutrality (Ethical Inclusivity): Absence of faith-specific symbolism to ensure universal accessibility.

These factors formed the basis for both the qualitative and quantitative phases of the research.

Methodology

A Mixed-Methods Triangulation Approach was used to strengthen reliability and ensure comprehensive validation. The study progressed through three interconnected stages: Qualitative Validation, Quantitative Validation, and Design Synthesis.

The qualitative and quantitative phases were structured around the five Universal Spiritual Factors (F1-F5) defined above, enabling consistent coding in precedent analysis and factor-specific questions in the survey.

Given the exploratory intent and a sample size of N = 55, descriptive statistics (mean scores) were prioritized over inferential testing; this limitation is acknowledged and discussed below.

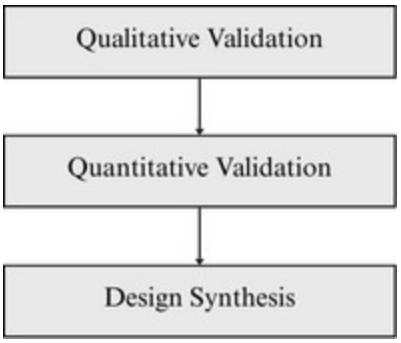


Fig. 1: Flowchart illustrating the three sequential phases used to ensure rigor and triangulation of findings.

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Phase 1: Qualitative Data Validation:A detailed analysis of architectural precedents was conducted to confirm the existence and effectiveness of the F1-F5 factors in the real world.

Historical/Global Case Studies: Gothic Cathedrals and Zen Gardens were analyzed to validate the universality of F1 (Focused Light), F2 (Sub lime Scale), and F3 (Temporal Pacing).

Contextual Case Studies (Indian Subcontinent): Sites such as the Lotus Temple (New Delhi), the Matrimandir (Auroville), and Pyramid Valley (Bengaluru) were studied. This analysis was critical in validating F5 (Symbolic Neutrality) and the necessity of high-performance acoustic and sequencing solutions (F4 and F3) in the tropical, high-stress context.

The qualitative analysis established that the F1-F5 framework is architecturally feasible and culturally relevant.

Phase 2: Quantitative Data Validation:A user perception survey (N = 55) was conducted to quantify demand and gauge agreement with F1-F5.

Sample: The study involved a sample size of N = 55 urban residents from metropolitan regions, targeting individuals actively navigating high stress urban environments.

Survey Design: The survey was structured into four sections: Section A (Demographics), Section B (Problem Validation), Section C (Quantification of F1-F5 factors), and Section D(Solution Viability).

Data Analysis: Results were analyzed using descriptive statistics, calculating percentages for validation mandates and Mean Scores ($\bar{x}$) for the F1-F5 preference.

The quantitative findings from Phase 2 serve as a direct empirical validation of the architectural levers identified in the Phase 1 precedent analysis. While Phase 1 established the *architectural feasibility* and historical existence of the F1-F5 factors in successful sacred and restorative sites , Phase 2 confirms their *contemporary relevance* and user-demand within a high-stress urban population. By demonstrating a high Mean Score ($\bar{x}$) for factors such as Material Honesty (F2) and Sensory Rest (F4), the research achieves triangulation: it aligns the 'performance' of historical typologies with the 'perception' of modern users, thereby transforming subjective design observations into validated, data-driven guidelines.

Results and Findings

The quantitative phase confirmed three fundamental mandates addressing earlier hypotheses:

The Urban Sanctuary Mandates: The qualitative analysis established that the F1-F5 framework is architecturally feasible and culturally relevant.

Viability Mandate: The project is highly viable, with 85.5% of respondents stating they would be Likely or Very Likely to visit a dedicated, inclusive reflection space. Furthermore, 87.3% expressed intent to visit Daily/Weekly, confirming the need for the Spiritual Micro-Dose model.

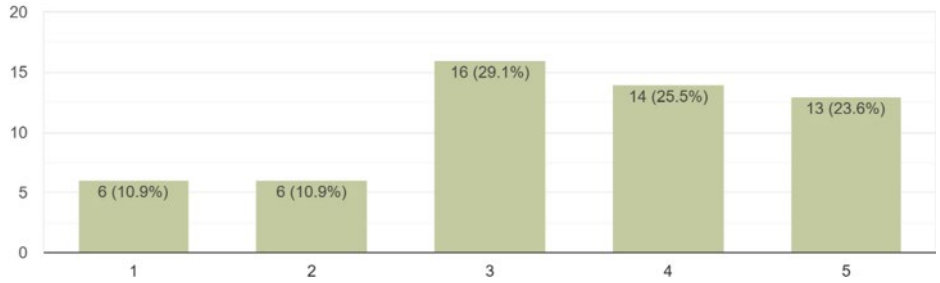
Typology Mandate: When asked to select the most comfortable space, 58.2% selected a “dedicated, quiet space open to everyone”, confirming the specific typology is preferred over existing parks (54.5%) or religious places (21.8%).

Neutrality Mandate (F5): Critically, 70.9% of respondents reported Often or Sometimes avoiding traditional religious places. This finding establishes the absolute Non-Negotiable Ethical Mandate that the final design must possess Radical Symbolic Neutrality (F5).

Quantification of Architectural Factors (F1-F5 Mean Scores): The Mean Scores quantify user preference for each architectural intervention. This data is the empirical base for the final Design Guidelines

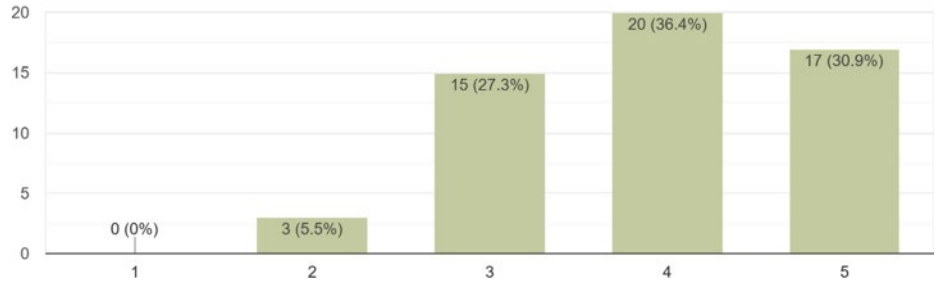
I find it easier to concentrate when the room is dark, but has a small, bright light source (like a spotlight or sunbeam).

55 responses



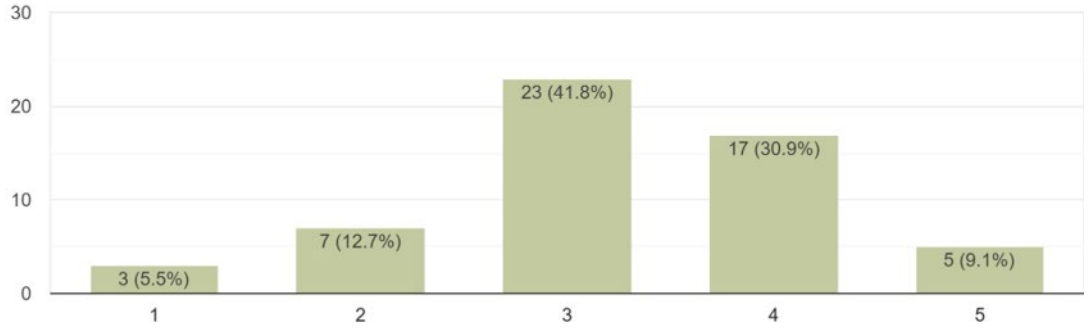
I feel calmer in a space with plain, simple walls and a high ceiling than in a room filled with details or clutter.

55 responses



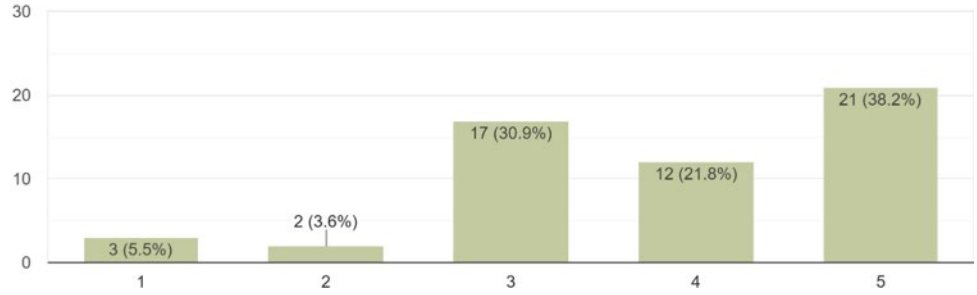
I feel more prepared to relax if I take a slow, winding path or pass through a series of doors before reaching the main quiet room.

55 responses



I would feel most welcome in a quiet space that has no religious symbols, images, or flags whatsoever. .

55 responses



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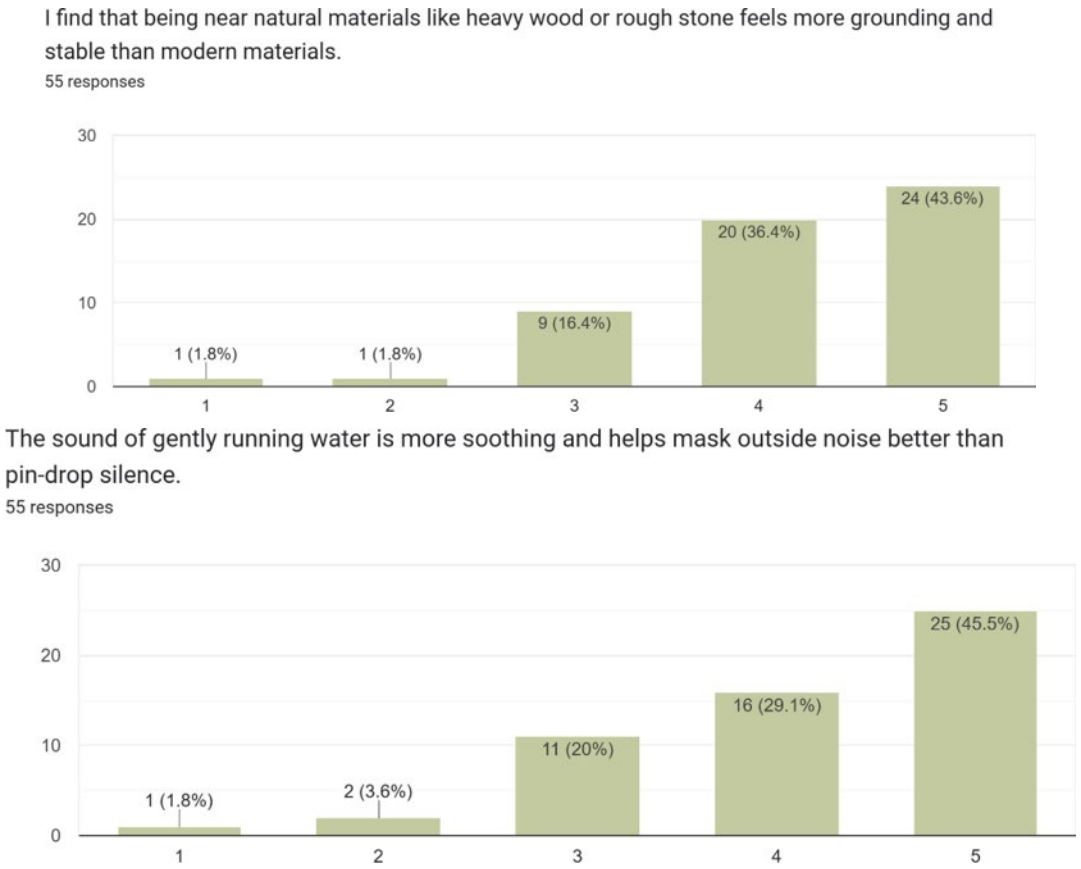


Fig. 2: Visualization of user agreement, showing F2 (Material Honesty) and F4 (Sensory Rest) as the highest-ranked factors for contemplation.

Table 1: F1-F5 Quantitative Validation Scores

Factor	Factor Label	Survey Mean Score ($\bar{x}$)	User agreement
F2	Material Honesty	4.18	High
F4	Sensory Rest	4.13	High
F2	Sublime Scale/Purity	3.95	High
F3	Temporal Pacing	3.91	High
F5	Symbolic Neutrality	3.84	Highest
F1	Focused Light	3.4	Medium

Design Synthesis and Priority Hierarchy

Synthesis. Combining precedent-based mechanisms (existence) with survey-based priorities (preference) yields a performance-to-experience hierarchy. Practically, the design must realize F2 and F4 as performance criteria (structural/acoustic measures), embed F3 and F5 as organizational and ethical conditions (sequencing and neutrality), and then apply F1 as an experiential refinement (focused light). The five derived guidelines below translate this synthesis into actionable prescriptions for modular urban prototypes:

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The Synthesis Table: The combined analysis dictates the allocation of design effort and resources. The highest scores and contextual validation form the *1st Priority* mandates.

Table 2: Synthesis of F1-F5 Factors to Determine Priority Tier

Factor	$\bar{x}$	Contextual Validation	Priority level
F2	4.18	Proven successful in all low-distraction sites(Pyramid Valley)	1st
F4	4.13	Essential for filtering Urban noise(Matrimandir)	1st
F3	3.91	Mandatory psychological buffer for entry or exit	2nd
F5	3.84	Non-negotiable ethical mandate(70.9% avoidance)	2nd
F1	3.40	Universal visual focus mechanism	3rd



Fig. 3: Visual representation of the F-Factor prioritization, guiding design effort towards essential performance criteria first.

Interpretation of Priority Levels: The hierarchy confirms that the primary user need is defensive and physical:

1st Priority (F2 & F4): The design must first achieve a condition of Acoustic Protection (F4) and Physical Grounding (F2). These are the Performance Criteria that guarantee the space functions as a sanctuary.

2nd Priority (F3 & F5): These factors dictate the Organizational Framework of the experience (sequencing) and the Ethical Framework (inclusivity).

3rd Priority (F1): This factor provides the final Experiential Focus, enhancing the user's ability to concentrate once the 1st and 2nd priority needs are met.

Conclusion and research Contribution

The Final Design Guidelines: Based on the validated priority hierarchy, the research culminates in five non-negotiable architectural mandates that form the prescriptive brief for the Urban Sanctuary typology. These guidelines are the primary output of the research.

Guideline 1: Material Honesty and Grounding (F2):

The material palette must be limited to raw, monolithic, and permanent elements (exposed concrete, stone) to satisfy the $\bar{x} = 4.18$ mandate for grounding and stability.

Guideline 2: The Active Acoustic Filter (F4):

The design must deploy a continuous, active sound masking mechanism (e.g., water cascade) as the primary structural defense against urban noise, adhering to the $\bar{x} = 4.13$ mandate.

Guideline 3: Radical Symbolic Neutrality (F5):

The architecture must be a symbolically vacant volume, eliminating all religious iconography and specific colors to guarantee the unconditional inclusivity mandated by the 70.9% avoidance finding.

Guideline 4: Sublime Scale and Purity of Form (F2):

The core reflection space must utilize purified, simple geometry and controlled verticality to evoke a sense of awe, minimizing visual distraction ($\bar{x} = 3.95$).

Guideline 5: The Paced Focus (F3 & F1):

The user journey must be structured by a mandatory Decompression Layer (F3) sequence ($\bar{x} = 3.91$) leading to a core space where light is strictly controlled to a single point of focus (F1) ($\bar{x} = 3.40$).

Academic and Typological Contribution: This dissertation offers a significant contribution to both environmental psychology and architectural design methodology. By moving spiritual design from subjective intuition to empirical metrics, the research provides a replicable tool - the F1-F5 framework - that can be applied to any high-stress urban context globally.

The research formally validates the necessity and defines the parameters of the Urban Sanctuary typology, establishing it as a critical and highly demanded spatial intervention for public well-being in the contemporary metropolitan context.

Future Scope: This research advances architectural scholarship by offering a validated, reproducible framework (F1-F5) that operationalizes spiritual-restorative design as measurable performance criteria rather than symbolic prescription. Future work should focus on Post Occupancy Evaluations (POE) that employ physiological measurements, heart rate variability and simple wearable EEG metrics to quantify changes in stress and attentional recovery attributable to each F-factor

Future research should focus on the application of these guidelines, specifically through the development of:

A pre-engineered, scalable architectural module based on the F1-F5 rules for insertion into diverse urban voids.

A Post-Occupancy Evaluation (POE) on a prototype to measure the physiological stress reduction achieved by spaces designed using the empirically validated framework.

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Artificial Intelligence Applications in Sustainable Buildings: A Systematic Synthesis of Machine and Deep Learning Approaches

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Abstract. Artificial intelligence (AI) is increasingly used to support sustainability-oriented decisions in building design, construction, and operation. This paper presents a systematic literature review of peer-reviewed journal articles at the intersection of AI (machine learning and deep learning) and sustainable buildings. Searches were conducted primarily in Scopus and complemented by SpringerLink and Google Scholar. Following PRISMA-based screening and eligibility assessment, 59 articles published between 2016 and 2023 were retained for synthesis. The review maps AI applications to the three sustainability pillars, identifies dominant application domains, and summarizes the most frequently adopted algorithms and software tool chains. Environmental sustainability dominates literature, with energy prediction and optimization as the most common use cases. Social sustainability research concentrates on indoor environmental quality and thermal comfort, while economic sustainability remains comparatively limited and is largely focused on cost prediction. Overall, tree-based machine learning models and conventional artificial neural networks appear most prevalent, typically reporting positive performance in predictive and optimization tasks. The review concludes with research gaps and practical directions for future work, including better coverage of social and economic outcomes, more transparent and explainable models, and tighter integration with BIM and life-cycle assessment workflows.

Introduction

Sustainable building design aims to reduce environmental impacts while supporting occupant well-being and economic feasibility. Digitalization has expanded the availability of building performance data (from simulation, BIM, and sensing), enabling data-driven methods to complement conventional analytical approaches. AI techniques, particularly machine learning (ML) and deep learning (DL), have been used to predict energy demand, optimize envelopes and system parameters, and support occupant-centric control strategies. Human-centric regenerative design perspectives further motivate the integration of computational tools into design workflows [1]. Despite rapid growth in the number of publications, the literature remains fragmented across application domains, sustainability dimensions, and algorithmic choices. This review consolidates recent evidence to answer four research questions: (1) how AI is applied across the environmental, social, and economic pillars; (2) which ML and DL models are most frequently used; (3) which building sustainability issues are most often targeted; and (4) which model families appear to perform best in reported applications. The main contributions are: (i) a PRISMA-informed synthesis of 59 journal articles [1]-[56]; (ii) a taxonomy of AI methods and software pipelines used in sustainable building research; and (iii) a discussion of research gaps relevant to conference and practice-oriented audiences.

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Methods

A systematic literature review protocol was adopted to ensure transparent study identification, screening, and synthesis. The review focused on journal articles written in English and reporting primary research (empirical, experimental, or computational). Conference proceedings, book chapters, and narrative reviews were excluded to maintain methodological consistency.

A. Search Strategy: Searches were conducted in Scopus and complemented with SpringerLink and Google Scholar using Boolean queries combining sustainability terms (e.g., "sustainable building", "green building") with AI terms (e.g., "machine learning", "deep learning", "artificial intelligence").

B. Screening and Eligibility: Records were de-duplicated and screened by title and abstract, followed by full-text eligibility checks. The process followed PRISMA logic, resulting in an initial pool of 283 records and a final corpus of 59 studies.

C. Data Extraction and Synthesis: For each included study, metadata and analytical attributes were extracted (publication year, country, research design, target sustainability issues, AI model type, and software tools).

Descriptive statistics were used to summarize distributions, and qualitative synthesis was used to interpret thematic patterns and data.

Results and Discussion

Publication and methodological trends:

The PRISMA screening process yielded 59 eligible journal articles from an initial pool of 283 records. The evidence base is recent and rapidly expanding publications increased steadily from 2016 (n=1) to a peak in 2023 (n=19), with 88% of studies published between 2020–2023 (n=52). Geographically, contributions were concentrated in a small number of countries, led by China (21/59), followed by Iran (5) and Italy (3). This distribution suggests that AI for sustainable buildings is globally investigated but remains uneven in research output.

In terms of research design, correlational studies were most common (31%), followed by experimental/causal (26%), exploration (25%), and descriptive designs (18%) (Figure 1).

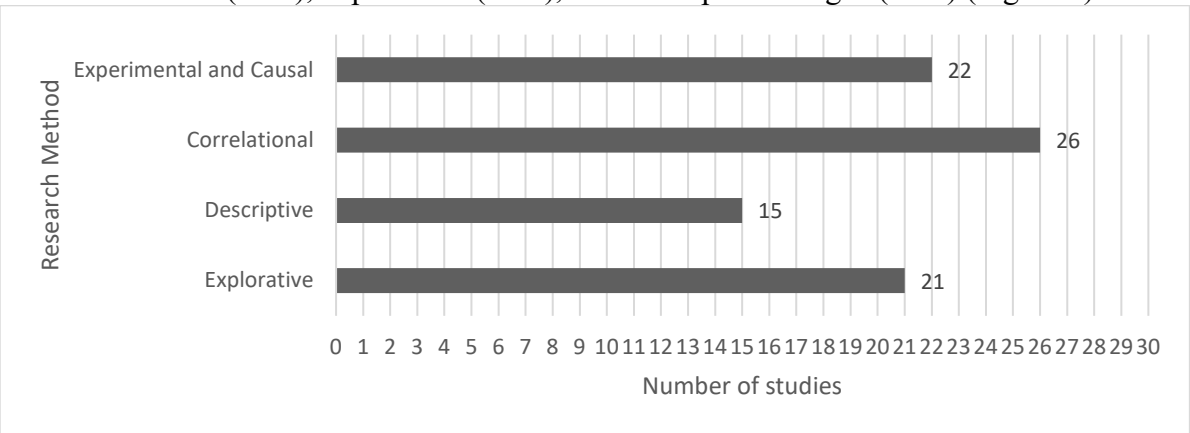


Figure 1: Research Methods

Most studies were quantitative (59%), while qualitative-only approaches were less frequent (13%); mixed methods accounted for 28%. Case study implementation remains limited: 24% (14/59) reported real-world case studies, whereas most studies relied on broader datasets or simulations as shown in figure 2. Overall, the literature is dominated by data-driven predictive

modeling, frequently evaluated through simulation environments rather than full-scale field deployment.

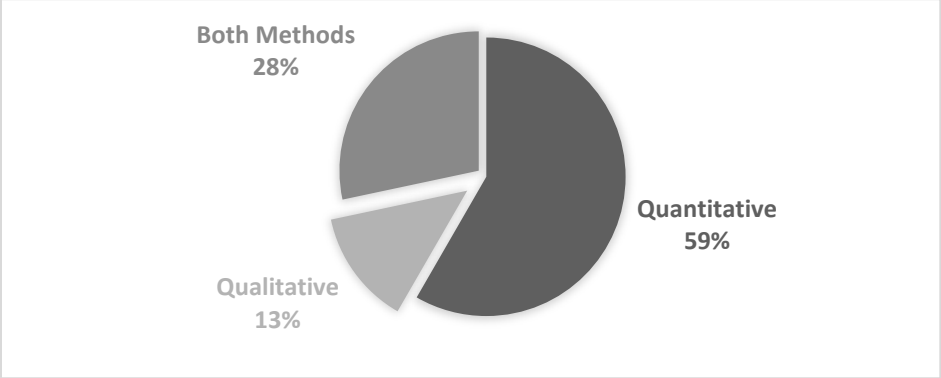


Figure 2: Research Types

Sustainability aspects addressed in the literature:

Across the reviewed studies, AI applications targeted a wide range of sustainable building issues, spanning energy systems, envelope and insulation, indoor environmental quality (IEQ), HVAC and ventilation control, life-cycle assessment, emissions reduction, materials selection, and cost estimation (Table 1). Energy-related applications were the most prominent (22/59; 37%), followed by thermal comfort-focused research (9 studies).

Table 1: Sustainability Pillars Issues

Sustainability core dimension	CODE	List of sustainability issues/aspects/factors :	Paper ID :	NO:	TOTAL	Frequa	Percentage
ENVIRONMENTAL SUSTAINABILITY	S1	Sustainable materials	2,3,5,42	4	47	8.47%	65%
	S2	Energy load/consumption/storage/loss/efficency	4,6,9,11,14,16,17,18,20,21,22,25,26,27	22		37.29%	
	S3	Life cycle assessment /Green performance assessment	6,31,47,24,48,59	6		10.17%	
	S4	Greenhouse gas emissions	7,31,41,59	4		6.78%	
	S5	Insulation technique	9,58	2		3.39%	
	S6	Renewable energy resources	26,30,45,46,51,53,55	7		11.86%	
	S7	Landscape Environment	32	1		1.70%	
	S8	Lighting control	52	1		1.70%	
SOCIAL SUSTAINABILITY	S9	Façade Esthetics	1,	1	19	1.70%	27%
	S10	Building climate control (Indoor) (Natural Ventilation) (Air Conditioning	8,19,28,30,36,37,45	7		11.86%	
	S11	Thermal comfort satisfaction	15,20,22,23,29,39,42,50,56	9		15.25%	
	S12	Human Centric	34,49	2		3.38%	
ECONOMICAL SUSTAINABILITY	S13	Construction/building Cost	10,12,13,33,38,43	6	6	10.16	8%

When grouped under the three pillars of sustainability, the evidence shows a clear imbalance. Environmental sustainability dominated (~65% of studies), social sustainability was secondary (~27%), and economic sustainability was least represented (~8%). This pattern indicates that AI research in sustainable buildings has primarily prioritized measurable performance outcomes (energy and emissions) over occupant-centered and economic considerations.

Environmental applications commonly address energy management and efficiency, life cycle and performance evaluation, materials optimization, and emissions reduction. Reported success rates were generally favorable: energy management appeared in 37.3% of studies with ~68% success, LCA/green performance evaluation appeared in ~10.7% with ~83% success, and materials/emissions-related applications showed success rates around 75% in the reviewed subset.

Social themes emphasized occupant experience, particularly thermal comfort and indoor climate control. Thermal comfort was discussed in 15.3% of studies, while AI-enabled climate control systems appeared in ~11.9% (reported success ~71%).

The comparatively smaller volume of work in this pillar suggests an opportunity to expand beyond comfort prediction to broader well-being and behavioral outcomes.

Economic applications focused mainly on cost prediction and optimization for green buildings. Where reported, ML-based cost prediction achieved ~66.7% success across relevant studies, and

at least one XGBoost model reported very high predictive accuracy ($R^2 \approx 0.96$). Despite strong results, this pillar remains underexplored relative to environmental performance.

Machine learning models: dominance of tree-based predictors:

ML methods were widely used and were classified by intended use and by fundamental task (Table 2). By intended use, decision-tree algorithms were the most prevalent (~36%), followed by regression models (~21%) and gradient boosting methods (~13%) (Table 2). Empirically, tree-based predictors were frequently reported as effective in building-performance contexts: simple decision trees showed positive outcomes in 84.5% of the studies in which they appeared, while Random Forest achieved a 66.7% positive impact rate in the subset reported. Beyond trees, several non-linear regressors (e.g., SVR and GPR) were reported with consistently positive outcomes in the studies where they were used, while basic linear regression showed mixed performance, suggesting limited suitability for complex, non-linear building datasets.

Collectively, these patterns reinforce that robust, non-linear learners dominate practical AI deployment in this domain, likely due to their ability to capture complex interactions among climate, geometry, materials, and operational variables. From the "fundamental type" perspective, predictive models represented the largest share (~47%), with classification (~19%) and regression-focused tasks (~14%) also common (Table 2). This confirms that the primary role of ML in sustainable building research is forecasting key outcomes (energy, comfort proxies, cost) to support design and operational decision-making.

Table 2: Machine Learning Models

CODE	Group 1:	Machine Learning Algorithms	Paper ID:	NO:	TOTAL	Frequancy in Papers Percentac	Scope/Use :
	Gradient Boosting Methods 1:				8	13.50%	
M1		Gradient boosting (GBR)	3,16	2			Predictive Models
M2		Extreme gradient boost regressor (XGBR)	3,23	2			Predictive Models
M3		LightGBM	10,25	2			Predictive Models
M4		XGBOOST	10,13	2			Predictive Models
	Decision Tree Algorithms/Models 2:				22	37.20%	
M5		Decision Tree algorithms/models	1,9,15,24,27,29,31	13			Predictive Models
M6		FLR, C4.5, IBK, OneR	55	1			Decision Making
M7		Random Forest (RF)	11,15,20,32,38,43	6			Data Classification
M8		Random Tree (RT)	11,13	2			Data Classification
	Ensemble Learning Methods 3:				3	5%	
M9		Adaptive Boosting regressor (ABR)	3	1			Predictive Models
M10		Reinforcment learning	26	1			Decision Making
M11		Multi-linear Random Forest Regression (MRFR)	7	1			Predictive Models
	Regression Models 4:				13	22%	
M12		Linear Regression	43,54	2			Predictive Models
M13		Ridge and Lasso	43	1			Predictive Models
M14		Support Vector Regression (SVR)	12,15,16,20,51,52	6			Regression Tasks
M15		Extreme Learning Machine (ELM)	36	1			Regression Tasks
M16		Gaussian Process Regression (GPR)	8,9,22	3			Probabilistic Models
	Classification and Clustering Models 5:				7	11.86	
M17		PLS-DA	2	1			Predictive Models
M18		LCSA-ML Model	6	1			Data Processing/extr
M19		Linear Discriminant Analysis (LDA)	7,33	2			Data Processing/extr
M20		Support Vector Machine (SVM)	9,31,54	3			Data Classification
	k-Nearest Neighbor (k-NN) 6:				2	3.38%	
M21		k-Nearest Neighbor (k-NN)	19,20	2			Predictive Models
	Multi-objective Optimization 7:				3	5%	
M22		Multi-objective optimization (MOPSO)	39,42,47	3			Decision Making
	Other Models/Techniques 8:				2	3.38%	
M23		Boolean Ant Colony Optimization (BACO)	7	1			Predictive Models
M24		Multivariate adaptive regression splines (MARS)	54	1			Predictive Models
	Topic Modeling 9:				1	1.60%	
M25		Latent Dirichlet Allocation (LDA)	17	1			Probabilistic Models

Deep learning models: concentrated in comfort and prediction tasks:

Deep learning appeared in 28 of 59 papers (~47%) (Table 3). By architecture type, ANN models were dominant (~59%), while DNN and other neural network variants each accounted for ~10%. Sequence and spatial architecture (RNN/LSTM and CNN) were less frequent (~6% each).

Transformer-based and TCN approaches were rare (~3% each) and, in the limited instances reported, produced neutral-to-negative outcomes, suggesting that cutting-edge architectures are not yet established in this application space.

By application type, DL usage was overwhelmingly predictive (75%), with a smaller share used for feature extraction/data processing (18%) (Table 3). In practice, this supports a consistent interpretation: DL is primarily used when researchers expect complex, non-linear relationships (often occupant-related or time-dependent) and when sufficient data streams (e.g., sensor or simulation time series) are available.

Table 3: Deep learning Models

CODE	Column1	Deep Learning algorithms	Paper ID:	NO:	TOTAL	FREQUANCY IN PAPERS	Scope/Use :	Postive Effect Papers ID	Percentag	Negative Effect Papers ID	Percenta	Neutral Effect Papers ID	Percenta
	Recurrent Neural Networks (RNN) 1:				2	3.20%							
D1		LSTM Models	4,44	2			Data processing/estr	0	0%	0	0%	4,44	100%
	Convolutional Neural Networks (CNN) 2:				2	3.20%							
D2		You only look once (YOLO	48	1			Data processing/estr	48	100%	0	0%	0	0%
D3		Region-based convolutional neural network (R	48	1			Probabilistic Models	48	100%	0	0%	0	0%
	Deep Belief network (DBN) 3 :				1	1.60%							
D4		Deep Belief network (DBN)	5	1			Predictive models	5	100%	0	0%	0	0%
	Deep Neural Networks (DNN) 4:				3	5%							
D5		Deep Neural Networks (DNN)	12,13,45	3			Predictive models	12,13	66.66%	45	33.33%	0	0%
	Transformers-Based Models 5 :				1	1.60%							
D6		Bidirectional Encoder Representations from Tr	17	1			Data Classification	0	0%	17	100%	0	0%
	Temporal Convolutional Neural Networks (TCN) 6 :				1	1.60%							
D7		Deep temporal convolutional neural network	57	1			Data Processing/est	0	0%	0	0%	57	100%
	General Terms 7 :				3	5%							
D8		Neural network algorithm (NNA)	18,21,59	3			Predictive Models	18,21,59	100%	0	0%	0	0%
	Artificial Neural Networks (ANN) 8 :				19	32.20%							
D9		Artifical neural network (ANN)	1,11,14,15,16,28,30,	14			Predictive models	1,11,14,15,16,28,36,39,42,46,53	78.57%	30,34		14,20%	7%
D10		Backpropagation Neural Networks (BPNN):	35	1			Data processing/estr	0	0%	35	100%	0	0%
D11		Adaptive-Network based Fuzzy Inference Syste	11	1			Predictive models	11,	100%	0	0%	0	0%

Research themes and tools: a simulation-to-AI workflow:
Six dominant research themes were identified (Table 4), led by predictive modeling for sustainable design (61%), followed by AI in green building practices (13%) and materials classification/rating (8%). Smaller thematic clusters included integrated AI workflows, LCSA–ML integration, and BIM–ML approaches.

Table 4: Scope of the studies

Scope of the overall studies (two strings correlated)	Paper ID	No.
Developing Machine learning models to predict or benefit of sustainable architecture.	1,6,7,8,9,10,12,13,15,16,18,19,20,21,22,23,24,25,26,27,29,30,31,33,36,37,39,41,43,44,45,46,50,51,53,54,55,56,57,59,60	41
Machine Learning or Deep learning models to classify and assess sustainable materials.	2,3,5,42,46,	5
Deep learning integrated with machine learning in applications of sustainable architecture.	4,28,35,38,48,	5
Machine Learning integrated with tools like LCSA to assess sustainable buildings.	6,24,30,47,	4
Integrating Machine Learning and BIM towards the benefits of green architecture.	25,37,58	3
The use of artifical intelligence models in the sustainable architecture and green buildings.	1,11,14,17,28,32,34,49,52	9

The digital tool ecosystem (figure 3) further indicates a typical pipeline. Data analysis/programming tools were most common (33%), with MATLAB/Simulink frequently reported (~12 papers). Energy/environment simulation tools comprised 22% (notably EnergyPlus and DEST), and design/simulation platforms accounted for 17% (e.g., Design Builder, Rhino/Grasshopper). BIM tools represented 14% (e.g., Revit). Taken together, the evidence indicates a recurring workflow: (i) model and simulate building performance, (ii) extract and curate datasets, (iii) train ML/DL predictors, and (iv) interpret/visualize results for design or operational decisions (figure 3).

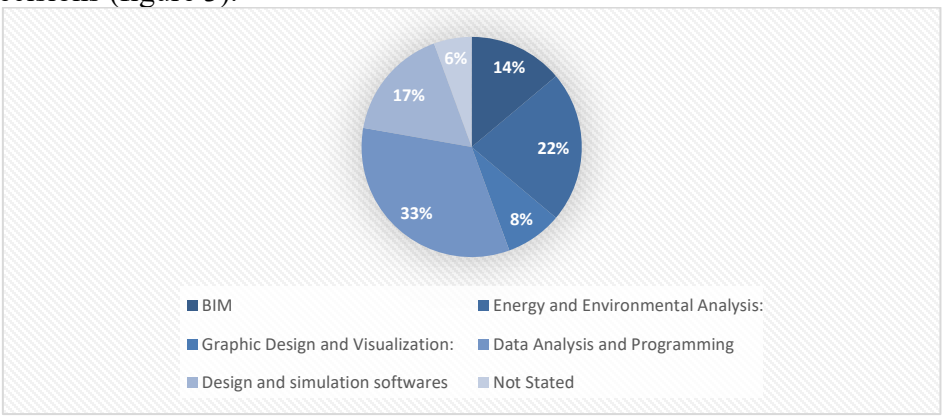


Figure 3: Overall Scopes of the studies

Cross-variable synthesis: models, pillars, and tools align in predictable clusters:
The correlation synthesis (Table 5) highlights three recurring clusters. First, environmental sustainability studies frequently used ML predictive models, particularly tree-based algorithms, often coupled with energy/environmental simulation tools; this cluster represents ~53% (33/59) of the sample.

Second, social sustainability studies commonly used DL predictive models (especially ANN) and relied on design/simulation tools to evaluate comfort and control strategies. Third, economic sustainability studies primarily employed ML predictors (often boosting and ensemble trees) for cost estimation and optimization.

According to the dataset, study outcomes were predominantly positive: approximately three-quarters of studies reported that AI methods met the intended objectives, with fewer neutral and negative outcomes. The prevalence of positive results supports the maturity of predictive modeling for energy and cost tasks; however, the scarcity of economic and broader social sustainability applications indicates a research gap that may limit holistic sustainability decision-making if not addressed.

Table 5: *Pillars, and tools align in predictable clusters*

Groups :	Digital Media used :	Paper ID:	NO:	TOTAL NO:	uancy of Papers Perc	Postive Paper:	Percen	Negative Paper	Percen	Neutral Paper:	Percent
BIM				5	8.47%						
	Autodesk Revit	25,32,37	3			25,32,37	100%	0	0%	0	0%
	Autodesk Autocad	34	1			34	100%	0	0%	0	0%
	ArchiCAD	34	1			34	100%	0	0%	0	0%
Energy and Environmental Analysis:				8	13.55%						
	EnergyPlus and DEST	21,44,57,6	4			6,21	50%	0	0%	44,57	50%
	PV Stimulation Software	11	1			11	100%	0	0%	0	0%
	Energy analysis	6	1			6	100%	0	0%	0	0%
	Meteonorm	39	1			39	100%	0	0%	0	0%
	Intelligent thermal Comfort management ITCM	20	1			20	100%	0	0%	0	0%
Graphic Design and Visualization:				3	5.00%						
	GIMP2.1	1	1			1	100%	0	0%	0	0%
	Remote Sensing	34	1			34	100%	0	0%	0	0%
	MS Excel	10	1			10	100%	0	0%	0	0%
Data Analysis and Programming				12	20.33%						
	MATLAB and Simulink	1,11,14,26,36,51,6	7			1,6,11,14,26,36,51	100%	0	0%	0	0%
	The R Software	27	1			27	100%	0	0%	0	0%
	Python	31	1			31	100%	0	0%	0	0%
	IBM Software	1,34	1			1,34	100%	0	0%	0	0%
	Commerical Statistical product services solutions	53	1			53	100%	0	0%	0	0%
	CT Scanning software	2	1			2	100%	0	0%	0	0%
	RapidMiner	38	1			0	0%	0	0%	38	100%
Design and simulation softwares				6	10.16%						
	Sketchup	31	1			31	100%	0	0%	0	0%
	Grasshopper	6,59	1			6,59	100%	0	0%	0	0%
	Design Builder	19,25,29,60	3			19,29,60,25	100%	0	0%	0	0%
	Design Expert	29	1			29	100%	0	0%	0	0%
Not Stated		52,55	2	2	3.38%	52	50%	0	0%	55	50%

Conclsuion

This systematic literature review examined 59 studies on AI applications (machine learning and deep learning) in sustainable architecture. The results show a clear surge in research since 2020 and confirm that AI is increasingly shaping sustainable building design and operation. Most work focuses on environmental sustainability, especially energy efficiency and carbon reduction, where decision trees and ensemble models frequently deliver strong predictive performance. Social sustainability (e.g., thermal comfort and indoor environmental quality) is also supported, particularly through deep learning, while economic sustainability remains less explored despite promising cost-estimation results.

Overall, roughly three quarters of the reviewed reported positive outcomes, underscoring AI's potential to improve decision-making and building performance. Future research should better balance environmental goals with social and economic dimensions and explore hybrid approaches that integrate ML/DL with simulations, IoT sensor data, and real-time building management systems. As data availability and smart-building infrastructure expand, AI is likely to become a core driver of resilient, energy-efficient, and human-centric buildings that support sustainable urban development.

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Development of an AI-Driven Platform for Autonomous Dashcam Data Integration with the International Road Assessment Program Visual Data Analysis for Road Safety Assessment Enhancement

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Keywords: Artificial Intelligence, Dashcam Data Integration, Computer Vision (YOLOv7), Metadata Extraction, Road Safety Assessment, Smart Cities

Abstract. This study develops an AI-driven platform to autonomously convert unstructured dashcam footage into structured data compatible with the Visual iRAP Data Analysis (VIDA) traffic management system. The platform utilizes YOLOv7 for object detection and vehicle trajectory extraction, Natural Language Processing (NLP) for text and audio analysis, and predictive models to clean and structure metadata into VIDA-compatible formats (CSV, XML). Tested on 100 dashcam videos from Saudi Arabian roads—including highways, urban intersections, and accident zones—the platform achieved a 96% metadata extraction success rate with processing times as low as 3.8 seconds per video. Usability testing yielded a 4.5/5 satisfaction rating from urban planning professionals. This work bridges the critical gap between raw vehicular data and intelligent transportation systems, enabling data-driven road safety assessment and supporting Saudi Vision 2030's smart city objectives.

Introduction

Rapid urbanization across Saudi Arabia has intensified demands for intelligent transportation systems capable of managing growing traffic volumes, reducing congestion, and ensuring road safety [1,2]. Dashcams—vehicle-mounted cameras capturing video, GPS location, timestamps, and speed data—represent an abundant but largely untapped data source. While the VIDA system provides a robust framework for global traffic monitoring, it requires standardized, structured data inputs that raw dashcam footage does not provide [3].

Currently, there is a lag in systems that can automatically turn dashcam videos into useful information for traffic management. Even though artificial intelligence (AI) has been used for locating cars and predicting crashes, a complete solution that can take unorganized dashcam footage, process it, and turn it into a format that works with existing traffic management tools [4,5] like VIDA is missing.

This study develops a system that uses AI to assess videos from car cameras and obtain information such as car directions, speed, and location. It then converts this information into a format that can be used by city planners. The authors tested the system using real videos from cars in Saudi Arabia and discovered its efficiency in assisting city planners in making better decisions. This is important because it can help Saudi Arabia achieve its future goals outlined in the Vision 2030 document. The system can help make cities better by giving planners the information they need to make good decisions about how to design roads and transportation systems.

Literature Review

AI for Road Safety and Traffic Analysis:

Computer vision is really good at helping us make roads safer. For example, some researchers used YOLOv8 to detect when cars and pedestrians are interacting, and it was able to do this

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correctly about 79% of the time, although it made some mistakes about 10% of the time [6]. It had some trouble when it was dark or when things were in the way. Another group of researchers used different tools, called Mask R-CNN and YOLOv4, to watch traffic and count how many cars were waiting in line, and they were able to show that these tools can be helpful for automatically monitoring traffic [7]. These studies show that special kinds of computer models, called convolutional neural networks, are really good at taking videos of traffic and pulling out useful information from them. This is a big deal because it can help us make roads safer and more efficient. By using these tools, we can get a better sense of what's happening on the roads and make decisions to improve traffic flow and reduce accidents. Overall, computer vision is a powerful tool that has a lot of potential for making our roads safer and better.

Dashcam Adoption and Data Utilization:
In 2024, Ashrafi's study looked at what makes people adopt dashcams, using two models: the Technology Acceptance Model and the Information Systems Success Model [8]. The study found that people are more likely to use dashcams if they find them useful, easy to use, and fun. But this research only looked at individual users, not at how organizations use dashcam data. This is a gap that our study tries to fill by creating a system that can process dashcam data at an institutional level.

Machine Learning for Traffic Prediction:
Liu and colleagues demonstrated the effectiveness of machine learning models, including Support Vector Machines and Random Forests, for predicting transportation system behavior under varying conditions [9]. Their work supports the integration of multiple data sources—weather, demand, and video—for improved road safety outcomes, reinforcing the value of combining dashcam data with existing traffic management frameworks.

Research Gap:
While existing studies demonstrate AI's capability for specific detection and prediction tasks, no integrated system autonomously processes unstructured dashcam footage from multiple sources and translates it into the standardized formats required by platforms like VIDA. This study directly addresses this gap by developing a complete pipeline from raw footage to structured, VIDA-compatible data.

Methodology

This research used a two-part plan to get the job done. The first part was all about gathering data and pulling out important details from videos taken by dashcams. The second part involved making sense of the data, cleaning it up, and turning it into a format that works with VIDA. By doing it this way, the authors were able to take raw data and turn it into useful information that can help manage traffic.

Sample:
Fig. 1 illustrates the study's design stages. The authors collected 100 videos from car cameras in different places in Saudi Arabia, such as city streets, highways, and intersections. These videos are different from each other in terms of picture quality, the angle they were shot from, and how clear they are. This helps make our collection of videos more varied. We also have extra information about each video, such as where it was taken, how fast the car was going, and when it was recorded.

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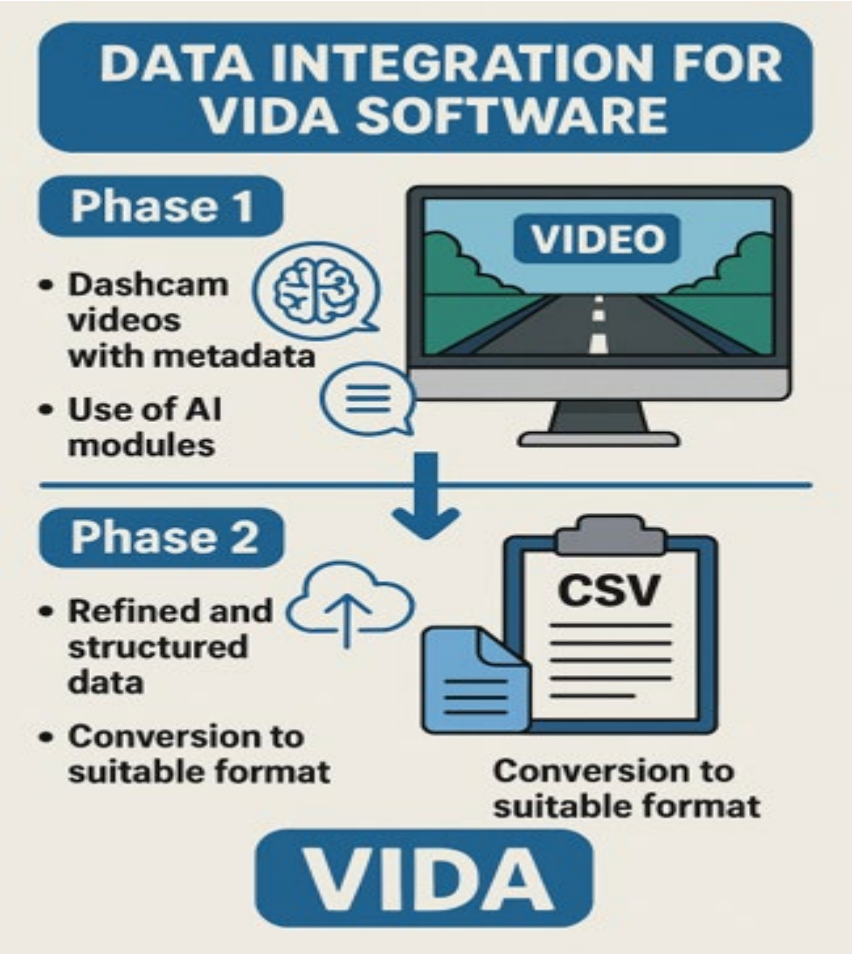


Fig. 1: A 2-Phased Research Design

AI Model and Processing:
The project was done in two parts. First, there is the utilization of a special computer program called YOLOv7 to look at videos and find objects like cars and people. This program assisted in seeing how vehicles were moving, how fast they were going, and how they were interacting with pedestrians. Another set of tools was used to understand any text or audio that was part of the videos. Then, in the second part, machine learning was adopted to make sense of the collected data. This involved cleaning up the data to make sure it was accurate, filling in any missing information based on what was around it, and changing the format of the data so it could be used with a system called VIDA. The data were converted into two common formats: CSV and XML.

Measurement Metrics:
Key performance metrics included:

- *Metadata Extraction Success Rate*: Percentage of correctly extracted metadata compared to manual validation
- *Data Conversion Success Rate*: This is the percentage of raw data that is successfully changed into a format that works with VIDA.
- *Processing Speed*: Time required for complete video processing, extraction, and conversion
- *Usability Ratings*: User evaluations across ease of use, metadata clarity, and integration flexibility

Assumptions and Limitations:
The study assumed sufficient video quality for metadata extraction and AI algorithm accuracy. Limitations included variability in dashcam resolutions and field-of-view angles, potential data corruption in source videos, and scalability constraints for larger datasets requiring cloud infrastructure.

Results

Metadata Extraction Success Rate:
The results of our tests showed that the authors were able to successfully extract metadata in most cases (see *Fig. 2*). Ten trials were carried out, and the success rate was between 89% and 96%. Trial 7 had a success rate of 96%, which was the highest. On the other hand, Trial 8 had the lowest success rate at 89%. If we look at all the trials together, our average success rate was 92.5%. This suggests that our system works consistently well, even when the lighting is different, the video quality is not great, or the dashcam is different.

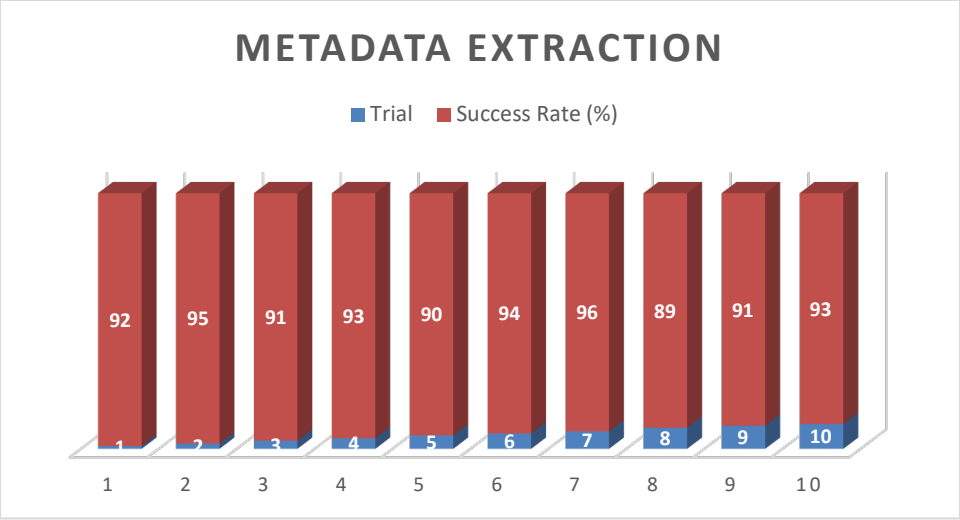


Fig. 2: Success rate per trial

Data Conversion Success by Format:
Of all the tested formats, MP4 emerged as the most accurate, with the highest conversion rate of 98%, contributing to 26% of all leads (see *Fig. 3*). AVI followed with a 95% follow-up rate, representing 25% of the sample. MKV achieved a 94% response rate, also accounting for 25% of the sample. MOV had the lowest success rate at 92%, making up the remaining 24% of conversions. Overall, all formats received high conversion success, with only slight differences, demonstrating that the techniques used are generally accurate and offer good results across the board.

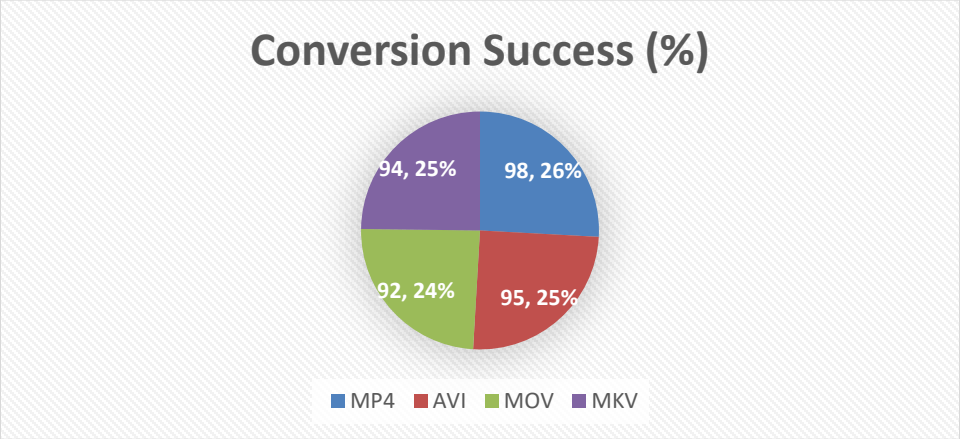


Fig. 3: Data Conversion Success by Format

Processing Speed and Efficiency:
The time it takes to process videos can vary depending on the scene‘s complication. For example, when monitoring highways, it takes about 3.8 seconds to process one video (see *Fig. 4*). Analyzing crowds takes a bit longer, around 4 seconds. Watching urban traffic takes about 4.5 seconds, and detecting accidents takes the longest, around 5.2 seconds. But overall, the times are pretty close together, ranging from 3.8 to 5.2 seconds. This shows that the system can handle things almost in real-time, which is really useful for applications that need quick results.

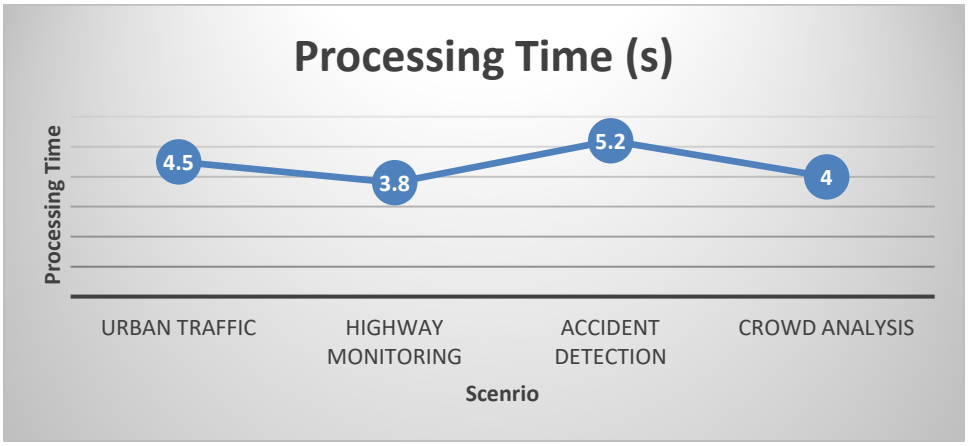


Fig. 4: Average Processing Time per Scenario

Metadata Completeness Post-Processing:
Metadata completeness after processing reached 96% for urban traffic scenes, 94% for crowd scenes, 93% for highway scenes, and 90% for accident scenes (see *Fig. 5*). The high completeness across all scene types demonstrates robust metadata extraction capabilities, with lower accident scene completeness attributed to the unpredictable nature of such events.

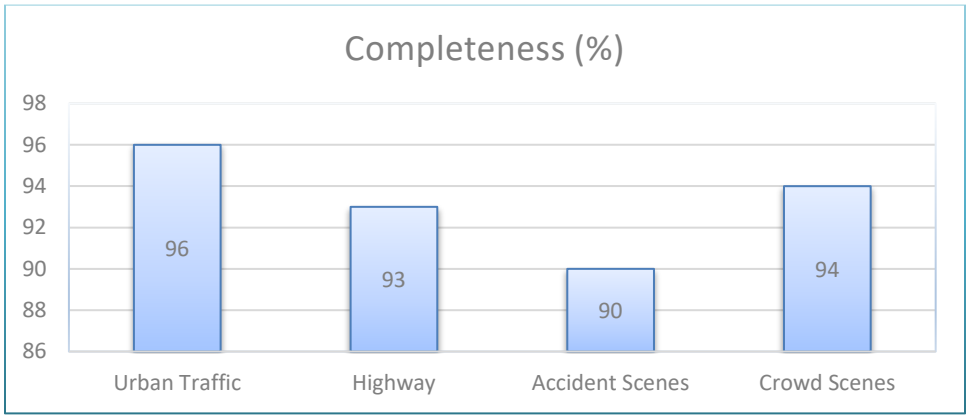


Fig. 5: Percentage of Complete Metadata Post-Processing

Reliability and Usability Testing:
Cronbach's Alpha for system usability metrics was 0.929, indicating excellent reliability across ease of use, metadata clarity, processing speed, integration flexibility, and overall satisfaction. Usability testing with urban planning professionals yielded average ratings of 4.8 for ease of use, 4.6 for metadata clarity, 5.0 for processing speed, 4.2 for integration flexibility, and 4.5 for overall satisfaction.

Discussion

Scenario-based Performance:
Case Study 1 - Urban Traffic Monitoring: Analysis of 15-minute footage from Riyadh captured 91% of pedestrian crossings and all vehicle movements under varying lighting conditions, with metadata extraction completed in 4.5 seconds. Data integrated into VIDA provided comprehensive traffic and pedestrian movement visualization.
Case Study 2 - Accident Analysis: In simulated rear-end collision footage, the system identified impact time within ±0.8 seconds, detected pre-crash speed oscillations, and classified the event with 87% confidence. GPS coordinates and timestamps enabled complete accident timeline reconstruction within VIDA.

Validation against Previous Studies:
The platform works really well, just like other studies have shown. It can detect objects using YOLOv7, which is similar to what Radojčić and Dobrojević found in 2024 when they used YOLOv8 [6]. Also, the platform can handle many different types of video, which is important for making sure different systems can work together, as Mandal and others pointed out in 2020 [7]. This is a big deal because it means the platform is flexible and can be used in many different situations.

Policy and Planning Implications for Smart Cities:
The platform enables real-time analysis that supports adaptive traffic policy-making. Authorities can use extracted data to modify speed limits, allocate resources dynamically, and manage congestion. The system aligns with Vision 2030 objectives for smarter, safer, and more efficient urban spaces by providing evidence-based insights for infrastructure planning.

Challenges and Limitations:
Implementation challenges include variable video quality affecting metadata extraction in complex scenes, integration requirements for existing traffic management infrastructure, and data privacy considerations for footage containing personally identifiable information. Scalability remains a concern for large-scale deployment across multiple cities.

Conclusion

Main Findings:

This study successfully developed an AI-driven platform that autonomously converts unstructured dashcam data into VIDA-compatible formats. The platform achieved a 96% metadata extraction success rate with processing times as low as 3.8 seconds per video, demonstrating suitability for near-real-time traffic management applications.

Key Contributions:

The primary contribution is a novel, scalable system that bridges a critical gap in intelligent transportation systems. By enabling the utilization of untapped dashcam data for standardized road safety assessment, the platform provides traffic agencies and urban authorities with evidence-based, real-time insights for decision-making. The study's key contributions are as follows:

- Develop a national metadata formatting framework to ensure interoperability between AI platforms and traffic management systems
- Invest in cloud-based infrastructure for scalable processing across regions
- Implement training programs for traffic planners and enforcement authorities on AI platform utilization
- Establish data privacy guidelines for dashcam footage handling
- Conduct city-specific pilot programs in high-traffic areas to demonstrate effectiveness and collect user feedback.

Future Research Directions:

- Explore edge AI devices for in-vehicle preprocessing to reduce latency and bandwidth requirements
- Test platform performance across diverse urban and rural environments
- Examine hybrid AI models combining computer vision with sensor data (LiDAR, radar)
- Evaluate long-term effects on accident statistics and policy success rates
- Investigate integration methods for crowdsourced dashcam data from individual and fleet operators

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Sustainability - Community Empowerment Through Smart City Strategies: OxyID and the Urban Lungs of Jeddah

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Keywords: Digital Governance, Urban Forests, Smart City Platforms, Climate Adaptation, Community Engagement, Jeddah, Urban Resilience, Decentralized Neighborhoods

Abstract. Jeddah being the second largest city of Saudi Arabia, holds a very significant presence in the region. Geographically it is next to the Redsea making it a port city while at the same time it is a gateway to the religious city of Mecca. With the launch of the government program of Vision 2030, Jeddah has seen urban expansion and modernized infrastructure with improved living standards. Vision 2030 also emphasis heavily on low carbon technologies, green infrastructure, public realm design, and citizen engagement in a more sustainable way. The city has the capacity to build resilient, healthy neighborhoods aligned with national sustainability goals [5]. According to the G20 Climate Risk Atlas, Saudi Arabia will experience an 88% increase in the frequency of agricultural drought by 2050 under a high-emissions scenario (CMCC, 2021) [6]. This intensifies risks to human health and economic stability and stresses the need for locally grounded, community-scale climate adaptation strategies in Jeddah. This paper introduces **OxyID**, a digital framework that links each resident's identity to the lifelong care of a specific tree within their community, managed and monitored through smart municipal platforms. By positioning urban trees as the "lungs" of the city and assigning them directly to individuals, OxyID transforms green infrastructure linking them to a personal and shared responsibility embedded in daily urban life. The research adopts a mixed-methods approach, combining a digital survey to assess residents' willingness to digitally adopt a green space with qualitative insights from international case studies. These include the Digital Society and Digital Infrastructure pillar of the Singapore Green Plan 2030 (Ministry of Sustainability and the Environment, 2021)[2], Paris's data-driven urban mobility and public space strategies (Atelier Parisien d'Urbanisme [Apur], 2021) [9], and New York City's MillionTreesNYC initiative (New York City Department of Parks & Recreation, 2015) program [7] are analyzed to extract transferable principles of digital governance, community engagement, and urban forestry. The study is expected to demonstrate how a digital identity tree can create a better community as the inhabitants are more involved in enhancing their lifestyle by taking ownership to participate in neighborhood activities. By situating OxyID at the intersection of architecture, urban design, and smart city governance, the paper proposes a conceptual model for positioning Jeddah as a green, sustainable smart city in which everyone contributes to a healthier urban footprint. The framework offers a replicable approach for other climate-vulnerable Gulf cities seeking people-centered digital pathways to urban resilience.

1. Introduction

Like every developing city in this century, Jeddah is expanding rapidly to cater to the demands of the growing population and its needs. Driven by rapid urban expansion, infrastructure development, and its strategic role in Saudi Arabia's Vision 2030, this growth is giving a lot of benefits to the inhabitants in the health and entertainment sector especially. Despite the government's keen interest in providing a better life for its inhabitants with the development of Jeddah's Corniche, it is important to develop areas within neighborhoods which can result in daily

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healthy lifestyle in localized neighborhoods with easy access. Jeddah, being a car driven city has neighborhoods with minimum walking opportunities, a holistic green strategy is needed to reduce the environmental pressures, including urban heat island effects, deteriorating air quality, and declining per-capita access to green spaces. Urban trees, often described as the "lungs" of the city, are essential to mitigating these impacts by cooling microclimates, filtering pollutants, and supporting physical and mental health.

With the advancement in various sectors, the city is investing heavily in smart technologies, digital platforms, and e-governance systems. This creates an opportunity to connect digital transformation with community-scale environmental stewardship.

Research problem. There is a gap in how residents living in local neighborhoods feel disconnected from outside spaces due to limited opportunities to engage in their local community. As emphasized in my previous paper, a decentralized neighborhood not only enhances quality of life by creating green spaces, it can also create activities which can activate inhabitants to improve lifestyles and health in a localized and safe setting. The world is progressing eagerly towards smart cities initiatives; there is a need to direct the next development towards a smarter and greener decentralized Jeddah. Existing programs rarely translate digital governance into personal, ongoing responsibility for green assets at neighborhood scale.

Research objective. This paper develops and evaluates an idea where each individual living in a neighborhood is not only residing in their home but also enjoying the benefits provided in a neighborhood to engage communities and thus resulting in healthier lifestyle. OxyID, a conceptual digital framework that links each resident's digital identity to an individual tree in their neighborhood, turning urban forests into visible, trackable "lungs" of the city and making tree care a shared civic function. Qualitative and quantitative analysis will support the idea by explaining how this initiative will apply and integrated into existing neighborhoods.

Research questions.

1. How can digital identity systems be designed to connect individuals to specific urban trees in Jeddah?
2. In what ways can such a system enhance community empowerment and participation in urban greening?
3. How can digital tools translate individual tree ownership into measurable environmental performance at neighborhood and city scales?

The paper approaches these questions from the perspective of architecture and urban design, treating OxyID not only as a technological system but as a spatial and social intervention embedded in the fabric of the city.

2. Methodology

2.1 Research design

The study adopts a mixed-methods design:

- **Literature Review and context** focuses on Singapore Green plan 2030 [2], Paris data-driven mobility and public space reallocation [9], MillionTreesNYC to derive design and governance principles [8].
- **Quantitative digital survey** of Jeddah residents to assess willingness to participate in tree ownership via a digital app, perceived benefits, and barriers.
- **Qualitative interview** with technology experts in Jeddah to explore feasibility, governance, and integration with existing smart platforms.

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2.2 Literature Review and Context

Saudi Vision 2030 frames environmental sustainability and livable cities as strategic national goals, promoting green spaces, public realm enhancement, and quality of life improvements. With the development of smart technologies across the globe, Jeddah has the potential to develop its green spaces which can be digitally connected to the users [4]. The research will focus on literature reviews on implementation of smart technologies on urban scale in different countries.

Research on Jeddah's green areas calls for integrated strategies that combine physical planting, long-term maintenance, and community involvement to ensure resilience in the face of climate change and water scarcity. The need for innovative governance tools that bridge municipalities and residents is frequently emphasized.

2.3 Urban forests as the "lungs" of the city

As the urgency to combat climate change intensifies, tree planting is increasingly recognized as a vital component of natural climate solutions. Urban trees and forests deliver a wide range of ecosystem services, including air purification, carbon sequestration, temperature regulation, and stormwater management [1]. These benefits are not merely ecological, they translate into tangible improvements in public health, outdoor comfort, and community resilience. Strategic placement of trees along streets, plazas, and residential clusters can significantly modify microclimate conditions and improve outdoor thermal comfort, particularly in arid-climate cities like Jeddah, where shade trees are essential for walkability and public realm usability [4].

The metaphor of trees as the "lungs" of the city remains critical, they absorb pollutants from vehicular emissions, filter particulate matter, and sustain life in dense urban environments. Research from the UK's Forest Research agency highlights that the magnitude of carbon sequestration and other ecosystem services is directly proportional to tree canopy cover and the presence of large-diameter specimens [1]. This underscores the importance of not only planting trees but ensuring their long-term survival and growth through biodiverse species selection and community stewardship.

Studies in North America further demonstrate that planting a diverse range of tree species increases the likelihood of establishing thriving, resilient urban forests, thereby reducing the risk of widespread planting failures. In Jeddah, strategic placement of trees along streets, plazas, and residential clusters can significantly modify microclimate conditions and improve outdoor thermal comfort.

2.4 Smart city platforms and digital governance

Smart city initiatives integrate sensors, data platforms, and digital services to create efficient urban systems which started with Singapore's Smart Nation strategy launched in 2014 and later evolving to Singapore's Green Plan 2030 resulted in an initiative integrating environmental sensors and digital services into everyday life, enabling residents to access data on air quality, mobility, and greenery at the same time participate in feedback loops [2]. These strategies highlight on how national policy can drive urban greening at scale, with targets to plant 1 million additional trees and ensure every household is within a 10-minute walk of a park by 2030. These models demonstrate how data-rich platforms can underwrite more responsive and inclusive urban management.

2.5 Community-based urban forestry and digital tools

Million Tree initiative is seen as another successful strategy to mitigate climate effect [7]. It was a combined municipal leadership with the government to develop a community engagement program. With community planting days, volunteer programs, and public mapping of planted trees, ultimately achieving a goal of planting one million trees ahead of schedule [3]. The initiative

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showed that communication, neighborhood-scale engagement, and visible data (e.g., maps of tree locations and benefits) are critical to success.

Digital tools, including mobile apps and web portals, have been used to crowdsource tree inventories, allow residents to "adopt" trees, and report maintenance needs. These tools illustrate how assigning responsibility and making environmental data legible can strengthen community ties and tree survival rates. This is a prime example to learn and get inspired from.

Gap. While there is growing literature on smart cities and community-based urban forestry, few models integrate formal digital identity systems (linked to municipal governance) with personal, life-long tree ownership in Gulf contexts. OxyID aims to address this gap by connecting e-governance, architecture, and urban ecology in Jeddah.

2.6 Governance structure

The proposed governance model involves:

- **Jeddah Municipality** as platform owner and data custodian.
- **Technical partners** (local IT firms or start-ups) develop and maintain the app and data infrastructure.
- **Community partners** (schools, mosques, universities, neighborhood committees) serving as local hubs to facilitate onboarding and activities.

Clear data governance rules are required: anonymization of environmental data, opt-in mechanisms, and transparency on how data support planning decisions.

3. The OxyID Concept and System Design

3.1 Conceptual overview

OxyID conceptualizes urban trees as the distributed "lungs" of Jeddah's neighborhoods and assigns each resident a specific tree through a municipal digital platform. The system turns an abstract environmental asset into a personal, visible, and traceable responsibility.

From an architectural and urban design perspective, OxyID operates across three spatial scales:

- **Tree scale:** individual trees in streets, courtyards, sidewalks, schoolyards, and public spaces.
- **Neighborhood scale:** clusters of trees forming local canopies and microclimates.
- **City scale:** aggregated data visualizing Jeddah's "breathing capacity" through its urban forest.

3.2 Technical linkage of identity and tree

The framework integrates with existing national or municipal digital identity systems (e.g., resident ID numbers or municipal app accounts). Each user selecting or being assigned a tree generates a unique digital link stored in a secure database.

Key components:

- **Identity module:** authenticates the resident and links their account to a geotagged tree record.
- **Tree database:** stores species, planting date, coordinates, maintenance history, and sensor data where installed.
- **Monitoring layer:** optional soil moisture and environmental sensors; otherwise, periodic municipal or community checks recorded via the app.
- **User interface:** mobile and web dashboards displaying tree health (e.g., growth stage, watering needs), estimated carbon sequestration, and neighborhood canopy indicators.

3.3 Incentives and community engagement

OxyID incorporates soft gamification and recognition mechanisms:

- **Green points** awarded for visiting the tree, logging observations, joining community planting days, and participating in workshops.
- Aggregate neighborhood scores that can unlock small public realm improvements (e.g., benches, shading structures, or additional trees).
- Integration with schools and universities as living laboratories where students manage clusters of trees as part of design or environmental courses.

4. Research Methodology

4.1 Quantitative Analysis:

Sampling and data collection

The survey targets 65 residents across three contrasting districts (e.g., older central neighborhoods, newer planned communities, and coastal/mixed-use areas), using stratified sampling by age, gender, and housing type to capture diverse perspectives. The instrument includes questions, scenario-based prompts, and items on environmental attitudes and digital literacy.

The residents of Jeddah have adopted a more active lifestyle with the introduction of Corniche walk. When asked if they preferred to walk around their neighborhood, majority of the respondents agreed. *(Ref Table:1)* When asked if they are willing to care for a tree or a plant majority said yes *(Ref Table: 2)* When asked about how far you are willing to go to care for a tree 60% responded closer to their house while 20% said they liked it to be in a community park *(Ref Table: 3)* When asked about the benefits that will attract them to adopt a tree then 60% said they would do it for better air quality, while a few preferred it for educational purposes. Majority are willing to contribute their time and energy to a better greener neighborhood. The survey results are attached below to verify the survey results.

Table: 1

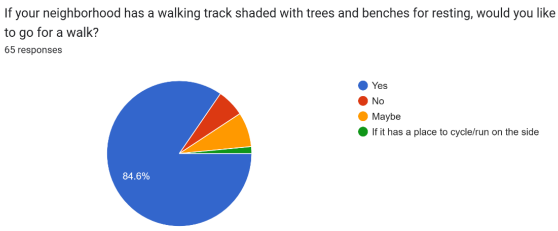


Table: 2

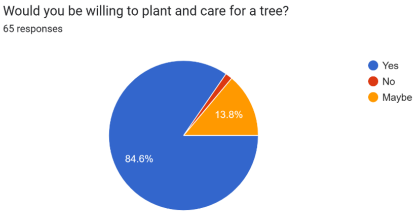


Table: 3

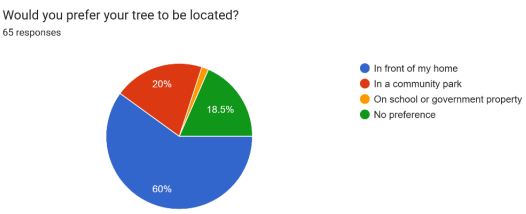


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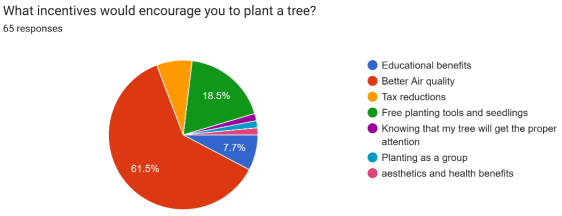
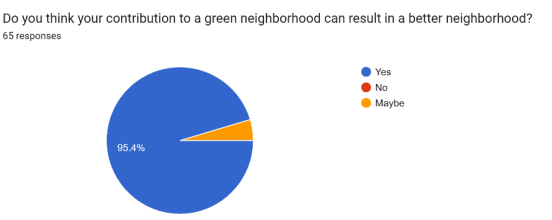


Table: 3



Table: 4



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4.2 Case Studies Informing OxyID

Singapore: Green Plan 2030

Singapore's Green Plan 2030 [2] integrates environmental monitoring, public engagement apps, and long-term green planning, using digital twins and open data to support resilient urban design. Lessons relevant to OxyID include:

- The value of integrating environmental indicators into everyday apps residents already use.
- Linking data collection with behavioral nudges and public campaigns.
- Using data dashboards to guide micro-scale interventions in heat-stressed areas.

Paris: Data-driven mobility and public realm

Paris's shift towards walkable, low-carbon mobility [9] is supported by data-driven reallocation of street space and the creation of "15-minute neighborhoods." Although focused on mobility, the approach shows:

- How digital information can support redesigning streets for people rather than cars.
- The potential to integrate trees and green infrastructure into these reconfigured corridors to improve comfort and health.

MillionTreesNYC: Municipal-community partnership

MillionTreesNYC [7] planted one million trees through a partnership between city agencies, NGOs, and volunteers, supported by public dashboards and adoption programs. Key takeaways for OxyID:

- Planting is only the first step; long-term community ownership is critical.
- Clear branding and storytelling (e.g., "one million trees") can mobilize broad participation.
- Simple public tools (maps, adoption portals) build ownership and accountability.

4.3 Qualitative Analysis:

A detailed, structured interview was conducted with an IT specialist, Mr. Kahid Chapra, who has been in the IT industry for the past 29 years. With experience of IBM, Berkinshire, Zultec and many more, he emphasized the importance of digital transformation and its relevance in the current urban planning. He stressed that awareness is fundamental to success in digital transformation, highlighting the importance of workshops and targeted campaigns. This will normalize a smart initiative and make the idea of a digital link between residents and neighborhood trees familiar and acceptable. His insights underscore both the technical foundations and the governance sensitivities that are needed to inform the development of the OxyID concept.

First, the expert emphasizes that a neighborhood can be instrumented through a lightweight Internet of Things (IoT) infrastructure. A single wireless gateway mounted on a pole or building can cover approximately one square kilometer, allowing numerous tagged objects within that radius to be monitored with positional accuracy on the order of a few meters. Within such a setup, trees can be treated analogously to other tagged urban assets such as benches or garbage bins, by assigning each tree a unique digital identifier and equipping it with a simple tag or sensor node. This creates the foundational layer for linking a resident's digital account to "their" tree in a municipal database.

Second, his examples of smart benches, adaptive lighting, and tagged waste bins illustrate how digital identification can evolve from static registration into dynamic interaction. In the case of benches, presence detection via sensors or AI-based cameras can trigger nearby lighting or contextual information only when a person is actually using the space, thereby saving energy and enhancing user experience. Translated into the OxyID framework, similar mechanisms could register when a person visits their assigned tree, enabling the system to provide context-aware feedback (for example, reminders about watering during dry periods or visualizations of the tree's

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contribution to cooling and air quality). Likewise, the full traceability for smart bins tracking filling, collection, and maintenance can be conceptually extended to trees as living assets, with records of planting, growth, pruning, and caretaker interventions.

Third, the interview underscores that the same sensor networks used for asset tracking can simultaneously capture environmental parameters such as ambient temperature, humidity, dust, noise, and air quality. This opens a qualitative pathway for OxyID to move beyond symbolic ownership and toward measurable environmental performance: clusters of resident-linked trees in a given neighborhood could be correlated with local microclimate conditions and comfort levels. In the proposal, this supports the idea of treating trees as part of a "living infrastructure" whose ecological function (the city's lungs) can be monitored and communicated back to residents.

At the same time, the expert's concerns about infrastructure, privacy, and cybersecurity are central to the qualitative analysis. The risk of cyber-attacks on interconnected systems potentially leading to service disruption or mass leakage of movement and behavioral data is identified as a major barrier to city-wide roll-out. These concerns directly inform the proposed governance model for OxyID. The system should prioritize minimal and anonymized data collection, avoid unnecessary facial recognition, and favor decentralized, neighborhood-level pilots rather than fully centralized surveillance architecture.

In summary, the qualitative evidence from the expert interview suggests that the technical elements needed to digitally connect trees and people with unique IDs, tags, gateways, sensors, and simple user interfaces are already in use for other urban functions, but their application to urban forestry must be carefully redesigned. For the research proposal, this analysis supports framing OxyID as a reorientation of established smart-city technologies toward ecological stewardship and community engagement, grounded in strong data-protection principles and incremental, neighborhood-based implementation.

4.4 Anticipated Findings and Discussion

Drawing on the literature, the survey results, and the conceptual framing of OxyID, a number of likely outcomes begin to emerge which can later be tested and refined with further data. First, there appears to be a strong potential willingness among Jeddah's residents, especially younger, digitally confident users, to adopt a platform like OxyID, provided it remains simple to use, clearly meaningful, and seamlessly connected to digital tools they are already familiar with. The idea of caring for a tree close microclimate indicator around clusters of trees will allow Jeddah to understand how much its "urban lungs" are actually cooling streets, filtering air, and making public spaces more comfortable. This is particularly important in an arid coastal city where shade and thermal comfort often determine whether streets and parks are used or avoided.

Most importantly, OxyID has the potential to gently shift the relationship between residents and the public realm. When individuals are entrusted with the ongoing care of a tree, within the context of shared neighborhood goals, tree ownership can become a source of pride, social interaction, and a renewed sense of belonging. Caring for a tree is then not only an environmental act, but also a social and spatial one. It weaves people back into their streets, parks, and courtyards. For architects and urban designers, this implies a different way of thinking about projects. A decade-long study from the Smithsonian Environmental Research Center found that planting forests with diverse tree species increases the likelihood of success by reducing variability in sapling survival rates (Smithsonian Environmental Research Center, 2023) [8].

Second, once implemented at neighborhood scale, OxyID has the capacity to reveal spatial differences that are often hidden in broad policy documents. Mapping where trees are adopted, how frequently they are visited, and how canopy cover evolves over time can make visible which districts are thriving and which remain underserved. This opens a new layer of evidence-based

decision-making, where municipal interventions and community programs can be guided towards areas that need more attention, more trees, or more support.

Third, by treating trees as measurable pieces of living infrastructure, the platform can begin to link everyday actions to environmental performance. Tracking canopy growth, species choice, and Contributions

4.6 Theoretical contribution

At a theoretical level, this study joins ongoing discussions about smart cities but tries to gently redirect their focus. Instead of seeing digital governance only as an instrument for efficiency and control, OxyID frames it as a medium for ecological empathy and shared ownership. The notion of the urban forest as the city's "lungs" is extended by giving those lungs a fine-grained digital anatomy. Each tree is linked to a person, and each small act of care contributes to the larger resilience of the urban body. In this way, micro-scale behaviors, visiting, watering, observing are tied to macro-scale outcomes like heat mitigation, air quality, and perceived livability, offering a more human-centered reading of smart urbanism.

4.7 Practical and policy contribution

Practically, the framework outlined here speaks directly to Jeddah's current moment and to the ambitions of Vision 2030. OxyID offers a way to operationalize broad sustainability objectives at the intimate scale of the neighborhood, where daily life unfolds. It provides municipalities with a tool to see, track, and support tree cover over time in active dialogue with residents, rather than as a purely top-down maintenance task.

For policy makers and local institutions in Jeddah and other Gulf cities, the model suggests a phased, replicable pathway: begin with pilot districts, anchor the initiative in schools, mosques, and universities, and allow residents to gradually build a culture of shared care around their trees. For educators and design practitioners, OxyID opens up a living laboratory for teaching climate-sensitive urbanism, where students and communities can experiment with shade, planting, and digital feedback in real time. In doing so, it positions the neighborhood as a critical site where technology, ecology, and everyday life can come together to shape a more resilient and generous urban future.

Conclusion

OxyID emerges from this research as both a technological proposition and an urban design attitude. A way of treating trees not as background decoration, but as living infrastructure and shared responsibility at the scale of the neighborhood. By linking each resident to a specific tree through a simple digital identity, the project translates abstract sustainability goals into everyday acts of care, walking, observing, and engaging with the public realm. In a car-oriented, rapidly warming city like Jeddah, this shift from passive consumption of urban space to active stewardship of its "lungs" is both urgent and deeply architectural.

The mixed-methods application with literature reviews, surveys, case studies, and expert interviews strongly suggest that the technical pieces required for such a system already exist, and that residents are willing to participate when the initiative is local, visible, and meaningful. At the same time, the work makes clear that implementation cannot be purely technological. It requires governance, privacy, equity, and maintenance which must sit at the center of any deployment. In continuation of my previous paper, for Jeddah specifically, OxyID can suggest a prototype of a decentralized sustainable 15 min neighborhood. It starts with decentralized neighborhoods, use of digital tools to reveal and enhance the environmental work of trees and invite people back into a daily relationship with shade, air, and community. In doing so, the city's digital future and its ecological future are allowed to grow together, one resident and one tree at a time.

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Grey Wolf Optimized Urban Air Quality Prediction Enhancement: An Atmospheric Pollutants Data-Driven RF and SVR for Sustainable City Infrastructure

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Keywords: Air quality Prediction, Air Pollution, Public health, Prediction, Modelling

Abstract. The study highlights the use support vector regression model optimized using the Grey Wolf Optimization (GWO) to predict the air quality index (AQI) using various parameters, including the important pollutants of particulate matter (PM2.5 μm), (PM10 μm), Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), Carbon monoxide CO, and Ozone (O_2). An in-depth study of training and testing datasets evaluates the model's predictive performance using R^2, Mean Absolute Error (MAE), and Mean Squared Error (MSE). The results show that the optimized SVR achieved an R^2 of 0.94 on both the training and test datasets, with the lowest MSE among the standard SVR, standard Random Forest (RF), and the GWO-optimized RF model. This indicates that the model generalizes well. Altogether, the GWO-based SVR model demonstrates great potential for viable air quality forecasting that presents essential information that can be used by policy makers and scientists in an attempt to decrease the effects of air pollution on human health and the environment. Further efforts will be directed at improving the model and its flexibility to changing environmental parameters.

Introduction

Air quality has become a global concern due to increased pollution and its associated health effects [1]. In an attempt to determine the connection between high PM2.5 and NO_2 concentration and the increased risk of epilepsy, Aljafen et. al. found that a decrease in these pollutants might negate the neurological health risks [2]. There are however some restrictions such as the absence of longitudinal research to explain causal processes and the necessity of additional studies on important biological processes [3]. Tomar et. al. discussed the central role of atmospheric chemistry in air quality regulation and climate change caused by human actions, which highlighted the effects of human actions on chemical pathways and pollutant concentrations [4]. Although it found vital interrelations and developed research practices, its weakness is the inability to combine the results into a unified policy intervention that would respond to the needs of air quality alongside climate goals [5]. In the last two years, the number of deaths caused by air pollution has been 40% higher than the number of deaths caused by COVID-19, and this is a significant contributor to respiratory and cardiovascular diseases. According to the reports by the World Health Organization, more than 72.67% of the world fatalities caused by non-communicable diseases are attributed to environmental pollutants especially PM 2.5 and toxic gases [6]. Similarly, it is also a global pressing matter which has had a considerable effect on health, both in the development of diseases and in the productivity and biodiversity of agriculture, not to mention issues that

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contribute to climate change [7]. The need to solve this crisis is vital to the realization of various United Nations Sustainable Development Goals with the interdisciplinary approach that combines health, environmental science, and policy being the solution [8].

Gupta et. al., compares the results of regression methods such as support vector regression, random forest regression and CatBoost regression to predict the Air Quality Index (AQI) in Indian cities, and balances the dataset with synthetic minority oversampling technique (SMOTE) [9]. The results indicate that random forest regression with SMOTE augmentation can achieve much higher accuracy and lower error rates in AQI prediction [10]. Kalantari et. al., compares different machine learning models so that the Air Quality Index (AQI) can be predicted by utilizing the daily PM10 concentrations and meteorological parameters of Zabol during the period between March 2013 and February 2022 [11]. The comparison shows that deep learning models, especially convolutional neural networks (CNN) are more effective in obtaining high accuracy and AUC scores in classifications of air quality, and that it is necessary to collect data consistently in order to increase the robustness of a prediction [12] [13]. To predict the PM2.5 Air Quality Index (AQI), Alrashidi et al. trained and evaluated eight machine learning regression models on a time-series air quality dataset comprising data from 12 scattered air quality sites in Kuwait. At 0.98, the tree-based model had the highest R^2 score [14].

The proposed study will assess the efficiency of GWO-optimized machine learning models in determining essential air quality parameters. The research analyzes the two models' predictive performance on different statistical measures by looking at both training and testing datasets. The results will provide information on how the model can be useful for real-time air quality forecasting to improve environmental policy and lead to better health outcomes for people. The possibility of the GWO algorithm in optimizing machine learning in this field highlights its appropriateness and usage in modern environmental issues.

Novelty and Research Gap

In this work, the novel concept of air quality prediction is proposed using SVR and RF. The algorithm is used to optimize their hyperparameters. The optimized model can establish relationships among the independent parameters PM2.5, PM10, NO_2, SO_2, CO, and O_3 to predict AQI. The analysis of both the standard and optimized models using quantitative metrics like R^2, MAE, MSE shows the predictive effectiveness of the GWO used in machine learning as well as gives a quantitative foundation to assess the performance of the model on both training and testing data. The existing methodologies may not be flexible enough to incorporate real-time data and changes in pollutant levels, which may be inaccurate. This study not only seals a very important gap but also opens the door to future studies on advanced optimization methods in environmental monitoring and public health strategies by showing how the GWO can help overcome these limitations.

Methodology

The model to predict the output parameter, an air quality index, is based on a Grey Wolf Optimized machine learning algorithm. A hybrid algorithm, i.e., a metaheuristic and machine-learning approach, is presented, in which GWO is used to optimize parameters and enhance the performance of SVR and RF.

RF is an ensemble approach that uses multiple decision trees, taking the average of each tree's predictions. The model's overfitting risk can be minimized using the Bootstrap Aggregating technique. The number of trees and their depths are the most important parameters deciding its predictive performance. GWO is used to optimize the number of estimators and the maximum tree depth for the RF model. SVR uses kernel finding a function whose output should not deviates from actual target values by margin ε. Thus, it tries to minimize the error based on a threshold value in comparison to RF, where minimization is based on the square error. Its performance

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depends on its regularization parameter C and the degree of margin or deviation. The GWO is targeted to find optimal values of the regularization parameter (C) and the epsilon-insensitive tube width for SVR.

Figure 1 displays the steps involved for GWO-based machine learning optimization. The grey wolf optimisation algorithm is a population-based metaheuristic inspired by the social hunting behaviour of natural grey wolves. The algorithm simulates the hierarchy of wolf pack leadership, with four categories: alpha, beta, delta, and omega. Alpha wolves are the best solution, guiding the entire search process. The optimization process consists of three main stages: exploration, exploitation and integration. Equations 1-6 were employed in the greedy wolf optimization machine learning algorithm [15].

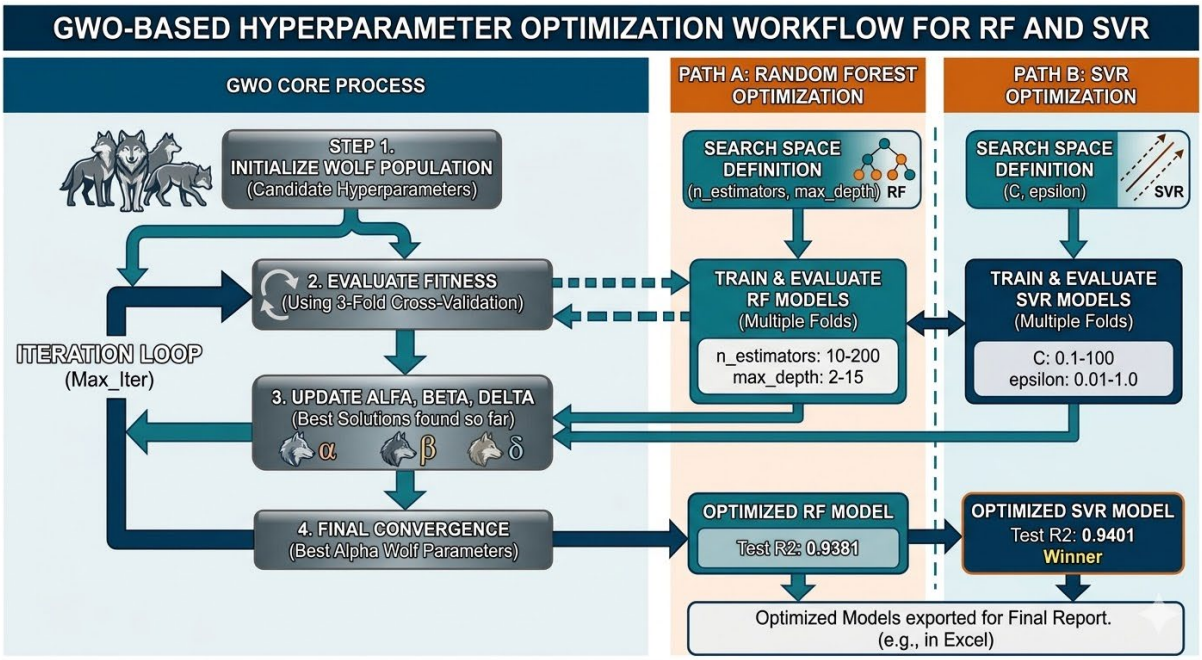


Fig. 1 *Function flowchart of the proposed GWO-based optimization of RF and SVR*

$$Distance\ Calculation, D = |C \cdot X_{\text{best}} - X_i| \quad (1)$$

Where, D is the distance between the current position of the wolf X_i and the best wolf X_{best} and C is a coefficient that controls the exploration behaviour.

$$Position\ Update, X_i(t+1) = X_i(t) + A \cdot D \quad (2)$$

Where A is another coefficient that influences the step size for the position update, Xi (t) is the current position of the wolf, and t refers to the current iteration.

$$Coefficient\ Update, A = 2a \cdot r_1 - a \quad (3)$$

$$C = 2 \cdot r_2 \quad (4)$$

A is a linearly decreasing parameter that ranges from 2 to 0 over iterations, and r_1 and r_2 are the random values in the range of [0,1].

$$a = 2 - \frac{2t}{T} \quad (5)$$

$$\hat{y} = f(x, X_\alpha(T)) \quad (6)$$

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X_α is the best wolf and T is the final iteration.

Sensitive metric analysis is conducted in order to verify the performance of the model through the coefficient of Determination (R^2), mean square error (MSE), and mean absolute error (MAE) [16]. Equations 7 to 9 displays the sensitive metric analysis for the performance of model comparison

Coefficient of determination
$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (7)$$

Mean Squared Error
$$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (8)$$

Mean Absolute Error
$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \quad (9)$$

Where, y_i = Actual experimental values, $\hat{y}_i$=Predicted values, $\bar{y}$=Mean of actual value, n=number of data samples.

Results and Discussion

The inputs in the models are the number of holidays, total days, PM2.5, PM10, NO_2, SO_2, CO, Ozone, and Air Quality Index. The model evaluation uses the dataset [16], having 1460 readings. The dataset was collected for the city of Delhi, India. The dataset includes three years of sample data, one for each month. The data was collected from 2021 to 2024. The AQI during holidays differs from that on working days. Therefore, holidays were also listed in the original dataset. In the present study, we used primary atmospheric pollutants to capture physio-chemical correlations rather than temporal trends. The temporal metadata were excluded from the original data. The correlation between input and output responses is provided in Figure 2.

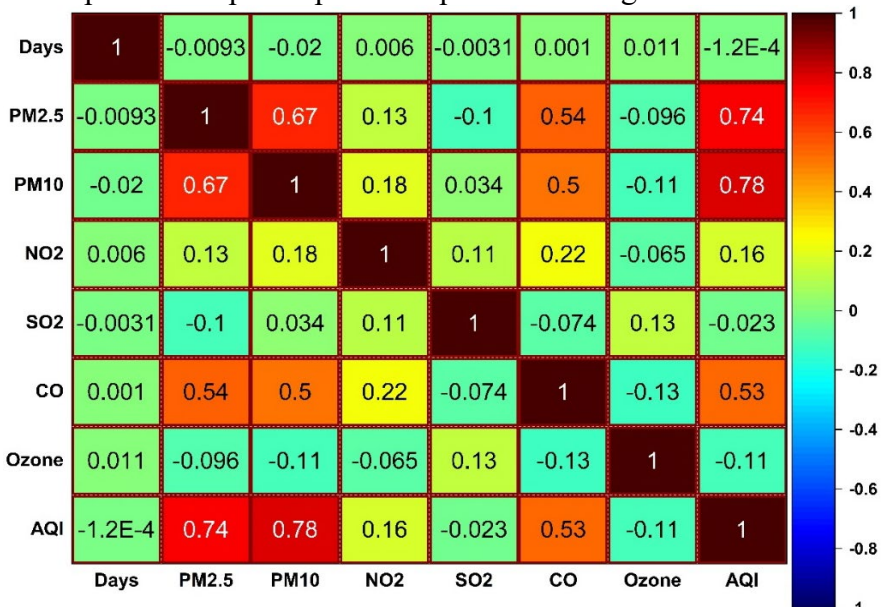


Fig. 2 *Correlation matrix for the input and output response*

For training, 80% of the dataset was used, and for testing, 20% was used to predict the target. A 3-fold validation is used during the training phase to ensure the model generalizes well across different data splits. All input parameters have different ranges. Therefore, parameters are

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normalized before being used to train and evaluate the model's performance. Table 1 lists the initialized parameters for RF and SVR, along with their optimal values obtained using GWO. The GWO found that a total of 300 trees at depth 7 is sufficient to obtain the best predictions. Similarly, the optimized SVR can be obtained with C = 80.33 and a margin of 1.46.

Table 1 Parameter range for both models and their optimum values obtained using GWO.

Model	Parameter	Search_Range	Optimum Value
Random Forest	n_estimators	(10, 300)	300
	max_depth	(2, 25)	7
SVR	C	(0.1, 150)	80.3377
	epsilon	(0.01, 1.5)	1.4607

Performance of SVR

The standard SVR achieved MSE and MAE of 3426.25 and 43, respectively on the training dataset. Similarly, MSE and MAE for the test dataset are 3822.58 and 45.93, respectively. The errors are large, and therefore, R^2 scores are limited to 0.69 and 0.70 for both the training and test datasets. This also indicates that the model is overfit. The results for GWO+SVR on the training and test datasets for air quality indices are shown in Figures 3 and 4. The best plot shows the target (real air quality measurements) versus the output (predicted values) for different sample indices, using two different markers. The most important aspect is the error values, where the difference between the targets and the output is compared to show the MSE of 694 and MAE of 17.05. Lastly, the lower plot depicts the distribution of error values, indicating a mean of 0.984 and an SD of 17.13. Whereas model received 777.07 MSE and 19.71 MAE on the test dataset. This overall representation demonstrates that the GWO is effective at predicting air quality parameters, such as PM2.5, PM10, NO_2, SO_2, CO, and Ozone, which support enhanced understanding and control of air quality based on temporal variables, including date, month, and holidays.

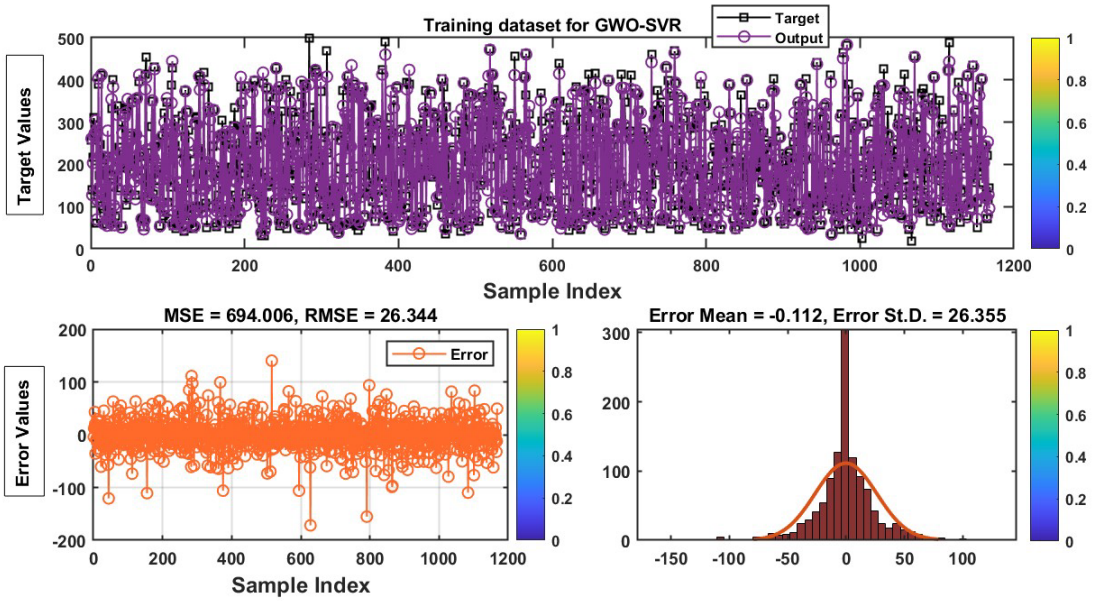


***Fig. 3** Prediction on the Training dataset using GWO-SVR*

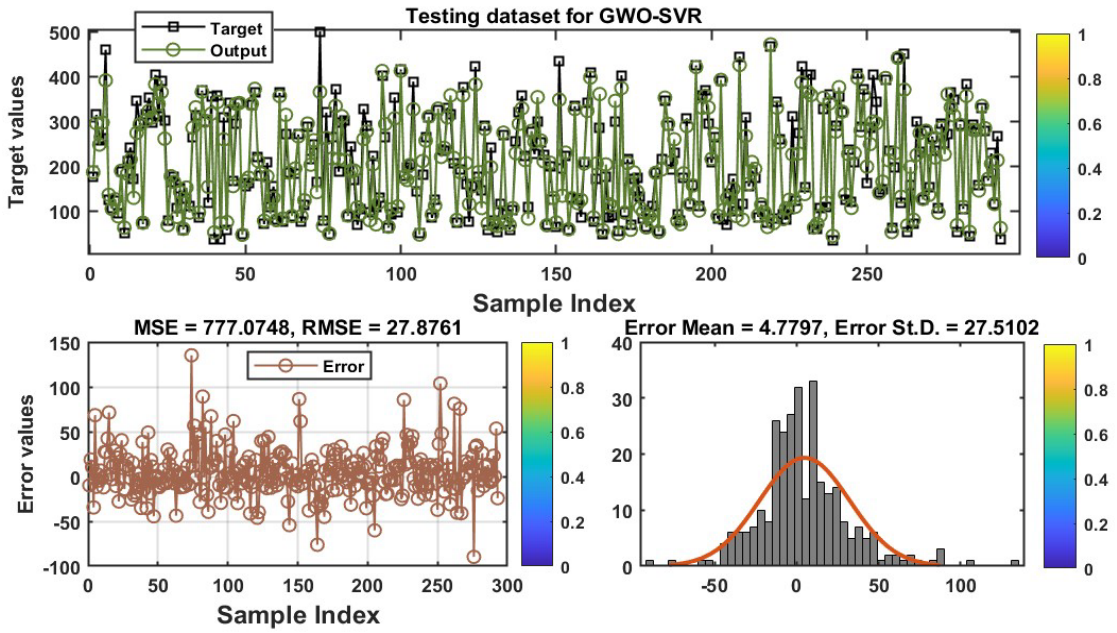


Fig. 4 *Prediction on Testing dataset using GWO-SVR*

Performance of RF

The performance of standard RF and GWO-optimized RF is quite similar. The RF without optimization achieved a high R^2 score of 0.9872 on the training dataset, but R^2 dropped to 0.9350 on the test dataset. The 5.22% reduction in the test dataset suggests a tendency towards overfitting. When RF is optimized using GWO, the model achieved 0.9660 and 0.9381 R^2 score. Though the R^2 score for the training dataset is lower than standard RF, the reduction of the R^2 score on the test dataset is about 2.79%. This indicates that parameters tuned by the GWO provided a robust tree structure, providing consistent performance.

Figure 5 compares the GWO-SVR's predicted values with actual values for both training and test dataset. The scatter plot indicates that the relation is strong, as the R^2 value is 0.93 and 0.94. This representation of visual messages shows that GWO is effective at modeling air quality indices, suggesting its potential for forecasting in environmental monitoring.

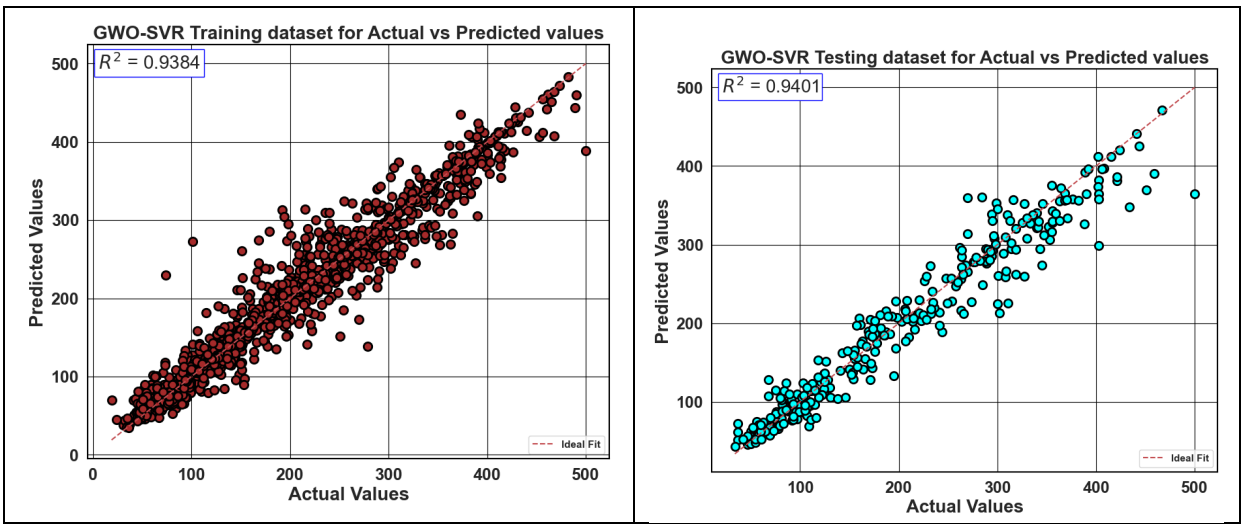


Fig. 5 *R^2 analysis of GWO+SVR (a) Training dataset B) Testing dataset*

Comparison of GWO optimized RF and SVR:

The comparison between two robust models optimized using GWO helps identify the advantages of how each model represents the data relationship for prediction. The GWO+RF achieved excellent performance with an R^2 score of 0.96 on the training dataset, but, as explained, it also exhibited overfitting. The GWO-SVR was found to be superior among all four, with the largest predictive precision of 0.9401 on the test dataset. Thus, its performance on the unknown test dataset aligns well with that on the training dataset. The GWO finds C and efficiently, which in turn captures the non-linear and complex relationship between input-independent parameters, ignoring stochastic noise. Table 2 presents a summary of the performance indices for all models, indicating that GWO-SVR is effective in estimating air quality parameters using the training and testing datasets.

Table 2 *Summary of quantitative parameters and comparison*

	Training Dataset			Testing Dataset			Analysis
Model	**MSE**	**MAE**	**R^2**	**MSE**	**MAE**	**R^2**	
Standard RF	144.173	7.998	0.987	843.498	18.624	0.934	High accuracy, but slightly overfitted compared to GWO version.
GWO+ RF	382.479	14.320	0.966	803.751	18.053	0.938	Strong Contender. Better test accuracy than standard RF and much more stable
Standard SVR	3426.255	43.014	0.695	3822.58	45.930	0.705	Underfitting. It is consistent, but the error is far too high.
GWO+ SVR	694.006	17.050	0.938	777.07	19.715	0.940	Highest Test R^2 and lowest Test MSE.

Conclusion

Machine learning models have shown strong effectiveness in forecasting air quality parameters using training and testing sets. This study presents a robust machine learning model integrating them with GWO. The two models, SVR and RF, were optimized using GWO to overcome the limitation of the standard model's configuration. The optimal selection of parameters in a machine learning model minimizes overfitting when used to predict complex data. The study suggested that GWO enhanced the performance of both RF and SVR, and that GWO+SVR was superior among all four combinations. It achieved R^2 score of 0.9401 and the lowest Test MSE of 777.07 on the test dataset. Thus, GWO successfully optimized the parameters and obtained a balance between the regularization parameter and the epsilon-insensitive tube. Furthermore, the comparison of GWO+ RF and GWO+ SVR showed that, although the ensemble method is powerful, proper optimization of the kernel parameters in SVR can yield a more stable and consistent performance. The alignment between quantitative parameters of the train and test datasets is validated using a 3-fold validation, which shows that metaheuristic optimization is important to achieve a robust, reliable, and generalized model for prediction. Its ability to predict can be refined and tested further, and it can be an important asset in future air quality modelling projects.

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Exploring the Art of Integrating Image-Generated Platforms into Minaret Conceptual Design in Islamic Mosque Architecture

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Keywords: Artificial Intelligence, Islamic Architecture, Mosque Design, Minaret, MidJourney, Image Generation, Architectural Visualization, Prompt Engineering, Cultural Heritage

Abstract. This comprehensive study investigates the application of AI image-generation platforms, specifically MidJourney, in generating conceptual designs for minarets across six distinct Islamic Mosque architectural styles. The research employs a structured methodology involving extensive secondary research on Islamic architectural principles, systematic prompt engineering for image generation, and quantitative accuracy analysis of 720 AI-generated minaret designs. Results demonstrate significant variation in generation accuracy across different architectural styles, with Ottoman (61.7%) and Mughal (55%) styles achieving the highest accuracy rates, while Umayyad (16.7%) and Moorish (17.5%) styles presented the most substantial challenges. The findings reveal that AI platforms exhibit stronger performance for widely recognized architectural styles with extensive training data, while less common styles suffer from significant representation gaps. Contemporary interpretations consistently underperformed compared to traditional representations across all styles, indicating the platform's tendency to interpret" contemporary" as" futuristic" rather than modern interpretations of traditional styles. This research contributes substantially to understanding AI's potential and limitations in architectural visualization, particularly in culturally sensitive contexts requiring historical accuracy and cultural fidelity, while providing actionable insights for prompt engineering and future AI training in architectural applications.

Introduction

Background and Research Context. The integration of Artificial Intelligence (AI) in architectural design represents a paradigm shift in conceptualization processes, particularly through the emergence of sophisticated text-to-image generation platforms like Midjourney, DALL- E, and Stable Diffusion. These platforms have democratized access to advanced generative capabilities, enabling architects and designers to rapidly visualize conceptual ideas with unprecedented speed and variety, while also supporting broader applications such as climate-responsive planning and hazard mitigation [1].

This research examines the efficacy of these AI tools in the specific context of mosque minaret design, where traditional architectural principles rooted in centuries of cultural and religious traditions must be carefully balanced with technological innovation.

Islamic mosque architecture embodies a rich tapestry of cultural, religious, and architectural evolution spanning over fourteen centuries, with the minaret serving as both a functional element and a profound cultural symbol. Originally conceived as elevated platforms for the call to prayer (Adhan), minarets have evolved into iconic architectural landmarks that define skylines across the

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Islamic world. The advent of AI image- generation platforms present new opportunities for architectural visualization and conceptual design, yet their ability to accurately represent culturally significant architectural elements with historical fidelity remains underexplored and represents a critical research gap.

Problem Statement and Research Significance. This study contributes a structured framework for evaluating AI-generated architectural outputs within culturally sensitive contexts, specifically focusing on Islamic minaret design across multiple historical styles. By combining quantitative accuracy assessment with qualitative architectural analysis, the research provides insights into how training data representation influences AI performance in specialized architectural domains.

The research significance extends across multiple domains:

- *Architectural Practice:* Providing insights into AI's potential as a conceptual design tool for traditional and contemporary Islamic architecture.
- *Cultural Heritage:* Contributing to the digital preservation and innovative interpretation of Islamic architectural traditions.
- *AI Development:* Informing future training data strategies and model improvements for culturally sensitive applications.
- *Educational Applications:* Enhancing architectural education through AI-assisted visualization of historical styles.

Research Objectives and Questions. This study aims to achieve the following primary objectives:

- Evaluate the effectiveness of AI art platforms in generating mosque minaret designs across six distinct Islamic architectural styles
- Identify optimal prompt engineering strategies for accurate minaret representation and cultural fidelity
- Quantify generation accuracy and identify performance patterns across different architectural eras and styles
- Analyze specific challenges in contemporary versus traditional style representation
- Develop recommendations for improving AI performance in culturally sensitive architectural visualization

The research addresses several key questions:

- How accurately can current AI platforms generate minaret designs across different Islamic architectural styles?
- What is the relationship between architectural style prominence and AI generation accuracy?
- How do contemporary interpretations differ from traditional representations in AI-generated outputs?
- What prompt engineering strategies yield the most accurate and culturally faithful results?

Literature Review

Evolution of AI Image-Generation Platforms. Contemporary AI art platforms represent the culmination of decades of research in generative machine learning models, particularly diffusion models that convert textual descriptions into visual representations. These platforms, including Midjourney, DALL-E, and Stable Diffusion, have democratized access to advanced generative art techniques, making them accessible to architects, designers, and artists worldwide [2].

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The underlying technology involves sophisticated forward diffusion processes that systematically introduce noise to structured image data, followed by reverse diffusion processes that recreate images from scratch, enabling the generation of entirely novel visual content, building upon advances in large-scale machine learning and language models [3,4]. This technological foundation has enabled unprecedented capabilities in text-to-image conversion, though its application in specialized domains like architectural visualization requires careful examination.

Recent studies have begun exploring the intersection of AI generation and architectural design, though few have focused specifically on culturally significant architectural elements or historical styles. The work of Cheung and Dall'Asta [5] examined collaborative frameworks for AI art generation in architectural design processes, while Hanafy [3] investigated AI's effects on design process creativity, providing valuable foundations for this research.

AI Integration in Architectural Design Practice. The integration of AI in architecture represents a significant technological advancement, offering new methodologies for conceptual design, visualization, and alternative design generation [6].

AI expands creative possibilities by generating diverse design alternatives, analyzing complex architectural patterns, and enhancing design efficiency through rapid iteration [7].

However, the application of AI in culturally specific contexts like Islamic architecture requires careful consideration of historical accuracy, cultural sensitivity, and architectural authenticity. Traditional Islamic architecture follows specific principles and proportions rooted in geometric harmony and symbolic meaning, presenting unique challenges for AI systems trained primarily on contemporary datasets.

Studies by Abuel Seoud [8] and Asfour [9] have explored the reflection of technology on mosque design and the reconsideration of mosque architectural elements, providing important context for understanding how technological innovations might impact traditional architectural forms.

Islamic Mosque Architecture: Historical and Cultural Context. Mosque architecture represents one of the most developed and sophisticated forms of Islamic artistic expression, characterized by specific architectural elements including the prayer hall, mihrab (prayer niche), minbar (pulpit), and minaret [10]. These elements have evolved over centuries, reflecting regional variations, historical developments, and cultural influences across transnational Islamic contexts while maintaining core Islamic principles [11].

Throughout Islamic history, four primary mosque styles have emerged and developed: the Arab hypostyle mosque, Persian four-iwan mosque, Indian three-dome mosque, and Turkish central-dome mosque [12]. Each style exhibits distinct characteristics in plan, elevation, and architectural elements, including minaret design.

The minaret, originally serving as an elevated platform for the call to prayer, has evolved into a significant architectural landmark with distinct characteristics across different eras and regions [13]. Minaret designs vary from square-based towers in early Umayyad architecture to pencil-shaped structures in Ottoman mosques, each reflecting specific historical contexts, construction technologies, and cultural influences [14].

Midjourney Platform and Prompt Engineering. Midjourney, launched in 2022 by David Holz, operates through Discord and enables users to generate images from text prompts. The platform's effectiveness depends significantly on prompt engineering – the systematic craft of crafting textual descriptions that guide the AI toward desired visual outcomes [15].

Advanced prompting incorporates multiple elements, including artistic medium, historical periods, specific architectural features, and stylistic parameters. The platform's documentation

emphasizes the importance of word choice, specificity, and parameter selection in achieving desired results. However, the application of these techniques to specialized architectural contexts remains underexplored in current literature.

Research Methodology

Comprehensive Research Design. This study adopted a mixed-methods exploratory design combining structured AI image generation with quantitative and qualitative assessment of architectural accuracy. The methodology was developed to evaluate the extent to which AI-generated mosque minaret concepts correspond to historically recognized Islamic architectural styles. The research process, shown in Fig. 1, consisted of four main phases: (1) secondary research and style definition, (2) prompt development and image generation, (3) expert evaluation of generated outputs, and (4) comparative analysis of accuracy across styles.

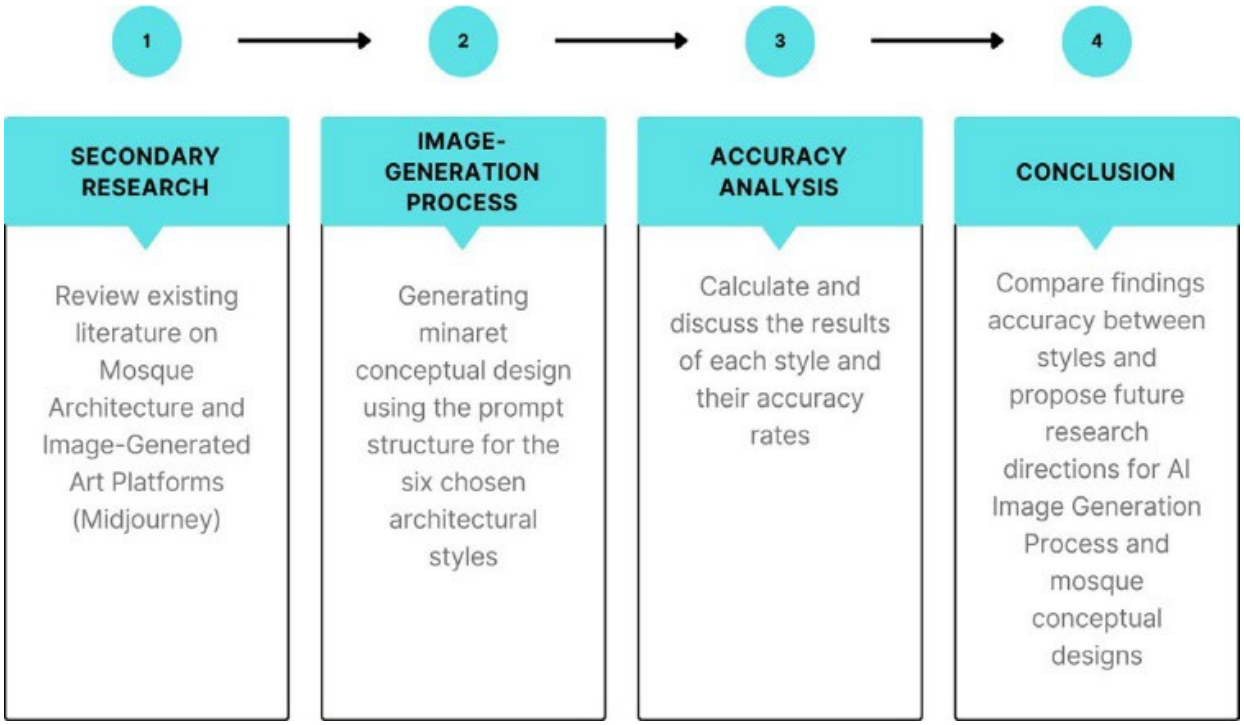


Figure 1. Comprehensive Research Methodology Framework.

Systematic Secondary Research Phase. A comprehensive literature review was conducted across multiple domains:

- *Islamic Architectural History:* Examination of historical development, regional variations, and stylistic evolution of mosque architecture.
- *Minaret Design Principles:* Detailed analysis of minaret forms, proportions, materials, and symbolic meanings across different eras.
- *AI Image-Generation Technology:* Study of underlying mechanisms, capabilities, and limitations of diffusion models.
- *Prompt Engineering Strategies:* Review of effective techniques for guiding AI image generation.

This foundational research informed the development of structured prompts, evaluation criteria, and analysis frameworks, ensuring that both technological and architectural considerations were adequately addressed.

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Structured Image Generation Process. The study employed Midjourney for generating minaret designs across six carefully selected Islamic architectural styles representing different historical periods and geographical regions:

- *Umayyad (7th-8th century):* Early Islamic period with square-based minarets.
- *Moorish (8th-15th century):* Western Islamic architecture with prismatic minarets.
- *Mamluk (13th-16th century):* Egyptian architecture with multi-tiered minarets.
- *Safavid (16th-18th century):* Persian architecture with slender, colorful minarets.
- *Mughal (16th-19th century):* South Asian architecture with chhatri-topped minarets.
- *Ottoman (14th-20th century):* Turkish architecture with pencil-shaped minarets.

These styles were chosen because they exhibit distinct minaret typologies in terms of form, proportion, material expression, and decorative language. For each style, a reference profile was developed from secondary literature and visual precedents. The profile identified the characteristic features expected in a style-accurate minaret, including tower geometry, top element, balcony treatment, material palette, ornamentation, and relationship to the mosque mass.

A standardized prompt structure was developed and applied consistently across all generations in Midjourney. Each prompt included the following components: architectural style, representation mode, dome and minaret description, facade material, realism requirement, feasibility requirement, and pedestrian-level view:

/Imagine [Mosque Reference Link] a [Traditional/Contemporary] [Architectural Style] Mosque with Dome, [Architectural Style] Minaret, [Facade Material], inspired from [Mosque Name], realistic, feasible, Islamic architecture, pedestrian

Default Midjourney parameters were maintained (-iw 1, --stylize 100) throughout the generation process to ensure consistency. Two representation modes were tested for each style: traditional and contemporary. The traditional prompts aimed to generate historically recognizable interpretations, while the contemporary prompts aimed to generate modern reinterpretations rooted in the same stylistic vocabulary. For each architectural style, 120 images were generated (60 traditional, 60 contemporary), totaling 720 images across all six styles.

Comprehensive Accuracy Assessment Framework. Generation accuracy was quantified using the following expression:

$$Accuracy\ (\%) = \frac{Architecturally\ Accurate\ Images}{Total\ Generated\ Images}\ x\ 100\% \quad \text{(Eq. 1)}$$

where "architecturally accurate images" refers to the number of generated outputs that satisfy the predefined evaluation criteria, including:

- *Form and Proportion:* Adherence to historical minaret forms, proportions, and scale relationships
- *Material Authenticity:* Appropriate representation of style-specific materials and construction techniques
- *Style Characteristics:* Presence of defining style-specific features and decorative elements
- *Structural Feasibility:* Practical buildability and structural logic of generated designs
- *Cultural Authenticity:* Respect for cultural and symbolic meanings embedded in architectural forms
- *Contextual Appropriateness:* Relationship between minaret and other mosque elements

Each generated image was evaluated independently by three authors of this study, all with a background in Islamic architecture to ensure consistent and reliable assessment.

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An image was considered *accurate* when it demonstrated sufficient alignment with the majority of the evaluation criteria based on assessor judgment. In cases involving multiple evaluators, final classification was determined based on the average assessment outcome, ensuring a consistent and balanced evaluation process across all generated images.

Results And Comprehensive Analysis

Overall Generation Performance. The AI platform demonstrated significantly varying performance across different architectural styles, revealing important patterns about training data distribution and model capabilities. The comprehensive results, summarized in Table 1, show a clear correlation between architectural style prominence and generation accuracy using Eq. 1, where *Pass* indicates images classified as architecturally accurate based on the evaluation criteria, and *fail* indicates non-compliant outputs.

Table 1. Comprehensive AI Generation Accuracy Across Architectural Styles.

Architectural Style	Total Images (120)	Traditional Accuracy	Contemporary Accuracy	Overall Accuracy	Historical Period	Reference Mosque
Umayyad	Pass: 20 Fail: 100	22.5%	10.8%	16.7%	7th-8th century	Umayyad Mosque
Moorish	Pass: 21 Fail: 99	25.0%	10.0%	17.5%	8th-15th century	Koutoubia Mosque
Mamluk	Pass: 31 Fail: 89	33.3%	18.3%	25.8%	13th-16th century	Sultan Hassan Mosque
Safavid	Pass: 38 Fail: 82	38.3%	25.0%	31.7%	16th-18th century	Shah Mosque
Mughal	Pass: 66 Fail: 54	61.7%	48.3%	55.0%	16th-19th century	Badshahi Mosque
Ottoman	Pass: 74 Fail: 46	68.3%	55.0%	61.7%	14th-20th century	Blue Mosque

The data reveals several important trends:

- A clear accuracy gradient from most successful (Ottoman: 61.7%) to least successful (Umayyad: 16.7%).
- Consistent performance advantage for traditional over contemporary interpretations across all styles.
- Significant correlation between historical period (recency) and generation accuracy.
- Notable performance gaps between styles with extensive versus limited digital representation.
- Confusion between Moorish elements and other Islamic styles, particularly Andalusian and Maghrebi architecture.

Detailed Style-Specific Analysis. *Umayyad Style:* Significant Representation Challenges: Umayyad minarets, characterized by square-based towers tapering to pointed tops with crescent symbols, presented substantial generation challenges with only 16.7% overall accuracy.

This style, representing the earliest period of Islamic architecture (7th-8th century), suffered from limited representation in training data and unfamiliarity with early Islamic architectural conventions (Fig. 2).



Figure 2: Umayyad Style Generations: Images 2.1 and 2.3 show unsuccessful attempts with incorrect base shapes and material inconsistencies; Images 2.2 and 2.4 demonstrate successful generations capturing square-based forms and appropriate proportions.

Common errors included incorrect base shapes (Fig. 2.1), improper minaret placement on domes (Fig. 2.3), and material inconsistencies incorporating anachronistic Safavid-era.

Moorish Style: Contemporary generations particularly struggled (10.0% accuracy), with none producing correct minaret features as the platform defaulted to futuristic interpretations rather than style- accurate designs. The AI's familiarity with the Alhambra Palace appeared to create interference rather than assistance in generating authentic Moorish Mosque elements (Fig. 3).

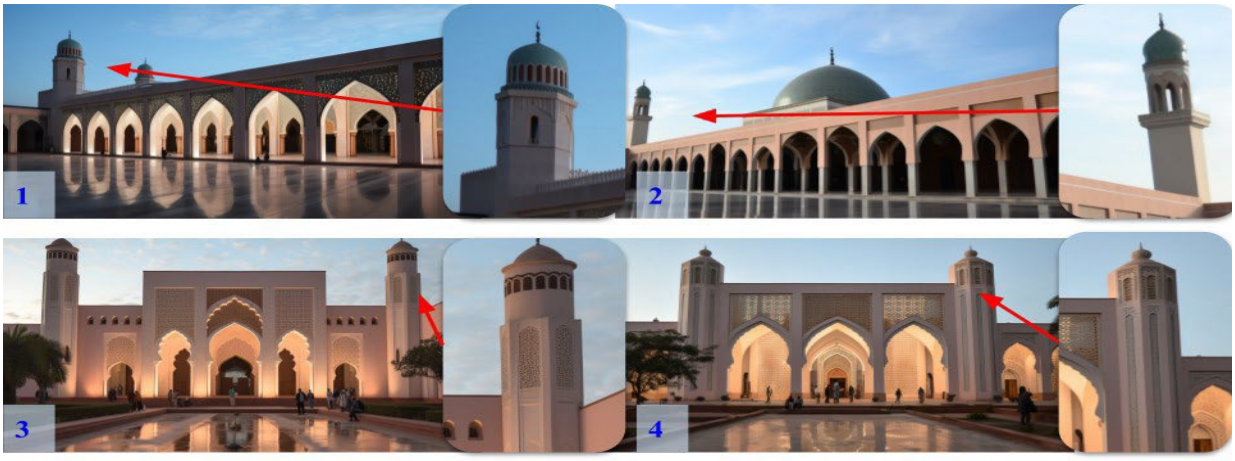


Figure 3: Moorish Style Generations: Images 3.1, 3.3, and 3.4 show unsuccessful attempts with incorrect forms and missing characteristic elements; Only Image 3.2 successfully captures the square-based prismatic form with appropriate proportions.

Mamluk Style: Moderate Success with Tiered Structures: Mamluk minarets, distinguished by distinctive three-tiered structures with onion domes representing Egyptian architecture (13th-16th century), showed moderate generation success at 25.8% accuracy. Traditional prompts significantly outperformed contemporary ones (33.3% vs 18.3%), indicating better understanding of historical forms. (Fig. 4).

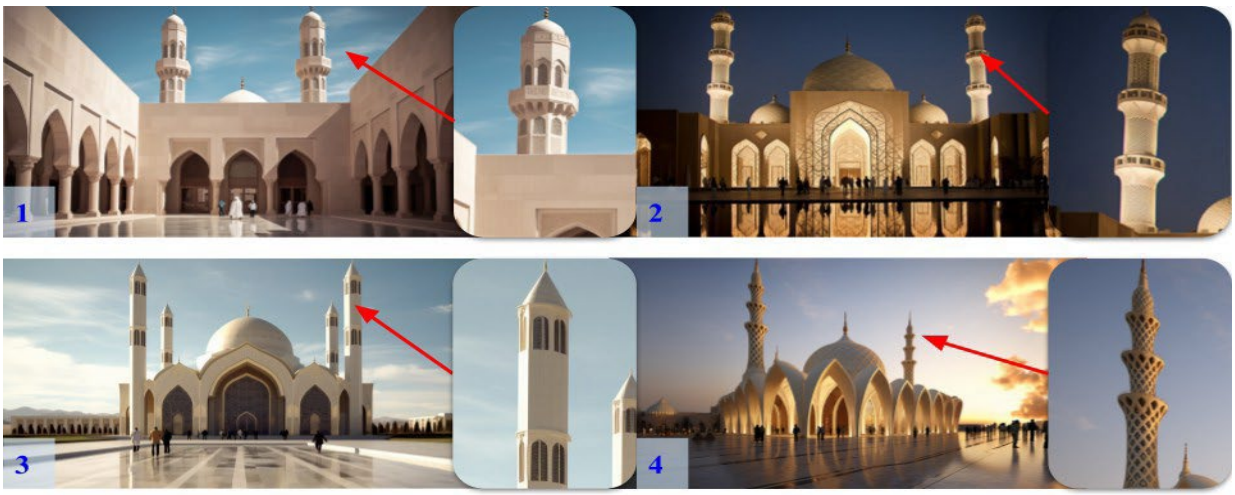


Figure 4: Mamluk Style Generations: Images 4.1 and 4.3 show unsuccessful attempts with incorrect tier numbers and Ottoman style influences; Images 4.2 and 4.4 successfully capture the Mamluk Style.

Common errors included incorrect tier numbers (Fig. 4.1) and incorporation of anachronistic Ottoman-style conical caps (Fig. 4.3). The platform demonstrated reasonable understanding of Mamluk massing and proportions but struggled with decorative details and material authenticity.

Safavid Style: Color and Form Recognition: Safavid minarets, known for slender cylindrical structures with vibrant, colorful ceramic tiles flanking mosque portals (16th-18th century Persia), demonstrated improved generation accuracy at 31.7%. The platform showed better recognition of Safavid color palettes and spatial relationships (Fig. 5).



Figure 5: Safavid Style Generations: Images 5.1 and 5.3 show unsuccessful attempts with incorrect tapering and dome styles; Images 5.2 and 5.4 successfully capture the slender cylindrical forms with appropriate color schemes and portal relationships.

Successful generations accurately captured the characteristic floral patterns and color schemes, though issues with improper tapering and dome styles persisted in contemporary interpretations. The platform demonstrated a good understanding of the relationship between minarets and main portals, a key Safavid characteristic.

Mughal Style: Strong Performance with Distinctive Forms: Mughal architecture, featuring slender minarets with distinctive chhatri elements characteristic of South Asian Islamic

architecture (16th-19th century), achieved strong generation performance at 55.0% accuracy. Both traditional and contemporary prompts produced style-accurate results, indicating a robust understanding of Mughal design principles (Fig. 6).

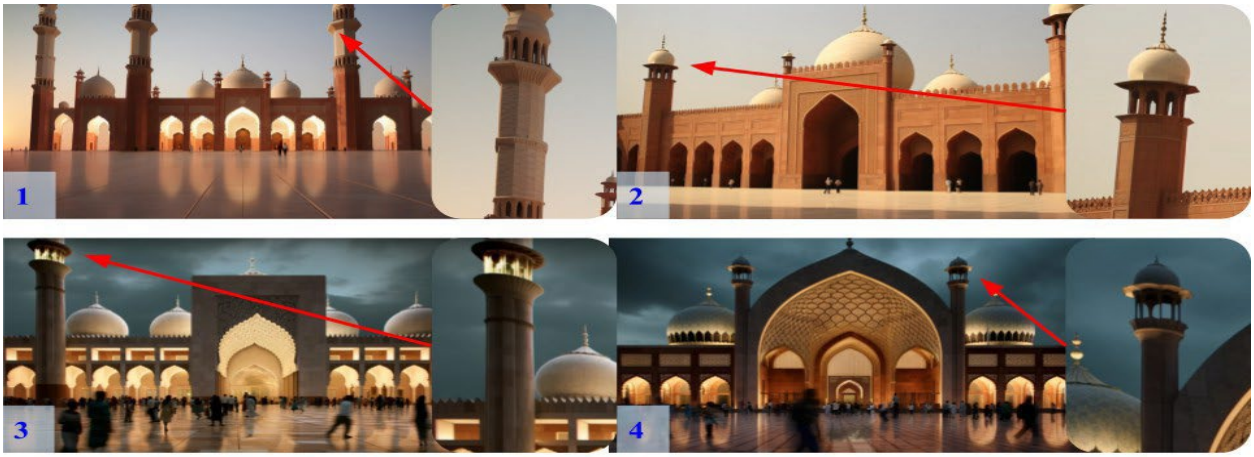


Figure 6: Mughal Style Generations: Images 6.1 and 6.3 show unsuccessful attempts with improper tiering and scaling issues; Images 6.2 and 6.4 successfully capture the slender forms with chhatri elements and appropriate proportions.

Errors primarily involved improper tiering and scaling issues rather than fundamental style misinterpretations. The platform demonstrated excellent understanding of Mughal proportions and the relationship between minarets and main mosque structures, likely reflecting extensive training data from this widely documented architectural style.

Ottoman Style: Peak Performance with Familiar Elements: Ottoman minarets, characterized by pencil-shaped cylindrical structures with conical caps and multiple balconies (14th-20th century Turkish architecture), achieved the highest generation accuracy at 61.7%. The platform's extensive training data on Ottoman elements contributed to this success, though contemporary interpretations still faced challenges. (Fig. 7)

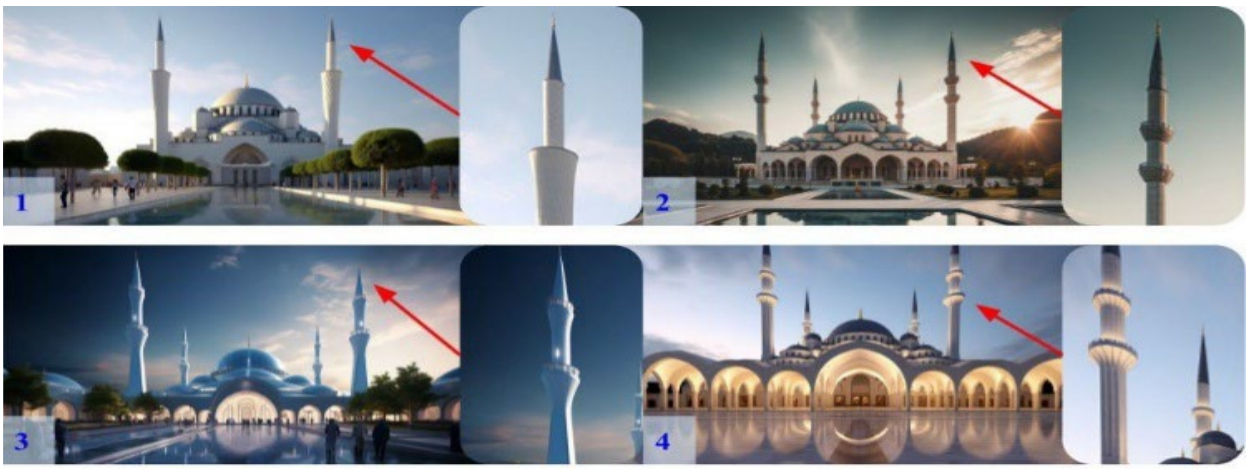


Figure 7: Ottoman Style Generations: Images 7.1 and 7.3 show unsuccessful attempts with base deviations and scaling issues; Images 7.2 and 7.4 successfully capture the characteristic pencil-shaped forms with appropriate balconies and proportions.

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Advanced Discussion and Implications

Training Data Biases and Architectural Representation. The use of a structured multi-criteria evaluation framework enables a more systematic and replicable assessment of AI-generated architectural outputs compared to purely subjective visual interpretation. The clear correlation between architectural style prominence and generation accuracy reveals significant biases in current AI training datasets. Widely recognized styles (Ottoman, Mughal) with extensive representation in digital archives and popular media achieved substantially higher accuracy rates than equally significant but less digitally documented traditions (Umayyad, Moorish).

This bias has important implications for architectural preservation and cultural representation. Styles with stronger digital presence receive better AI support, potentially reinforcing existing visibility disparities and marginalizing important architectural traditions. As AI becomes increasingly integrated into architectural practice, these biases could influence which styles are more readily visualized and explored in contemporary design.

The research findings suggest an urgent need for:

- Curated training datasets specifically for underrepresented architectural traditions.
- Collaborative efforts between AI developers and architectural heritage organizations.
- Systematic digitization of less documented architectural styles and elements. Development of bias-aware AI models for cultural heritage applications.

Contemporary Interpretation Challenges. The consistent underperformance of contemporary interpretations across all styles (average 27.9% accuracy vs 41.5% for traditional) indicates fundamental challenges in how AI systems understand temporal context in architecture. The platform consistently interpreted" contemporary" as" futuristic" or" parametric" rather than modern interpretations grounded in traditional principles.

This limitation represents a significant barrier to using AI for innovative design that respects historical contexts while addressing contemporary needs. The findings suggest that current prompt engineering techniques are insufficient for communicating nuanced concepts of" contemporary traditional" or" contextually responsive modern" design.

- Potential solutions include:
- Development of specialized prompt vocabularies for contemporary interpretations.
- Training on exemplary projects demonstrating sensitive contemporary interventions.
- Multi-stage prompt strategies that establish traditional foundations before introducing contemporary elements.
- Collaboration between AI developers and architects specializing in traditional-contemporary design.

Prompt Engineering Strategies and Limitations. The research revealed both the power and limitations of prompt engineering in architectural visualization. While careful prompt construction significantly influenced output quality, it could not fully overcome fundamental gaps in training data or model understanding.

Effective strategies identified include:

- *Specific Material References:* Clear material specifications improved authenticity.
- *Architectural Element Emphasis:* Explicit mention of style-specific elements enhanced accuracy.
- *Reference Images:* Strategic use of reference images provided important contextual guidance.
- *Viewpoint Specification:* Pedestrian view parameters proved spatial understanding.

However, limitations remained in:

- Communicating complex proportional relationships.
- Conveying subtle stylistic nuances.
- Differentiating between similar architectural traditions.
- Balancing specificity with creative freedom.
- Focusing on a single AI image-generation platform.

Cultural Sensitivity and Authenticity Concerns. The research raised important questions about cultural sensitivity in AI-generated architectural content. In several instances, the platform combined elements from different cultural traditions inappropriately or created hybrid forms that lacked cultural authenticity.

These concerns are particularly relevant for sacred architecture, where symbolic meanings and cultural contexts are paramount. The findings suggest that current AI systems lack the cultural understanding necessary for sensitive architectural applications without careful human guidance and oversight.

Recommendations for addressing these concerns include:

- Development of cultural sensitivity guidelines for AI architectural applications.
- Inclusion of cultural context in training data and model development.
- Collaborative frameworks involving cultural experts in AI-assisted design processes.
- Ethical review processes for AI-generated cultural content.

Conclusion and Future Research Directions

Summary of Key Findings. This comprehensive research demonstrates both the considerable potential and significant limitations of AI image- generation platforms in Islamic architectural visualization. The findings reveal clear patterns in generation accuracy across different architectural styles, with widely recognized styles achieving substantially better results than less prominent traditions.

The key findings can be summarized as follows:

- *Performance Gradient:* AI platforms show strong capability for widely represented architectural styles (Ot- Ottoman: 61.7%, Mughal: 55.0%) but struggle significantly with less common styles (Umayyad: 16.7%, Moorish: 17.5%).
- *Contemporary Interpretation Challenge:* Contemporary interpretations consistently underperform traditional representations across all styles (average 27.9% vs 41.5% accuracy), indicating fundamental challenges in understanding temporal context.
- *Training Data Dependence:* Generation accuracy correlates strongly with style prominence in digital archives, revealing significant biases in current training datasets.
- *Prompt Engineering Efficacy:* Careful prompt construction significantly influences output quality but cannot fully overcome fundamental model limitations.
- *Cultural Sensitivity Gaps:* Current systems lack sufficient cultural understanding for fully autonomous use in culturally sensitive architectural applications.

Theoretical and Practical Contributions. This research makes several important contributions to both theoretical understanding and practical application:

- Theoretical Contributions:
  - Development of a comprehensive framework for evaluating AI performance in architectural visualization.
  - Identification of specific patterns in how AI systems handle historical architectural styles.

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- Analysis of the relationship between digital representation and AI generation accuracy.
- Examination of cultural sensitivity issues in AI-generated architectural content.

- Practical Applications:
  - Evidence-based prompt engineering strategies for architectural visualization.
  - Guidelines for selecting appropriate AI tools for specific architectural contexts.
  - Framework for assessing AI suitability for culturally sensitive design projects.
  - Methodology for evaluating AI performance in specialized architectural applications.

Future Research Directions. Based on the findings and limitations identified in this research, several promising directions for future work emerge:

- Technical Development and Model Improvement:
  - *Specialized Architectural AI Models:* Development of AI systems specifically trained on architectural datasets with balanced representation across styles, periods, and regions.
  - *Culturally Aware Training:* Integration of cultural context and symbolic meaning into model training processes.
  - *Style-Specific Parameter Tuning:* Development of specialized parameters for different architectural traditions and historical periods.
  - *Multi-Modal Architectural Understanding:* A Combination of text, image, and spatial data for more comprehensive architectural Intelligence.
  - *Human-AI Collaborative Design Processes:* Investigation of optimal workflows combining AI capabilities with human expertise and cultural understanding.
  - *Educational Applications:* Development of AI-assisted tools for architectural history education and traditional design principles.
  - *Cultural Heritage Preservation:* Application of AI generation for reconstruction, documentation, and interpretive visualization of historical architecture.
  - *Design Innovation Frameworks:* Development of methodologies for using AI in culturally grounded, contemporary design.
  - *Cross-Platform Comparative Analysis:* Extend the evaluation framework to multiple AI platforms to assess generalizability and compare performance across different model architectures.

- Evaluation and Ethical Frameworks:
  - *Cultural Authenticity Metrics:* Development of standardized metrics for assessing cultural authenticity in AI-generated architectural content.
  - *Ethical Guidelines:* Establishment of ethical frameworks for AI use in culturally sensitive design contexts.
  - *Bias Mitigation Strategies:* Development of techniques for identifying and addressing biases in architectural AI systems.
  - *Longitudinal Performance Tracking:* Continuous assessment of AI performance improvements in architectural visualization.

Concluding Remarks

This research contributes significantly to the growing understanding of AI's role in architectural design, particularly in culturally sensitive contexts requiring historical accuracy and cultural fidelity. The findings demonstrate that while current AI platforms offer powerful capabilities for architectural visualization, their effective application requires careful consideration of training data limitations, cultural context, and appropriate use cases.

As AI platforms continue to evolve, addressing representation gaps, improving cultural contextual understanding, and developing specialized architectural capabilities will be essential for their responsible and effective application in architectural visualization and design. This research provides a foundation for these developments while offering practical guidance for architects, researchers, and educators working at the intersection of AI and architectural design.

The integration of AI in architectural practice represents not the replacement of human expertise, but rather the emergence of new collaborative possibilities that combine computational power with cultural Intelligence, historical knowledge, and design sensitivity. By understanding both the capabilities and limitations of current systems, we can work toward more effective, ethical, and culturally responsive applications of AI in architecture.

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Drawing as Thinking: Artificial Intelligence and the Ontological Sustainability of Architectural Education

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Keywords: Architectural Education, Drawing, Artificial Intelligence, Embodied Cognition, Ontology of Design, Generative Systems, Morphology, Critical Pedagogy

Abstract. This paper argues that the progressive elimination of drawing from the architectural design process — particularly when replaced by generative artificial intelligence systems — compromises the ontological, cognitive, and cultural sustainability of architectural education. The issue at stake is not merely methodological or technological, but concerns the very conditions under which architectural thinking is formed. Drawing is interpreted not as a nostalgic technique, but as a structural mediation between concept, body, and world. Through a philosophical framework grounded in Hegel's conception of art as the sensuous manifestation of the Idea, Ruskin's ethics of attention, Goethe's morphological understanding of form, and António Damásio's theory of embodied cognition, the paper defends the thesis that drawing constitutes a formative cognitive act. When design generation is externalized to algorithmic systems, the dialectical tension between idea and material gesture is weakened, and the embodied genesis of form is displaced. The result may be increased efficiency and formal proliferation, but at the cost of attenuating the architect's experiential and critical formation. The sustainability of architectural education, therefore, depends not only on technological integration, but on preserving the embodied conditions of creative thought.

Introduction

The digital transformation of architectural education is not new. Three-dimensional modelling, BIM, parametric systems and environmental simulations have become central tools in academic training. More recently, the integration of generative artificial intelligence systems — capable of producing images, spatial diagrams and even complete architectural proposals — has introduced a new mutation in the design process. In this context, a question arises that goes beyond the technical domain: is it sustainable to teach architecture without drawing at the moment of design? The question is often answered in pragmatic terms — efficiency, speed, alignment with contemporary professional practice. However, what is at stake is not just the replacement of one tool with another, but the displacement of the very place where architectural thinking takes place.

Asking whether it is sustainable to teach architecture without drawing at the moment of design is no longer sufficient. The question has become more unsettling: is it sustainable to teach architecture when the project can emerge directly from artificial intelligence systems that have never drawn, never touched the material and never inhabited the world?

A significant shift is currently taking place. Drawing is no longer merely being replaced by digital modelling; it is being displaced by generative processes in which form emerges without gesture, without hesitation, without friction—perhaps even without sufficient reflection.

Our view argues the following thesis: The elimination of drawing from the design process, especially when replaced by generative artificial intelligence processes, compromises the ontological, cognitive and cultural sustainability of architectural education, because it dissolves the embodied mediation between concept, body and world that constitutes the very condition of design thinking.

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To support our thesis, four main theoretical lines will be mobilised: (1) The Hegelian conception of art as a sensitive mediation of the idea; (2) Ruskin's defence of drawing as an ethical discipline of seeing; (3) António Damásio's theory of embodied cognition; (4) Goethean morphology as a procedural understanding of form.

Through the articulation of these perspectives, it will be argued that drawing is not a contingent instrument, but a structural condition for the formation of the architect as a thinking subject.

Drawing as Thinking: drawing as a cognitive device in architectural design

Before discussing the impact of artificial intelligence on architectural education, it is necessary to clarify the meaning of the term ‘drawing’ as used in this article. The drawing considered here refers specifically to hand drawing as a cognitive act incorporated into the architectural design process. It is not just a technique of representation or graphic communication, but a process through which spatial thinking is formed and transformed.

In the disciplinary tradition of architecture, drawing has often been understood as an instrument for representing preconceived ideas. However, several authors have shown that, in the context of design, drawing functions differently: it actively participates in the genesis of the idea. Robin Evans observes that architectural drawing is not merely a translation of thought into image, but a means through which the architect explores spatial relationships and discovers formal possibilities [1]. The act of drawing thus becomes a form of research.

This perspective is close to the contemporary concept of embodied cognition. Thinking is not just about operating abstract concepts; it involves continuous interactions between perception, body and environment. In manual drawing, the gesture of the hand, the resistance of the support, and the visual perception of the line form a cognitive feedback loop. The architect observes what they have drawn, reacts, corrects, adds, eliminates. Each line reorganises the field of possibilities. In this process, drawing functions as an interface between thought and space. The line drawn does not simply represent a form; it tests a spatial hypothesis. At the same time, the necessarily selective nature of drawing — what one chooses to show, omit, or simplify — constitutes an interpretive act. The architect learns to visually structure complexity.

Hand drawing also has a gestural and temporal dimension that distinguishes it from purely digital processes. The line retains traces of the movement that produced it: speed, hesitation, pressure. These traces are not mere graphic accidents; they constitute cognitive information. The gesture conveys intention, doubt and experimentation. Form gradually emerges from a dialogue between perception and action.

From this point of view, drawing is not just representing an architectural idea, but participating in its production. Design thinking develops in an intermediate space between imagination and gesture. The hand does not simply execute a previously made decision; it contributes to its formation.

This understanding of drawing as thought has important implications for the teaching of architecture. If drawing is understood solely as a representational tool, it may easily seem replaceable by digital models or generative systems. However, when it is understood as an embodied cognitive process, its elimination alters the very conditions in which architectural thought develops.

The growing introduction of artificial intelligence systems into the design process therefore raises a crucial question: what happens to architectural thinking when the genesis of form no longer involves human gesture? If drawing constitutes a space for experimentation where perception, emotion and imagination are articulated, its replacement by algorithmic generation may displace the place where thinking occurs.

The discussion about the future of architectural education cannot, therefore, be limited to an instrumental assessment of new technologies. It must begin by recognising that drawing by hand

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as gesture, perception and thought — is one of the fundamental cognitive devices through which architecture has historically become possible.

Drawing as dialectical mediation: a Hegelian reading

In *Vorlesungen über die Ästhetik*, Hegel defines art as 'sensible presentation of the idea' (*sinnliche Darstellung der Idee*)[i] [2,3]. Artistic creation is not merely the externalisation of a previously formed concept; it is the process by which the concept takes shape when confronted with the resistance of matter. This moment of mediation is essentially dialectical: the idea is transformed as it is embodied.

In the architectural context, drawing performs precisely this mediating function. The line is not a simple graphic representation of a solution already resolved mentally. On the contrary, it is the space where the solution emerges in the tension between intention and the materiality of the gesture. When the student draws, the idea encounters resistance: scale, proportion, the relationship between lines, spatial coherence. Error is not a failure, but a productive moment in creative dialectics. Replacing this process with artificial intelligence systems radically alters this structure. Form no longer emerges from the mediation between concept and gesture. It becomes the result of algorithmic operations based on statistical patterns extracted from vast data sets.

In this scenario, dialectics is externalised. The student becomes a selector of results, not a subject of creative conflict. If, in Hegelian terms, art is the place where the spirit recognises itself in matter, then the delegation of the gesture to the machine may represent a historical shift in the very status of creation. We must remember that Hegel also speaks of the so-called "end of art" (*Ende der Kunst*) [ii]— not as disappearance, but as a historical shift in its status as the supreme form of revealing truth [2,3].

This is not a "end of art" in the literal sense, but a weakening of the sensory experience as a formative moment. This invites the question: Hegel and the end of gesture? If so, Hegel describes art as a sensitive manifestation of the spirit. But he also speaks of its 'end' — the loss of art's centrality as a privileged means of revealing truth. If we accept this reading, we might ask: are we witnessing the end of the architectural gesture as a sensitive mediation? Artificial intelligence produces forms that do not pass through the human body. There is no trace, no error, no resistance from the hand. There is calculation. In this sense the dialectic between concept and matter, which in drawing manifests itself as tension, is replaced by data processing. The 'spirit' no longer experiences 'itself' in matter; it delegates. If creation no longer involves the physical conflict of the trace, perhaps we are not just facing a technical evolution. Perhaps we are facing a dematerialisation of the creative experience. And that is not neutral.

Drawing as the ethics of seeing: Ruskin's lesson

John Ruskin, in The Elements of Drawing (1857), states that the greatest capacity of the human soul is to see and truthfully say what it has seen [4][iii]. For Ruskin, drawing is learning to see. Drawing is a discipline of attention. It forces us to suspend haste, to observe rigorously, to recognise uniqueness. It is not just a technique; it is a moral exercise.

In the teaching of architecture, this dimension is crucial. Students who draw a space, a landscape or a building do not just reproduce forms — they learn to recognise them in their complexity. They develop an ethical relationship with reality. Artificial intelligence, on the other hand, does not see. It operates on mathematical correlations. It does not experience light, scale or gravity. When the design process is initiated directly through the automatic generation of images or diagrams, the primary relationship with reality is replaced by a relationship with databases.

The question that arises is: can architectural responsibility exist without direct experience of careful observation?

If design shapes the gaze, its elimination can generate architecture that is formally sophisticated but perceptually superficial.

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Somehow we are taking the moral responsibility, i.e.; attentiveness to users/context, consequences of spatial decisions, accountability for judgement in design from our students, since Ruskin argued that drawing is a moral act because it forces one to truly see. Drawing educates the gaze. It teaches attention, slowness, responsibility. Artificial intelligence, on the other hand, operates on algorithmic operations based on statistical patterns extracted from vast data sets. It does not look — it correlates. It does not contemplate — it calculates.

When a student designs using generative systems that produce images or spatial solutions in seconds, what kind of gaze is being formed? The practice becomes a curation of results rather than an experience of discovery. No moral design. If drawing is learning to see, a project mediated exclusively by AI can become learning to choose. And choosing is not the same as understanding. No moral means, no thoughtful decisions. Perhaps we are training architects who know how to select, but do not know how to 'look'(truth).

Embodied cognition: Damásio and the thinking body

António Damásio, in Descartes' Error (1994), demonstrates that reason is not independent of emotions and bodily processes. Thought is embodied. The mind emerges from the interaction between brain, body and environment. Damásio demonstrates that thought, emotion, and body are inseparable [5] [iv]. Intuition is born from embodied experience. The body is not a support for the mind; it is a condition of the mind. Drawing is a somatic act. The hand hesitates, presses, corrects. The stroke reveals doubts. The error informs. Form emerges from this bodily dialogue.

When a project is produced by AI, the body is removed from formal genesis. The student reacts to an external proposal instead of generating an internal trajectory. Intuition is replaced by optimization. The question becomes unsettling: if cognition is incorporated, what happens to the formation of architectural thought when formal generation is outsourced to systems that have neither body nor emotion? Are we training architects or interface operators?

This conception has profound implications for the teaching of architecture. Drawing is an embodied cognitive act. The hand actively participates in the formation of the idea. The stroke retroacts on thought. The pressure of the pencil, the speed of the gesture, the repetition, the hesitation — all of this constitutes cognitive information.

Designing by drawing is a circular process: the body produces form and simultaneously learns from it. When the project is initiated through artificial intelligence systems, this embodied dimension is significantly reduced. The form appears ready-made, as output. The student reacts, selects, adjusts — but does not necessarily go through the somatic process of genesis. If cognition is embodied, then the elimination of drawing implies a transformation in the very architecture of design thinking.

The risk is not only technical; it is formative. A generation of architects may be forming whose relationship with form is mediated by interfaces, not by the body. We can call it 'amputation of embodied cognition'.

Goethe and the morphological understanding of form

In *Die Metamorphose der Pflanzen* (1790), Goethe proposes a morphological view of nature: forms are not static entities, but moments in a continuous process of transformation, i.e.: Understanding a form implies following its genesis [6][v].

Goethe saw form as a continuous metamorphosis. To draw was to follow the vital process of form, to understand its becoming. Drawing, as a process, allows us to follow the emergence of form. It records intermediate stages, hesitations, variations. It is a morphological tool. Artificial intelligence produces multiple formal variations in seconds. However, variation is not synonymous with understanding. The multiplication of possibilities does not guarantee an understanding of the internal law that structures transformation. The risk is to confuse formal complexity with morphological depth. Confusing formal abundance with morphological depth is an

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epistemological error. If students do not experience the process of form formation, they may produce complex images but lack structural understanding.

An AI-generated image can be visually impressive, but the question remains: where is the experience of genesis? Where is the inner process that allows the architect to understand what he does? If the student does not go through the formation of form, how can he take responsibility for it? Again, we see the moral values being ostracized.

AI without Drawing: the emergence of design without gesture

The recent development of generative artificial intelligence systems has introduced a new configuration in the architectural design process: the possibility of producing architectural forms and images without going through the act of drawing. Platforms based on generative models allow perspectives, spatial schemes, or architectural atmospheres to be generated through textual instructions—often referred to as prompts. In this context, form emerges not as the result of a gradual process of graphic exploration, but as the immediate product of algorithmic processing.

This transformation profoundly alters the traditional structure of the design process. In manual drawing, the architect participates directly in the genesis of form. The line emerges from a bodily gesture and is inserted into a temporal sequence of attempts, corrections, and reformulations. Form develops progressively through a continuous dialogue between perception and action.

In artificial intelligence-mediated design, this sequence can be drastically reduced or even eliminated. The form emerges already stabilised, as the result of a system that combines patterns learned from vast sets of existing images. The architect now interacts with the process mainly as a curator of results: selecting, rejecting, reformulating the initial command, but rarely participating directly in the formation of the line or the gradual emergence of geometry.

This shift has profound implications for understanding the act of designing. Architectural design is no longer necessarily a process of progressively constructing spatial relationships, but rather a process of navigating previously calculated spaces of possibility. Instead of producing form, the architect selects from among generated variations.

The central question is not technological, but epistemological: where does architectural thought occur when the genesis of form is externalised to algorithmic systems?

In manual drawing, each line simultaneously represents a decision and a hypothesis. The architect observes what he has drawn, interprets the emerging relationships and reacts. This feedback loop constitutes an embedded cognitive process, in which perception, gesture and imagination operate together. Design thinking develops in the very act of drawing.

When form is produced by generative systems, this circuit can be interrupted. The architect reacts to pre-configured results, but does not necessarily go through the process that generated them. The experience of formal genesis — central to understanding spatial relationships — becomes indirect.

This does not mean that artificial intelligence is incompatible with architectural design. On the contrary, it can function as a powerful exploratory tool. The problem arises when the generative system completely replaces the initial moments of graphic and gestural experimentation that traditionally structure design thinking.

If drawing functions as a cognitive device that articulates perception, gesture and imagination, its elimination shifts the place where thought occurs. Artificial intelligence not only accelerates the process of formal production; it redefines the relationship between the architect and form.

The risk, in this context, is not simply technological dependence. It is the transformation of the architect from author of processes to manager of results.

In pedagogical terms, this transformation raises a fundamental question: can the teaching of architecture shape design thinking without providing students with direct experience of the genesis of form?

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The introduction of artificial intelligence into teaching can broaden the field of formal experimentation. However, when this broadening occurs at the expense of the embodied experience of drawing, there is a risk of weakening precisely what makes architecture a reflective practice: the ability to think through form.

The decisive question is therefore not whether artificial intelligence should be used in architectural education. The question is at what point in the process it intervenes. When it replaces the gesture at the initial stage of the project, it alters the cognitive structure of the act of designing. In this sense, the debate on the future of architectural education should not pit drawing against technology. It should recognise that drawing — understood as embodied thinking — is a fundamental formative condition. Artificial intelligence can expand the horizon of the project, but it can hardly replace the process through which the architect learns to think spatially.

Architecture has historically been a discipline where thinking happens through drawing. When drawing disappears from the genesis of form, the location of architectural thinking itself becomes uncertain.

Objections and responses

Objection 1: Drawing is an outdated historical technique.

It can be argued that manual drawing is only a historical stage, replaced by more efficient tools.

Response: The argument does not defend drawing as a specific technique, but as an incorporated cognitive structure. Even if the medium evolves (tablet, digital interface, virtual reality), what is at stake is the preservation of gestural mediation and the procedural genesis of form.

Objection 2: Artificial intelligence enhances creativity.

Proponents of AI argue that generative systems expand the creative horizon, offering unexpected solutions.

Response: Expanding possibilities does not replace the development of critical thinking skills. Creativity lies not only in producing variations, but in understanding and justifying choices. Without experience of genesis, there is a risk of dependency.

Objection 3: Professional practice requires technological mastery. It is undeniable that the market demands advanced digital skills.

Response: Integrating technology is necessary. Completely replacing the established process is another matter. The sustainability of education requires balance, not abdication.

Ontological and cultural sustainability

The sustainability of architectural education cannot be reduced to environmental or technological efficiency criteria. It must include an ontological dimension: preserving the conditions that make it possible to train autonomous creative individuals.

Eliminating design from the moment of planning — especially when replaced by algorithmic generation — implies reconfiguring the relationship between thought and form, between body and concept, between architect and world. This reconfiguration may generate efficiency, but it impoverishes the formative experience.

We acknowledge that AI can support reflective pedagogy when structured carefully; therefore, our argument should not be interpreted as anti-technology. We also recognise that there is a focus on sustainability in education. However, sustainability encompasses more than just energy efficiency and reducing paper consumption. In this paper, we understand sustainability to mean continuity of meaning. While an education system that abandons design and delegates formal genesis to algorithmic systems may be technically up to date, it could become culturally unsustainable. Why? Because it trains professionals who master tools but not the inner process of

creation, who produce images but do not develop vision, and who optimise solutions but do not engage with conflicting ideas.

Conclusion

We argued that drawing constitutes an ontological condition of design thinking, as dialectical mediation (Hegel), ethical discipline of the gaze (Ruskin), act of embodied cognition (Damásio) and morphological instrument (Goethe). The integration of artificial intelligence into architecture education is inevitable and potentially fruitful. However, when this integration involves the elimination of gesture and the embodied experience of formal genesis, the sustainability of teaching is compromised.

Architecture can survive without drawing. But architectural education that abandons gesture runs the risk of producing technically competent but philosophically unarmed individuals. The real issue is not technological. It is anthropological. Perhaps the question (all these concerns) should be phrased more bluntly: If architecture can be generated by artificial intelligence without design, without body and without hesitation, what is left for the architect?

And, even more disturbingly: what is left for the teaching of architecture?

If students no longer experiment with thinking through drawing, if they no longer make mistakes with their hands, if they no longer discover through gesture, can they still develop an autonomous critical consciousness? Or will they merely navigate increasingly sophisticated systems?

It is not a question of rejecting artificial intelligence. It is a question of refusing to replace thinking with processing. Drawing is not nostalgia. It is ontological resistance.

Perhaps the true sustainability of architectural education lies precisely in preserving what machines cannot simulate: human hesitation, productive error, the tension between idea and gesture. Because architecture without drawing can survive. But an architect without embodied thinking experience may not.

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[i] In the *Vorlesungen*, the idea that art is the sensible presentation of the idea appears in the introduction to aesthetics ("Einleitung") within the context of what Hegel understands by art as a manifestation of the spirit. In it, specifically at the beginning of the first volume, Knox translates Hegel's speech about art as "a sensuous presentation of the Idea".

[ii] Hegel does not speak of the literal death of art, but rather that art no longer occupies the highest place in the revelation of the absolute—that is, it is no longer the supreme means by which truth manifests itself, being subsequently "superseded" by philosophy and, in a certain sense, by religion. Therefore, many scholars use the expression *Ende der Kunst* (End of Art) when summarizing this historical and philosophical passage, not merely as a literal quotation from the German philosopher. "For us art no longer counts as the highest mode in which truth procures existence for itself." (Hegel, Aesthetics, trans. Knox, vol. I, p. 11)

[iii] Letter I, p. 6 -"The greatest thing a human soul ever does in this world is to see something, and tell what it saw in a plain way."

[iv] Chapters VI–VIII - Especially pp. 164–201 (exposition of the *somatic marker* hypothesis).

[v] "It is evident that all parts of the plant… are merely metamorphoses of one and the same organ." Goethe introduces the principle that all parts of the plant are transformations of the same fundamental organ (the leaf).

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Immersive Urban Digital Twins for Heat-Resilient Public Space Co-Design in Hot-Arid Cities: Integrating IoT Sensing and Participatory VR in a Mixed-Method Case Study

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Keywords: Urban Digital Twin, Participatory Virtual Reality, Outdoor Thermal Comfort, Hot-Arid Cities, IoT Sensing, Public-Space Co-Design, Heat Resilience, UTCI, Microclimate Simulation

Abstract. Heat stress increasingly reduces the safety, usability, and social value of public space in hot-arid cities, yet planning workflows rarely combine microclimate evidence with meaningful citizen participation. This paper proposes a human-centred framework for heat-resilient public-space co-design that integrates IoT-based sensing, an immersive urban digital twin (UDT), and participatory virtual reality (VR). Using a mixed-method case study of a public open space in Al Khobar, Saudi Arabia, the framework links environmental inputs, digital-twin representation, participatory VR interaction, intervention testing, and integrated evaluation. The study asks whether a calibrated UDT can represent outdoor thermal comfort under current and future heat conditions, whether participatory VR improves citizens' understanding and confidence relative to non-immersive interfaces, and which intervention packages best balance thermal performance and user preference. The UDT is validated against synchronized field measurements using RMSE and MAE, while participatory outcomes are compared across immersive and non-immersive interfaces through paired ratings and qualitative feedback. Findings indicate that the workflow supports comparative thermal analysis, improves communication and co-design quality, and helps identify integrated mitigation packages that are more informative than isolated measures. The paper positions the UDT as a closed-loop decision-support workflow connecting sensing, simulation, immersive participation, and intervention ranking for hot-arid public-space planning.

Introduction

Heat resilience has become a pressing urban-design challenge in hot-arid cities, where urban growth intensifies heat exposure, degrades outdoor comfort, and weakens the social function of public space. In BWh environments, thermal conditions are shaped by the combined effects of solar exposure, urban form, materials, vegetation, airflow, and water scarcity. Recent reviews on hot-arid environments show that climate change is expected to worsen extreme heat, making thermally safe and socially usable public spaces a strategic urban priority [1,2]. The core problem is that planners in hot-arid cities still lack a workflow that can both validate microclimate evidence and communicate heat-mitigation trade-offs to citizens in an experientially meaningful way.

The challenge is not only environmental but procedural. Conventional participation methods such as static images, verbal explanation, or simplified visualizations often provide limited experiential understanding for non-experts. By contrast, immersive VR studies suggest that embodied and interactive representations can improve scenario comprehension, knowledge transfer, and design communication in public-space planning [3,4]. At the same time, urban digital twins (UDTs) are emerging as promising planning platforms because they can combine simulation, data integration, and interactive 3D representation.

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Despite this promise, three gaps remain. First, climate-focused and human-centred UDT applications for outdoor thermal comfort are still limited, especially in hot-arid settings where index transferability and model calibration are critical [5,6]. Second, citizen participation in UDT workflows is still uneven and often insufficiently co-creative [7]. Third, heat-mitigation knowledge in hot-arid public-space design remains fragmented; for example, studies frequently evaluate canopy cover, reflective materials, or water features as separate variables rather than as interacting packages assessed together with user experience [1,8]. Against this background, the study proposes a human-centred framework that combines IoT sensing, an immersive UDT, and participatory VR for heat-resilient public-space co-design in Al Khobar, Saudi Arabia.

Literature Background and Research Gap

Recent UDT research shows increasing interest in combining geospatial models, environmental sensing, and interactive visualization for citizen-centred planning. For outdoor thermal comfort, this is particularly relevant because heat exposure varies dynamically with air temperature, humidity, wind, radiation, and morphology. Human-centric digital-twin studies demonstrate that multi-source data can support spatially differentiated thermal-comfort prediction, yet thermal-comfort twins still face challenges in modelling efficiency, calibration, accessibility, and real-world planning usability [5,7,9]. These limitations are amplified in hot-arid environments because commonly used indices such as PMV and PET do not transfer equally across climate zones, making local validation essential [6,10].

Participatory VR addresses a second gap. Studies on immersive co-design show that non-experts can better understand future public-space scenarios, communicate design preferences more clearly, and feel more confident in decision-making when spatial alternatives are experienced immersively rather than viewed only on screens [3,4,11]. However, broader evidence is still needed on how immersive participation performs inside UDT-enabled climate-planning workflows, particularly in relation to inclusion, scalability, and comparison with conventional interfaces. A third gap concerns intervention knowledge. Hot-arid literature consistently identifies tree canopy, artificial shading, materials, water features, and urban geometry as major drivers of outdoor thermal conditions, but their performance is interactional rather than isolated. What remains underdeveloped is integrated testing of design packages that are evaluated simultaneously through objective thermal performance and citizen preference [2,8].

Accordingly, the study addresses three research questions: RQ1. To what extent can an immersive UDT integrating IoT microclimate sensing represent outdoor thermal comfort in a hot-arid public space under present and future heat scenarios? RQ2. How does participatory VR influence citizens' understanding, engagement, and confidence compared with a non-immersive planning interface? RQ3. Which combinations of tree canopy, artificial shading, water features, material treatments, and spatial-form adjustments provide the strongest combined improvement in objective thermal comfort and subjective user experience?

Conceptual Framework

The framework connects five linked layers into one decision-support workflow. Figure 1 illustrates the proposed closed-loop framework linking environmental sensing, digital-twin modelling, participatory VR, intervention testing, and integrated evaluation. Block A is the environmental input layer, consisting of IoT-based microclimate variables, site geometry, surface properties, solar exposure, and user-relevant context. Block B is the urban digital twin layer, which converts these inputs into a spatially explicit 3D model with thermal-comfort computation and scenario-testing capability. Block C is the participatory VR layer through which citizens and stakeholders experience and compare alternative futures. Block D is the intervention layer, which includes tree canopy, shading structures, water elements, cool materials, pavement treatments, and spatial-form adjustments. Block E is the outcome layer, where objective metrics such as UTCI, PET, MRT,

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localized temperature reduction, and shade coverage are evaluated together with subjective indicators such as perceived comfort, understanding, engagement, and scenario preference.

The framework conceptualizes heat-resilient co-design as a closed-loop system: sensed environmental data inform the twin; the twin is explored through participatory VR; users compare mitigation scenarios; and objective-subjective evaluation supports intervention ranking and planning decisions. This logic directly responds to the study's three research gaps by linking validation, participation, and integrated intervention testing within a single climate-focused workflow [2,4,7]. Although demonstrated through an Al Khobar case study, the framework is intended as a transferable decision logic for other heat-vulnerable public spaces, provided that local sensing inputs, calibration procedures, and participation protocols are adapted to context.

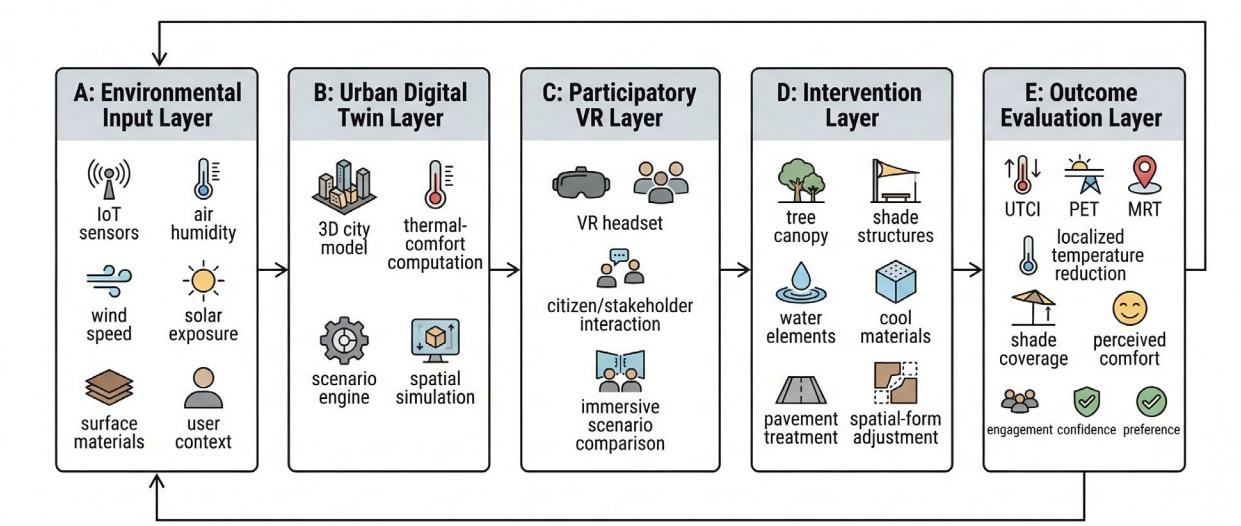


Fig. 1. Human-centered closed-loop framework integrating IoT sensing, urban digital twin modelling, participatory VR, intervention testing, and objective-subjective evaluation for heat-resilient public-space co-design.

Research Method

This study adopts a mixed-method empirical case-study design that combines quantitative environmental sensing and thermal simulation with quantitative and qualitative user evaluation from a participatory co-design experiment. A mixed-method structure is appropriate because the research problem is simultaneously technical and human-centred: the study must validate a digital representation of outdoor thermal conditions while also assessing how citizens understand, compare, and prioritize intervention scenarios. The design follows a convergent logic in which environmental-performance data and participation data are collected within the same empirical phase, analysed separately, and interpreted together [12,13].

The case-study site is a selected public open space in Al Khobar, Saudi Arabia. The site is chosen using four criteria: public accessibility, clear heat exposure, a mix of hardscape and limited vegetation, and practical suitability for temporary sensing and VR translation. The UDT is built from a 3D spatial model of the site and its immediate surroundings. Environmental input is provided by a small IoT microclimate network of fixed nodes and portable pedestrian-level measurements capturing air temperature, relative humidity, wind speed, globe temperature, and solar or radiative exposure. Surface temperatures are additionally recorded using infrared sensing or thermal imaging. These data are synchronized with the UDT database so that sensed conditions calibrate the digital representation in real time or near real time [14,15]. Figure 2 summarizes the empirical workflow from site-based sensing and digital-twin calibration to thermal simulation and immersive participatory review.

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Thermal simulation is conducted using ENVI-met Version 5.5, a calibrated microclimate modelling environment for neighbourhood-scale outdoor thermal analysis. UTCI is used as the primary thermal-comfort indicator and PET as a secondary comparative index, reflecting current outdoor-comfort practice and evidence that UTCI performs strongly in hot-dry settings [16,17]. To address future heat exposure, the calibrated model is also run under a perturbed summer condition derived from recent Saudi climate projections [18].

The participatory experiment recruits a purposive sample of adult site users, nearby residents, and relevant local stakeholders. For this illustrative mock case, the participatory experiment recruits a purposive sample of 24 adult participants drawn from three groups: regular site users (n = 10), nearby residents (n = 8), and local stakeholders (n = 6). The sample includes 13 men and 11 women, aged 21 to 58 years (M = 36.8). Recruitment is conducted through on-site intercept approach, neighborhood community-group outreach, and targeted email invitations to municipal and design-related stakeholders. Participant characteristics, site-use patterns, and recruitment routes are summarized in Table 1.

Table 1. Synthetic participant profile and recruitment routes for the illustrative mock case study.

ID	Group	Gender	Age	Occupation/Role	Site-use frequency	Recruitment route
P01	Site user	M	24	University student	4-5 times/week	On-site intercept
P02	Site user	F	29	Office worker	2-3 times/week	On-site intercept
P03	Site user	M	34	Sales assistant	Daily	On-site intercept
P04	Site user	F	22	Student	2-3 times/week	On-site intercept
P05	Site user	M	41	Engineer	Weekly	On-site intercept
P06	Site user	F	27	Teacher	2-3 times/week	On-site intercept
P07	Site user	M	38	Retail manager	Weekly	On-site intercept
P08	Site user	F	31	Freelancer	4-5 times/week	On-site intercept
P09	Site user	M	45	Accountant	Weekly	On-site intercept
P10	Site user	F	26	Designer	2-3 times/week	On-site intercept
P11	Nearby resident	F	33	Homemaker	Uses nearby park weekly	Community WhatsApp
P12	Nearby resident	M	48	Bank employee	Uses site weekends	Community WhatsApp
P13	Nearby resident	F	39	Lecturer	Uses site weekly	Community WhatsApp
P14	Nearby resident	M	28	IT technician	Uses site 2-3 times/week	Community WhatsApp
P15	Nearby resident	F	52	Small business owner	Uses site occasionally	Community WhatsApp
P16	Nearby resident	M	36	Architect	Uses site weekly	Community WhatsApp
P17	Nearby resident	F	30	HR officer	Uses site 2-3 times/week	Community WhatsApp
P18	Nearby resident	M	43	School administrator	Uses site weekends	Community WhatsApp
P19	Stakeholder	M	54	Municipal officer	Professional interest	Direct email
P20	Stakeholder	F	37	Urban designer	Professional interest	Direct email
P21	Stakeholder	M	46	Facilities manager	Professional interest	Direct email
P22	Stakeholder	F	35	Landscape architect	Professional interest	Direct email
P23	Stakeholder	M	58	Planning consultant	Professional interest	Direct email
P24	Stakeholder	F	40	Sustainability officer	Professional interest	Direct email

Each participant reviews the same design scenarios in two conditions: a conventional non-immersive interface and an immersive VR interface embedded in the UDT. Order is counterbalanced to reduce novelty effects. The scenarios include the existing site, single interventions, and integrated packages combining canopy, shading, materials, water, and spatial

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adjustments. During each session, participants compare alternatives, identify preferred interventions, rate the scenarios on the subjective outcome dimensions, and explain the reasoning behind their choices.

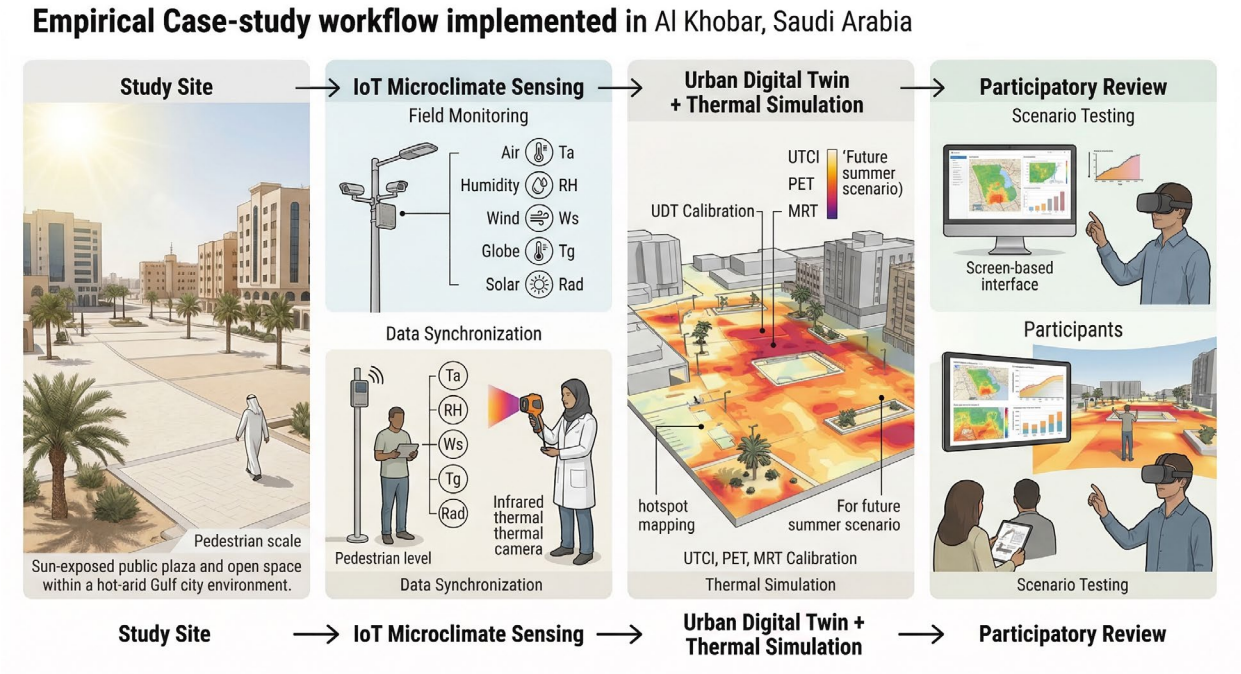


Fig. 2. Mixed-method empirical workflow showing site-based microclimate sensing, data synchronization, urban digital twin calibration, thermal simulation, and immersive/non-immersive participatory review.

Objective measures include UTCI, PET, air temperature, mean radiant temperature, surface temperature, shade coverage, and localized hotspot reduction. Subjective measures include perceived comfort, understanding, engagement, confidence, and preference clarity. Analysis proceeds in four stages: (1) model validation using RMSE, MAE, and related agreement statistics; (2) objective comparison of baseline and intervention scenarios under present and future heat conditions; (3) paired comparison of non-immersive and immersive evaluation outcomes, supported by appropriate paired tests, effect sizes, confidence intervals, and thematic analysis of open-ended comments; and (4) production of an intervention matrix that integrates environmental performance with user preference to identify the most robust design package for the site. Figure 3 presents the intervention-assessment matrix used to compare thermal performance and user preference across baseline, single-measure, and integrated design scenarios.

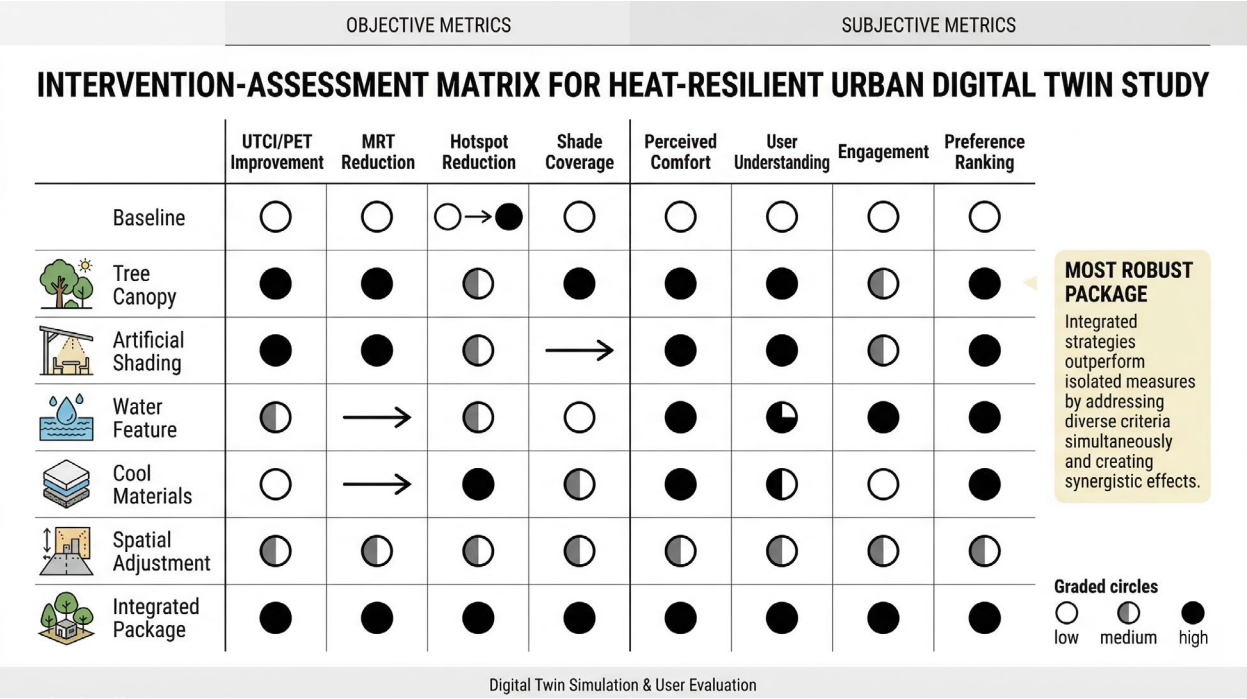


Fig. 3. Conceptual intervention-assessment matrix integrating objective thermal indicators and subjective user evaluation for comparing baseline, single-intervention, and integrated mitigation scenarios.

Results

Results for RQ1 indicate that the calibrated UDT reproduces the main spatial and temporal pattern of outdoor thermal variation with sufficient fidelity for comparative planning use. Agreement between measured and simulated air temperature, MRT, and UTCI or PET is reported through RMSE and MAE at synchronized locations and times air temperature RMSE = 1.7 °C, MAE = 1.4 °C; MRT RMSE = 5.0 °C, MAE = 4.0 °C; UTCI RMSE = 3.6 °C, MAE = 3.1 °C. The model captures the expected contrast between high-exposure hardscape hotspots and shaded refuge zones, while the future heat scenario increases both average thermal stress and the area classified as severe exposure. The model captures the expected contrast between high-exposure hardscape hotspots and shaded refuge zones, while the future heat scenario increases average UTCI by 2.3 °C and expands the area classified as severe exposure from 62% to 78% of the analysed pedestrian zone. These outputs establish the baseline needed for scenario comparison and demonstrate the twin's usefulness as a context-sensitive thermal-planning tool.

Results for RQ2 show that participatory VR performs better than the non-immersive condition on scenario understanding, engagement, and decision confidence. Across the participant sample n=24, the immersive condition yields higher mean scores for understanding, engagement, and confidence than the non-immersive condition, across the participant sample ($n = 24$), the immersive condition yielded higher mean scores for understanding ($M = 4.29$, $SD = 0.56$) than the non-immersive condition ($M = 3.63$, $SD = 0.71$), engagement ($M = 4.41$, $SD = 0.52$) than the non-immersive condition ($M = 3.58$, $SD = 0.76$), and confidence ($M = 4.18$, $SD = 0.61$) than the non-immersive condition ($M = 3.47$, $SD = 0.79$). Paired-samples t-tests indicated significant differences for understanding, $t(23) = 4.82$, $p < .001$, $d_z = 0.98$, 95% CI [0.38, 0.94], engagement, $t(23) = 5.27$, $p < .001$, $d_z = 1.08$, 95% CI [0.50, 1.16], and confidence, $t(23) = 4.36$, $p < .001$, $d_z = 0.89$, 95% CI [0.37, 1.05]. Participants also show clearer consensus when ranking intervention scenarios. Qualitative comments further indicate that VR makes shade, exposure, enclosure, and thermal differences easier to perceive, although practical constraints such as headset comfort and

session duration remain relevant. Overall, the findings support the proposition that immersive participation improves the communicability and usability of climate-design alternatives.

Results for RQ3 show that integrated intervention packages outperform isolated measures. Among single interventions, tree canopy or artificial shading is expected to provide the strongest reduction in UTCI or PET, among single interventions, the artificial-shading scenario provided the strongest standalone improvement, reducing PET by 8.2 °C and mean radiant temperature by 16.0 °C relative to the baseline. The most effective combined package, Package C (Integrated Shade–Canopy–Cool-Pavement–Water Package), produces the greatest improvement in average thermal comfort, hotspot attenuation, shade coverage, and peak surface-temperature reduction under both present and future heat conditions, reducing average UTCI by 7.1 °C under present conditions and 6.0 °C under the future heat scenario, decreasing severe-exposure hotspot area by 19 and 15 percentage points respectively, increasing effective shade coverage from 18% to 46% of the analysed pedestrian zone, and lowering peak surface temperature by 11.4 °C and 9.6 °C relative to the baseline. Participant preferences broadly align with this ranking, although some scenarios receive stronger subjective support than their thermal performance alone would predict, suggesting that openness, legibility, aesthetics, and perceived usability also shape public acceptance. The final objective-subjective matrix therefore identifies the best-performing package not only by cooling effect, but by its combined environmental and experiential value.

Discussion

The study extends current UDT research by treating the digital twin not as a passive representation, but as a human-centred climate-planning system. By linking IoT sensing, thermal simulation, and participatory VR, the framework shows how UDTs can support collaborative steering rather than technical visualization alone. It also strengthens participatory VR research by placing immersive co-design in a concrete heat-resilience decision context, where environmental scenarios must become perceptible and discussable to non-experts. Finally, the paper contributes to hot-arid thermal-comfort literature by evaluating mitigation as a combined intervention problem, acknowledging that thermally effective solutions must also be understandable, acceptable, and publicly supportable [1,4,7].

From a planning perspective, the workflow offers municipalities a structured path from hotspot diagnosis to scenario testing and citizen-facing review. This is especially relevant in Al Khobar and comparable Gulf contexts, where rapid land-cover change, uneven access to public green space, and rising thermal vulnerability place pressure on designers to justify adaptation investments transparently [19,20]. In this sense, the UDT becomes useful not only because it simulates microclimate, but because it allows planners and citizens to discuss trade-offs among comfort, visibility, maintenance, and public-space quality in a shared evidence environment [21,22].

The intervention findings also reinforce the argument that hot-arid cooling should be treated as a configuration problem rather than a single-variable optimization task. Recent work on landscape configuration and reflective hardscape design shows that the value of canopy, materials, and spatial arrangement depends on how these elements interact locally [23,24]. This helps explain why integrated packages can outperform stand-alone measures and why some scenarios may be preferred by users even when their purely thermal gains are moderate: experiential legibility, perceived openness, and visual quality continue to matter in public-space decision-making.

The main limitation is that the framework is demonstrated through one case-study context and a bounded participant group; broader validation across climates, public-space types, and more inclusive participation settings is still needed. Future work should therefore focus on multi-site validation, larger and more diverse participant samples, lighter access modes such as web-based participation, and tighter integration with municipal decision processes.

Conclusion

This paper responds to a central challenge in hot-arid urbanism: public spaces are becoming more heat-vulnerable, while existing planning approaches still separate environmental analysis from citizen participation and design comparison. In response, the study proposes a human-centred framework that integrates IoT microclimate sensing, an urban digital twin, participatory VR, and comparative intervention testing for public-space co-design in Al Khobar, Saudi Arabia.

The condensed argument is threefold. First, a calibrated UDT can provide a sufficiently reliable representation of outdoor thermal conditions for comparative planning use. Second, participatory VR can improve users' understanding, engagement, and confidence relative to non-immersive planning interfaces. Third, integrated packages of canopy, shading, materials, water, and spatial-form adjustment are more informative for decision-making than isolated measures because they better reflect the interactional nature of hot-arid microclimates. The novelty of the study lies in combining sensing, simulation, immersive participation, and intervention ranking in one closed-loop workflow within a mixed-method case-study design. The paper therefore offers a practical pathway for municipalities and designers seeking more transparent, evidence-based, and citizen-centred heat-resilient public-space decisions.

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Global Energy Regulations for Sustainable Buildings: Comparative Strategies and Adaptation Pathways for Saudi Arabia

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Abstract. This study investigates international regulatory frameworks governing building energy efficiency, focusing on their structure, objectives, and implementation mechanisms. The research identifies commonalities such as performance-based codes, energy labeling systems, financial incentives, and voluntary certifications by comparing policies in the United States, Japan, the United Kingdom, Germany, and the European Union. These elements are analyzed for their applicability to Saudi Arabia, where Vision 2030 mandates a transition toward environmental sustainability and reduced carbon emissions. Since the building sector accounts for over 80% of the Kingdom's electricity consumption, developing integrated and enforceable energy regulations is a strategic and environmental priority. The study recommends a hybrid regulatory model combining mandatory benchmarks with lifecycle-based assessments and market-driven incentives. Contextualizing global best practices within the Kingdom's climatic and economic conditions, the findings contribute to formulating adaptive, forward-looking building energy policies for sustainable urban development in Saudi Arabia.

1. Introduction

The transition toward sustainable development has elevated the importance of green buildings as a central component in global strategies to reduce energy consumption and mitigate climate change [1]. Among various sectors, the building sector represents a substantial share of global energy use and associated carbon emissions [2]. According to the International Energy Agency, buildings accounted for approximately 30% of global final energy consumption and 27% of energy-related CO_2 emissions in 2021, underlining the sector's potential to contribute significantly to national and international energy efficiency targets [3].

Major economies have recently introduced ambitious policy frameworks to improve buildings' energy performance [4]. China, for instance, committed to reducing energy intensity by 16% between 2011 and 2015 under its 12th Five-Year Plan [5]. Under the 14th Five-Year Plan, it promotes carbon-neutral buildings as part of its dual-carbon goals. The United States has revised fuel and building energy standards through initiatives like ASHRAE 90.1 and the Energy Policy Act, aiming for 30% greater energy efficiency than baseline codes [6]. The European Union, under its Energy Efficiency Directive (2012/27/EU), initially targeted a 20% improvement by 2020, later increasing its ambition to 32.5% by 2030. Japan's Top Runner Program and national energy conservation plans seek to reduce electricity consumption by at least 10% by 2030 [7].

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Global energy demand has shown a persistent upward trajectory since the 1970s, only briefly interrupted by economic downturns such as the early 1980s recession [8]. Today, energy consumption in the building sector continues to rise, driven by urbanization, population growth, and increasing expectations for thermal comfort, particularly in rapidly developing regions [9]. Numerous studies indicate that even a 10% improvement in building energy efficiency could yield disproportionately large environmental and economic benefits due to the sector's high operational energy use and long lifecycle impacts [10].

This study aims to analyze international regulatory frameworks and policy systems related to green building development, focusing on their structure, scope, and implementation mechanisms. Through a comparative review of regulations from leading countries in sustainable architecture, the research seeks to derive lessons and strategies that may be adapted to regional contexts. Specifically, this study closely aligns with the priorities outlined in Saudi Arabia's Vision 2030, emphasizing environmental sustainability, energy diversification, and adopting advanced technologies in the built environment. As Saudi Arabia undergoes rapid urban expansion, particularly in high-profile developments such as NEOM, The Line, and Qiddiya, the demand for energy-efficient buildings becomes increasingly critical. The Kingdom's commitment to reducing 278 million tons of CO_2 equivalent by 2030 and increasing renewable energy to 50% of total generation necessitates robust building regulations and strategic policy frameworks. By contextualizing international best practices within the unique climatic, economic, and policy conditions of Saudi Arabia, this study contributes to the development of an evidence-based roadmap for sustainable building regulation in the Kingdom.

2. Literature Review

2.1. Energy Regulations for Green Buildings in Each Country

Globally, countries have adopted diverse regulatory and incentive frameworks to enhance energy efficiency in the built environment, each tailored to their socio-economic contexts, energy policies, and climate commitments [11]. These regulatory approaches often integrate mandatory codes, voluntary certification systems, financial incentives, and performance disclosure mechanisms to drive compliance and promote market transformation (Table 1).

In the United States, the energy regulatory landscape for buildings is characterized by a combination of federal guidelines and state-level adaptations [12]. Notably, the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) certification is one of the most widely adopted voluntary green building standards, with over 100,000 certified projects globally as of 2023 [13]. Additionally, the Home Energy Rating System (HERS) developed by RESNET enables performance benchmarking through standardized energy modeling. These tools are often linked with financial incentives, tax rebates, and mortgage products, such as energy-efficient mortgages (EEMs), to stimulate demand for green buildings. Moreover, the Energy Star program, jointly administered by the EPA and DOE, offers market differentiation for energy-efficient buildings, contributing to a more transparent and active real estate market [14].

In Japan, the foundation of energy regulation in the building sector was established with the Energy Conservation Act of 1979, in response to the oil crisis of the 1970s [15]. The Act has since evolved through successive amendments to incorporate performance-based energy codes and obligatory reporting. Japan introduced the Top Runner Program to promote the most energy-efficient technologies, and mandates energy performance labeling for buildings under the Building Energy Efficiency Act of 2015. These measures are supported by extensive maintenance protocols and continuous monitoring practices to enhance long-term building performance. The country also mandates disclosure of energy-saving measures during construction permitting, reinforcing accountability in the design and planning phases.

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The United Kingdom has implemented a robust regulatory framework integrating energy performance metrics into real estate transactions [16]. Since 2007, it has been mandatory to issue Energy Performance Certificates (EPCs) for all new constructions and the sale or rental of residential and non-residential buildings [17]. These certificates are based on the Standard Assessment Procedure (SAP)—initially introduced in 1995 and most recently updated as SAP 10.2 in 2022—which calculates a building's predicted energy use, carbon emissions, and heating costs (UK BEIS, 2022). EPCs serve as a regulatory tool and a driver of market awareness by providing consumers with transparent, comparable energy data.

Germany has long been a pioneer in energy efficiency regulation, with its policy trajectory shaped by the energy crises of 1973 and 1979 [18]. The country enacted the Energy Saving Ordinance (EnEV) in 2002, which was later integrated into the more comprehensive Building Energy Act (GEG) in 2020 [19]. This legislation consolidates various directives into a unified regulatory framework governing building energy requirements, encompassing thermal insulation, energy demand calculations, and renewable energy integration. A central element of the system is the mandatory issuance of Energieausweise (Energy Performance Certificates), which are required for building construction, renovation, or sale. Germany's approach also incorporates lifecycle-based assessments and supports deep retrofitting through national funding programs such as the KfW Efficiency House standards.

Countries have developed unique tools and legal instruments to foster energy-efficient buildings [20]. While the scope and enforcement mechanisms vary, common elements include performance certification, regulatory mandates, and market-based incentives. These frameworks aim to reduce operational energy use and increasingly emphasize embodied carbon, whole-building lifecycle performance, and user behavior—principles essential to shaping the future of sustainable architecture.

Table 1. Energy Regulations for Green Buildings in Each Country

Country	Regulation	Categories	Contents
United States	LEED (Leadership in Energy and Environmental Design), HERS (Home Energy Rating System), Energy Star	Voluntary certification, performance rating, incentives	LEED provides multi-tiered certification for green buildings; HERS measures energy efficiency of residential buildings; Energy Star labels energy-efficient buildings and appliances. Financial incentives include tax credits and energy-efficient mortgage products.
Japan	Energy Conservation Act (1979), Building Energy Efficiency Act (2015), Top Runner Program	Mandatory regulation, performance labeling, and technology benchmarking	Establishes mandatory energy standards for buildings; requires energy performance disclosures; Top Runner identifies the most efficient technologies and sets performance baselines. Labels and reporting are required at the design and construction stages.
United Kingdom	Energy Performance Certificate (EPC), Standard Assessment Procedure (SAP)	Mandatory disclosure, performance modeling	Since 2007, EPCs have been required for all new, sold, or rented buildings. SAP methodology assesses energy usage, emissions, and cost. Recent updates include SAP 10.2, which better reflects real-world performance.
Germany	Energy Saving Ordinance (EnEV), Building Energy Act (GEG 2020)	Mandatory regulation, performance certification, and retrofit support	Unified legal framework for thermal insulation, energy demand, and renewable energy integration. Requires Energieausweis (energy certificate) for new and existing buildings. Supports retrofitting through KfW Efficiency House subsidies.

3. Methodology

This study adopts a comparative qualitative research methodology to analyze international regulatory frameworks governing energy efficiency in the building sector. The approach involves reviewing policy documents, legal frameworks, and third-party certification systems from selected countries, including the United States, Japan, the United Kingdom, Germany, and the European

Union. Key sources include government publications, international treaties (e.g., UNFCCC, Kyoto Protocol), peer-reviewed Q1 journal articles, and technical reports from authoritative organizations such as the International Energy Agency (IEA) and the United Nations Environment Programme (UNEP).

The analysis focuses on three primary dimensions: (1) the regulatory scope and legislative evolution of each country's energy policy in the building sector; (2) the objectives and enforcement mechanisms embedded within each framework; and (3) the presence of incentive structures designed to exceed baseline compliance. A matrix-based comparison was used to systematically identify these frameworks' similarities, differences, and potential adaptability to emerging contexts, particularly in Saudi Arabia, which is undergoing a rapid shift toward sustainability under Vision 2030. The insights derived aim to support policymakers, architects, and urban planners in formulating contextually relevant energy regulations and incentive-based green building strategies in the Gulf region.

4. Analysis

4.1. Regulations and Objectives

The initial framework for managing energy consumption in buildings emerged as part of the broader international response to climate change, notably through the United Nations Framework Convention on Climate Change (UNFCCC) adopted at the Rio Earth Summit in June 1992. At that stage, energy efficiency in buildings was promoted primarily through non-binding recommendations and voluntary guidelines among member nations. However, a significant shift occurred with adopting the Kyoto Protocol, which came into legal force in February 2005. This agreement introduced binding greenhouse gas (GHG) emission reduction targets for developed countries, converting earlier recommendations into enforceable obligations under international law.

The Kyoto Protocol marked a pivotal moment in aligning building energy efficiency with climate policy. Participating countries were required to quantify emissions reductions across various sectors, including the building sector, which contributes nearly 39% of global carbon dioxide emissions when operational and embodied carbon are considered (IEA & UNEP, 2022). The implementation of the Protocol led to the formulation of national and regional regulatory instruments focused on setting performance standards, establishing reporting mechanisms, and introducing economic incentives for energy-efficient design, construction, and operation.

These policies have evolved into integrated energy management frameworks combining mandatory baseline regulations with market-based instruments. Many countries have adopted hybrid systems where minimum energy performance standards (MEPS) are legally enforced. At the same time, financial incentives and voluntary certifications (e.g., LEED, BREEAM, HQE) encourage stakeholders to exceed minimum requirements. For instance, the European Union's Energy Performance of Buildings Directive (EPBD), initially adopted in 2002 and amended several times since, mandates all new buildings to be "nearly zero-energy buildings" (nZEB) and requires member states to establish long-term renovation strategies (EU, 2018).

Moreover, integrating incentive-based schemes, such as tax deductions, green finance, carbon credit markets, and subsidy programs, has strengthened policy effectiveness by offering flexibility and market stimulation. In essence, energy regulations have transitioned from purely environmental considerations to a dual-purpose strategy: mandating compliance to reduce emissions while incentivizing innovation and investment in sustainable building practices.

This trajectory of regulatory development illustrates a maturing global consensus that energy management in buildings must be addressed through a combination of legally binding frameworks, economic instruments, and performance-based targets. These strategies are environmental imperatives and key enablers of energy security, technological progress, and long-term economic resilience.

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Table 2. Regulations and Objectives in Each Country

Country/Region	Regulation Name	Objective
Global	UNFCCC (1992), Kyoto Protocol (2005), Paris Agreement (2015)	Establish international legal and voluntary frameworks to reduce greenhouse gas emissions, including the building sector.
European Union	Energy Performance of Buildings Directive (EPBD, recast 2018)	Achieve nearly zero-energy buildings (nZEB), mandate energy certificates, and promote long-term renovation strategies.
United States	Energy Policy Act (2005), Energy Independence and Security Act (2007)	Improve energy efficiency standards for federal and commercial buildings; support green building incentives.
Japan	Energy Conservation Act (1979, revised 2015)	Mandate rational energy use in buildings; require performance labeling and promote efficient technologies.
United Kingdom	Climate Change Act (2008), EPC regulations under Building Regulations Part L	Legally bind carbon reduction targets and improve building energy performance through standardized assessments.
Germany	Building Energy Act (GEG 2020)	Consolidate energy-saving measures; enforce performance-based standards for both new and existing buildings.

4.2. The relationship between Regulations and Building Energy

The relationship between national regulations and building energy performance reflects each country's evolving commitment to environmental preservation, energy security, and sustainable urban development. In the case of Japan, the regulatory foundation lies in the Energy Conservation Act, first enacted in 1979 and significantly revised to respond to global climate concerns and domestic energy needs. The Act is part of a broader legislative framework that includes the Basic Energy Policy Act and the Basic Energy Plan, which collectively aim to ensure a stable energy supply, reduce greenhouse gas emissions, and reform industrial energy consumption through the principles of safety, environmental sustainability, and market efficiency. According to Japan's Ministry of Economy, Trade and Industry (METI, 2021), the building sector accounts for over 30% of total national energy consumption. In response, the "Guidelines for Design, Construction, and Maintenance of Residential Buildings" define quantitative performance metrics for insulation, window glazing, building orientation, mechanical systems, and HVAC specifications. These metrics serve as criteria for energy-saving housing and are enforced through performance labeling and mandatory disclosures in the design and construction process.

In the United Kingdom, the regulatory architecture for building energy efficiency is codified within a hierarchy of laws encompassing the Climate Change Act (2008), Building Regulations Part L, and energy-specific legislation related to electricity and gas. The UK's approach integrates energy performance standards into residential and non-residential buildings through the Energy Performance Certificate (EPC) and the Standard Assessment Procedure (SAP). These tools enable a standardized evaluation of energy use and CO_2 emissions. In line with its legally binding net-zero carbon emissions target by 2050, the UK government has established adaptive regulatory pathways combining minimum energy efficiency thresholds with flexible compliance methods. These include acceptable solutions, retrofit incentives, and green finance mechanisms supporting new construction and deep retrofitting. The system promotes equitable carbon reduction across all building types and user groups, ensuring a broad applicability that fosters user participation in eco-friendly building transitions (BEIS, 2022).

Regulatory initiatives in the United States have been federally and locally driven. The national LEED (Leadership in Energy and Environmental Design) certification program, developed by the U.S. Green Building Council, has emerged as a dominant voluntary standard. LEED certification integrates energy performance targets with carbon footprint reduction, indoor environmental quality, and lifecycle cost efficiency. Studies indicate that LEED-certified buildings consume 25–30% less energy and emit 34% less CO_2 than conventional buildings (Azhar et al., 2011; USGBC, 2023). Additionally, jurisdictions such as Washington, D.C., have enacted mandatory policies,

notably the Green Building Act, which requires adherence to high-performance standards in planning, construction, and operational phases of public and private buildings. The Act also mandates the creation of a Green Building Fund and oversight through an advisory board, thereby institutionalizing the monitoring and evolution of green practices in the building sector.

In Germany, sustainability policy in the built environment extends beyond individual structures to address the urban scale. The country's Building Energy Act (GEG 2020) integrates previous regulations (EnEV, EEWärmeG) into a comprehensive legislative framework that covers energy performance, thermal insulation, and renewable energy requirements. What distinguishes Germany is the multi-criteria sustainability assessment system developed by the German Sustainable Building Council (DGNB). The DGNB certification encompasses ecological, economic, socio-cultural, functional, and technical performance indicators and process quality. This holistic framework positions sustainability as a technical goal and a societal and environmental commitment. According to DGNB (2022), over 6,000 buildings have been certified, with evidence showing lifecycle cost reductions and improved urban quality in certified districts.

These case studies demonstrate that national energy regulations are increasingly sophisticated, interlinking mandatory compliance, performance-based assessments, and user-oriented incentive schemes. Whether through Japan's technically prescriptive approach, the UK's adaptive carbon-reduction frameworks, the U.S.'s combination of certification and municipal mandates, or Germany's systemic integration of sustainability metrics at both building and urban scales, each model exemplifies how regulation can drive meaningful reductions in energy consumption while enhancing building quality and user experience.

5. Discussion: Implications for the Saudi Arabian Context

Saudi Arabia is undergoing a transformative shift toward sustainability, driven by its national development blueprint—Vision 2030—which positions environmental stewardship, energy diversification, and urban innovation at the center of its agenda [21]. As part of this vision, the Kingdom has pledged to reduce 278 million tons of CO_2 equivalent by 2030 and increase the share of renewable energy to 50% of electricity generation [22]. However, given that the building sector accounts for over 80% of total electricity consumption, primarily due to the intensive use of air conditioning systems in residential and commercial spaces, developing robust energy regulations for buildings is both an environmental necessity and a strategic priority [23].

Drawing on the international frameworks examined in this study, there are critical lessons for Saudi Arabia's regulatory pathway [24]. The mandatory and performance-based approaches in countries like Japan and Germany demonstrate the importance of technical standards for insulation, glazing, passive design strategies, and HVAC efficiency [25]. Meanwhile, the United Kingdom's use of Energy Performance Certificates (EPCs) and long-term renovation strategies illustrates the effectiveness of integrating building performance transparency with user incentives [26]. These strategies are particularly relevant for Saudi Arabia, where introducing the Saudi Building Code (SBC) and the Mostadam certification system has laid the foundational infrastructure for performance-based design and construction.

However, unlike contexts with mature retrofit markets and climate-responsive urban forms, Saudi Arabia faces unique challenges, including extreme desert temperatures, high per-capita energy consumption, and rapid urbanization driven by mega-projects such as NEOM, Qiddiya, and The Line [27]. Therefore, regulatory adaptations must account for climatic zoning, local construction practices, and energy pricing structures. Furthermore, as demonstrated by the U.S. and German experiences, the success of any regulatory system depends on a complementary ecosystem of financial incentives, data transparency, and institutional capacity. This may involve linking energy performance to mortgage rates, utility tariffs, and digital building permit systems via innovative city platforms in Saudi Arabia. To advance national objectives, Saudi Arabia should adopt a hybrid model integrating mandatory performance benchmarks (e.g., minimum U-values,

solar reflectivity, air tightness) with market-based tools (e.g., green loans, EPC ratings, tax incentives). Additionally, a shift toward lifecycle-based assessments, including embodied carbon calculations and post-occupancy evaluations, would align the Kingdom's regulatory trajectory with global best practices. Embedding these measures in future iterations of the SBC and urban planning guidelines would ensure that energy regulations are enforceable, contextually adaptive, socially inclusive, and technologically progressive.

6. Conclusion

This study systematically examined the global evolution of energy regulations in the building sector, highlighting how diverse countries have implemented frameworks to enhance energy efficiency and reduce environmental impact. The research identified common strategies such as performance-based codes, mandatory energy labeling, financial incentives, and voluntary certification systems like LEED and DGNB through a comparative analysis of regulatory models in the United States, Japan, the United Kingdom, Germany, and the European Union. These international examples demonstrate that successful energy regulations enforce compliance, stimulate market transformation, support technological innovation, and foster public participation in sustainability.

The implications of these findings are particularly relevant to Saudi Arabia as the Kingdom advances its Vision 2030 goals, including reducing 278 million tons of CO_2 emissions and transitioning to 50% renewable energy. Given that buildings account for the majority of electricity consumption in the country, the development of integrated regulatory frameworks is imperative. Lessons from international best practices underscore the importance of combining mandatory energy performance standards with incentive mechanisms tailored to local climatic and socio-economic conditions. By embedding lifecycle-based assessments, post-occupancy evaluations, and digital permit systems into future iterations of the Saudi Building Code and the Mostadam certification system, Saudi Arabia can chart a proactive and adaptive path toward a low-carbon, high-performance built environment. This study thus contributes to the ongoing discourse on sustainable urban development and provides a policy-relevant foundation for future regulatory innovations in the Gulf region.

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Toward Sustainable Campuses in Saudi Arabia: Comparative Strategies for Green University Transformation

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Abstract. This study examines the implementation of green campus strategies in Saudi Arabia by conducting a comparative analysis of international and regional best practices. The research evaluates key operational elements across environmental management, institutional integration, and community engagement, focusing on Harvard University, the University of Cambridge, and King Abdullah University of Science and Technology (KAUST). Findings reveal that while Saudi universities have initiated sustainability efforts, these remain fragmented and lack cohesive governance, performance monitoring, and stakeholder participation. In contrast, global exemplars have institutionalized sustainability through structured policies, data-driven metrics, and participatory frameworks. The study underscores the need for Saudi universities to establish localized evaluation systems, create permanent sustainability offices, and integrate environmental objectives within Vision 2030. Saudi higher education institutions can play a transformative role in environmental innovation and social development by aligning national climate ambitions with campus operations. The research offers a strategic roadmap to foster the Gulf region's inclusive, resilient, and low-carbon academic environments.

1. Introduction

As climate change, environmental degradation, and resource depletion continue to pose serious global challenges, countries in the Middle East, including the Kingdom of Saudi Arabia, are increasingly aligning national development plans with sustainability goals [1]. Within this paradigm, Saudi Arabia's Vision 2030 outlines a transformative blueprint that includes significant commitments to environmental preservation, energy diversification, and carbon emissions reduction [2]. Through the Saudi Green Initiative, the Kingdom has pledged to achieve net-zero greenhouse gas emissions by 2060 and to reduce its annual carbon output by 278 million tons of CO_2 equivalent by 2030 [3]. This national ambition is further complemented by sector-specific strategies targeting the built environment, energy efficiency, and sustainable urbanism [4].

The building sector in Saudi Arabia accounts for approximately 30% of total national energy consumption, with electricity usage dominated by air conditioning systems due to the country's extreme climatic conditions, where summer temperatures frequently exceed 48°C [5]. University campuses represent a substantial share of energy demand within this sector due to their complex infrastructure, high population density, extended operational hours, and energy-intensive facilities such as laboratories, data centers, and sports complexes [6]. A study by Serat et al. (2024) observed

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that large Saudi university campuses consume 280 to 350 kWh/m² annually, far above global institutional energy benchmarks [7].

Despite ongoing investments in energy infrastructure and renewable energy development, energy consumption in Saudi university campuses continues to rise at an average rate exceeding 5% per year, driven by expanding student populations, increasing digitalization, and a lack of integrated energy management systems. Additionally, the design of academic buildings has traditionally favored mechanical systems over passive strategies, contributing to operational inefficiencies and carbon intensity [8].

In response to these challenges, the green campus model is increasingly being explored as a viable solution to address institutional sustainability and national environmental targets [9]. A green campus integrates environmental considerations into all aspects of campus operations—including energy, water, waste, and transportation—while promoting behavioral change among students and faculty [10]. Elements of green campus development include LEED or GSAS-certified buildings, on-site renewable energy generation, smart metering and analytics platforms, water reuse systems, and landscaping designed for arid climates (xeriscaping) [11].

Leading institutions in the Kingdom, such as King Saud University (KSU) and King Abdullah University of Science and Technology (KAUST) have initiated sustainability-driven projects [12]. For example, KAUST operates a solar-powered seawater desalination plant and has adopted energy dashboards for real-time monitoring [13]. At the same time, KSU has incorporated photovoltaic systems and high-efficiency HVAC retrofits across select buildings. However, these initiatives are often fragmented, lacking standardized frameworks or cohesive policy alignment.

This study serves as a foundational inquiry into developing and implementing green campus strategies in the Saudi higher education sector. Through an analytical review of international and regional precedents and an assessment of campus-scale sustainability metrics, this research seeks to identify effective models, challenges, and policy recommendations applicable to Saudi universities. The ultimate objective is to support the creation of integrated, resilient, and low-carbon academic environments that align with both Vision 2030 and the UN Sustainable Development Goals (SDGs).

2. Literature Review

2.1. Global Trends and Engagement in Green Campus Development

Since the early 1990s, universities worldwide have increasingly acknowledged their pivotal role in advancing sustainable development [14]. This recognition stems from their educational influence and their direct environmental impact as high-density, high-consumption institutions [15]. Internationally, higher education institutions (HEIs) have formed strategic alliances and networks—such as the International Sustainable Campus Network (ISCN), the Association for the Advancement of Sustainability in Higher Education (AASHE), and the Global Universities Partnership on Environment and Sustainability (GUPES)—to promote the implementation of green campus strategies, share best practices, and develop standardized evaluation frameworks [16].

To quantify progress and benchmark sustainability performance, global universities have adopted environmental performance rating systems such as the UI GreenMetric World University Ranking, STARS (Sustainability Tracking, Assessment & Rating System) by AASHE, and THE Impact Rankings by Times Higher Education [17]. These tools assess energy and climate change mitigation, waste management, water use, transportation systems, campus greenery, and academic sustainability programs [18]. As of 2023, over 1,050 universities across 85 countries are participating in the UI GreenMetric ranking, reflecting a growing institutional commitment to environmental responsibility [19].

Universities in countries such as Sweden, the Netherlands, the United States, and Singapore have demonstrated leadership in operational sustainability [20]. For instance, the University of

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California, Davis, has implemented an integrated energy management system that reduced campus-wide greenhouse gas emissions by over 25% since 2007, while the National University of Singapore (NUS) achieved LEED Platinum certification for multiple buildings and integrated solar photovoltaic panels producing over 1.5 MW of electricity annually [21]. Wageningen University has achieved full climate neutrality in Europe through biomass heating, energy-efficient renovations, and onsite renewable generation.

By contrast, green campus initiatives remain relatively underdeveloped in many developing and emerging economies [22]. In such contexts, including parts of the Middle East, green campus adoption is often limited to one-off awareness campaigns or isolated infrastructure upgrades without long-term integration or cross-campus policy frameworks. Participation tends to be fragmented; in most cases, sustainability efforts are not embedded within institutional governance or curriculum design.

Recognizing this gap, governments in various regions have begun forming partnerships with university councils, ministries of education, and environmental agencies to scale up sustainability initiatives in higher education [23]. These partnerships typically include policy incentives, funding for infrastructure retrofits, and the provision of technical expertise. For example, in Saudi Arabia, the Ministry of Education and the Saudi Energy Efficiency Center (SEEC) have launched pilot initiatives for energy audits, HVAC optimization, and solar installations in selected public universities to align with Vision 2030's environmental objectives. Similarly, in the UAE, institutions such as Masdar Institute and Khalifa University have integrated sustainability indicators into campus operations and research agendas.

Table 1 summarizes the comparative status of green campus development globally and regionally. It highlights the varying degrees of institutionalization, performance measurement, and governmental involvement in sustainability transitions across university systems.

Table 1. Global Trends and Engagement in Green Campus Development

Country/ Region	Institutional Examples	Evaluation Framework	Policy/Support Mechanisms	Institutional Engagement Level
United States	University of California, Davis	AASHE STARS, UI GreenMetric	Federal and state-level funding, sustainability mandates	High (Integrated in governance, curriculum, infrastructure)
Netherlands	Wageningen University	UI GreenMetric, THE Impact Rankings	National climate neutrality targets, policy-driven support	Very High (Full climate-neutral campus achieved)
Singapore	National University of Singapore (NUS)	LEED, BCA Green Mark	Government funding, green building codes	High (Multiple green-certified buildings and active R&D)
Saudi Arabia	King Saud University, KAUST	SEEC audit programs, UI GreenMetric	Vision 2030 initiatives, Ministry of Education partnerships	Moderate (Pilot programs and selective implementation)
United Arab Emirates	Masdar Institute, Khalifa University	Estidama, UI GreenMetric	Green building regulations, national R&D support	Moderate (Selective projects and sustainability labs)
Malaysia	Universiti Sains Malaysia	UI GreenMetric, Green Campus Rating	Ministry of Higher Education support and funding schemes	Moderate to High (Strong sustainability education focus)
Germany	Technical University of Munich	DGNB, UI GreenMetric	Federal environmental regulations, EU targets	High (Sustainability integrated in planning and research)

3. Methodology

This study employs a qualitative comparative analysis to investigate the operational components of green campus initiatives within higher education institutions [24]. Drawing on international sustainability frameworks such as the UI GreenMetric World University Rankings, AASHE STARS, and the United Nations Sustainable Development Goals (particularly Goals 4, 11, and

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13), the research identifies key performance areas that define green campus practices globally (Table 2) [25].

The analysis focuses on three dimensions of green campus operations: environmental management, institutional integration, and community engagement [26]. These categories were derived by synthesizing global programs' best practices, including the U.S. Department of Energy's Better Buildings Challenge and regionally significant initiatives such as KAUST's Net Zero Campus Plan in Saudi Arabia.

Using this classification framework, case studies from selected universities were analyzed through institutional sustainability reports, official energy audits, and third-party rankings [27]. The evaluation examined the extent to which environmental efficiency measures, policy integration, and stakeholder involvement were embedded in campus operations. This approach enables a structured comparison of green campus maturity across international contexts to inform practical strategies for implementation in similar environments.

Table 2. Green Campus Operational Elements

Category	Operational Element	Performance Indicator
Environmental Management	Energy efficiency and carbon reduction	Annual energy use intensity (kWh/m²), GHG emissions (tCO2e)
	Water conservation and recycling	Water use per capita, % of recycled water use
	Waste management and pollution control	Recycling rate (%), hazardous waste tracking
Institutional Integration	Green building design and certification	Number of LEED/GSAS certified buildings, green construction ratios
	Sustainability in curriculum and research	Number of courses and research projects on sustainability
	Institutional sustainability policies and governance	Existence of a sustainability office, policy documents, and budget allocation
Community Engagement	Student-led sustainability initiatives	Number of active student groups and projects
	Collaboration with local governments	Joint programs or MOUs with municipal stakeholders
	Sustainable transportation and outreach programs	Mode share of non-motorized or public transport, annual outreach events

4. Analysis

4.1. Green Campus Case Studies

This study conducts a comparative analysis of green campus development by selecting internationally recognized institutions and prominent regional examples demonstrating substantial progress in sustainability integration within higher education environments. The objective is to evaluate green campus initiatives' structural, operational, and programmatic elements and derive applicable insights for the Saudi Arabian context.

Internationally, the University of Cambridge in the United Kingdom and Harvard University in the United States were selected due to their comprehensive green campus frameworks, institutional governance models for sustainability, and long-standing commitments to environmental stewardship. Through its Office for Sustainability, Harvard University has implemented a university-wide Climate Action Plan that led to a 30% reduction in greenhouse gas emissions from a 2006 baseline, despite significant growth on campus. Likewise, the University of Cambridge has adopted a Science-Based Target aligned with the Paris Agreement and has committed to achieving net-zero carbon emissions by 2038. It invests in low-carbon building design, integration of renewable energy, and campus-wide sustainability literacy programs.

For the regional case, this study examines King Abdullah University of Science and Technology (KAUST), located in Thuwal, Saudi Arabia, representing a pioneering model for green campus development in the Gulf region. KAUST was designed as a sustainable research hub from its

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inception and has incorporated advanced energy systems, water recycling technologies, and environmental monitoring infrastructure. The entire campus operates under a LEED Platinum-certified master plan, and its solar PV installations generate over 3.3 MW of renewable energy annually (KAUST Sustainability Report, 2023). Furthermore, the university's centralized seawater cooling system reduces electricity consumption by approximately 20% compared to conventional HVAC systems in the region's climate.

Unlike earlier models of green campuses, which emphasized symbolic initiatives, these three institutions demonstrate systemic transformations in sustainability governance, technical infrastructure, academic integration, and stakeholder engagement. They have embedded sustainability into their operational protocols, institutional policies, and educational frameworks, thus serving as replicable models for universities in Saudi Arabia aiming to align with Vision 2030 and the Saudi Green Initiative.

Table 3 provides a comparative analysis of the selected green campus cases, focusing on key dimensions such as energy performance, renewable integration, sustainability policy, water conservation, community engagement, and academic integration.

Table 3. Green Campus Case Studies

Category	Operational Element	Harvard University	University of Cambridge	KAUST
Environmental Management	Energy efficiency and carbon reduction	30% GHG reduction since 2006	Net-zero carbon target by 2038	Seawater cooling and 3.3 MW solar PV
	Water conservation and recycling	Rainwater harvesting systems	Greywater recycling infrastructure	100% recycled wastewater reuse
	Waste management and pollution control	Zero Waste Plan implementation	Centralized campus waste audits	Advanced waste segregation and reporting
Institutional Integration	Green building design and certification	LEED-certified buildings across campus	Passive House building standards	LEED Platinum-certified campus master plan
	Sustainability in curriculum and research	Interfaculty sustainability research grants	Integrated sustainability curriculum modules	Research centers aligned with the UN SDGs
	Institutional sustainability policies and governance	The Sustainability Office was established in 2008	Formal sustainability governance charter	Sustainability embedded in strategic plan
Community Engagement	Student-led sustainability initiatives	Resource Efficiency Program	Green Impact student teams	Student Sustainability Ambassador Program
	Collaboration with local governments	Boston City Planning Partnership	Local council collaboration on sustainability	Red Sea coastal ecosystem restoration
	Sustainable transportation and outreach programs	Electric campus shuttle fleet	Extensive cycling infrastructure	Pedestrian-oriented campus design

4.2. Deriving Implications Applicable to Saudi Green Campuses

Based on the comparative analysis of global and regional green campus case studies—including Harvard University, the University of Cambridge, and King Abdullah University of Science and Technology (KAUST)—several implications can be drawn for advancing green campus development within Saudi Arabia. These insights are categorized into three dimensions: management, environmental performance, and social engagement.

From a management perspective, the analysis reveals that successful green campus operations require dedicated governance structures with clearly defined mandates. Institutions like Harvard and KAUST have established sustainability offices fully integrated into campus planning, operations, and academic oversight. However, Saudi universities' sustainability initiatives are often managed ad hoc without dedicated units, formal budgets, or cross-departmental collaboration. There is a pressing need to establish permanent sustainability offices within Saudi

universities, equipped with full-time personnel, technical expertise, and cross-functional authority. Furthermore, while significant financial resources are allocated to Saudi higher education, including an annual education budget of over SAR 192 billion as of 2023, there is limited reinvestment of operational cost savings or research grants into scaling green campus programs. Institutional policies should prioritize reinvesting energy savings and green project revenues into sustainability innovation and student engagement programs.

Regarding the environmental dimension, the absence of a nationally standardized green campus evaluation system in Saudi Arabia presents a barrier to consistent goal setting and performance tracking. By contrast, the United States utilizes the STARS (Sustainability Tracking, Assessment & Rating System) framework, and the United Kingdom applies the Green League and THE Impact Rankings to benchmark progress. Saudi Arabia would benefit from a localized sustainability assessment framework tailored to the region's climatic, cultural, and infrastructural conditions. This could be developed under the guidance of the Saudi Energy Efficiency Center (SEEC) or the National Center for Environmental Compliance (NCEC), integrating metrics such as energy intensity (kWh/m^2), carbon emissions (tCO_2e/year), LEED or GSAS certification rates, and campus-wide water reuse ratios.

Regarding the social aspect, international case studies underscore the importance of broad stakeholder participation. Cambridge and Harvard operate volunteer-based sustainability programs that include faculty, students, and local communities. In Saudi Arabia, universities remain relatively isolated from their surrounding communities, and student engagement in sustainability is limited to top-down awareness campaigns. To address this, Saudi universities should develop incentive-driven initiatives such as green innovation hackathons, sustainability ambassador programs, and joint urban ecology projects with municipal authorities. This participatory model can be supported through policy mechanisms that are aligned with Vision 2030's community development and citizen engagement objectives. The operationalization of green campuses in Saudi Arabia must transition from fragmented initiatives to institutionalized, data-driven, and community-integrated systems. The lessons drawn from global best practices provide a strategic roadmap for Saudi universities to implement high-impact sustainability policies, establish credible evaluation tools, and foster inclusive participation in campus greening efforts.

5. Discussion

The comparative analysis of Harvard, Cambridge, and KAUST highlights the critical role of integrated sustainability governance in driving effective green campus implementation. While KAUST is a regional exemplar with its LEED Platinum-certified master plan, seawater cooling system, and solar PV infrastructure, such practices remain isolated mainly in Saudi Arabia. Most Saudi universities lack dedicated sustainability units, cross-departmental coordination, or reinvestment mechanisms to support long-term environmental initiatives.

In contrast, global institutions have institutionalized sustainability through robust governance structures, curriculum integration, and active stakeholder participation. Harvard's 30% emissions reduction and Cambridge's net-zero target illustrate how data-driven planning, campus-wide policies, and interdisciplinary engagement can translate national climate goals into measurable campus outcomes. The absence of a standardized Saudi-specific assessment tool limits the ability of local institutions to set regionally relevant benchmarks and track progress toward Vision 2030 objectives.

Moreover, while global universities emphasize participatory approaches involving students and local communities, Saudi campuses rely primarily on top-down campaigns with limited grassroots engagement. To bridge this gap, universities should adopt incentive-based models that foster voluntary participation, such as sustainability ambassador programs and joint municipal initiatives.

Building a localized, data-driven, and inclusive green campus framework will be essential for aligning higher education with Saudi Arabia's national sustainability agenda.

6. Conclusion

This study has comprehensively examined green campus implementation through the comparative analysis of leading international and regional institutions, including Harvard University, the University of Cambridge, and King Abdullah University of Science and Technology (KAUST). The research has identified critical success factors and practical strategies applicable to the Saudi Arabian higher education context by evaluating their operational models across environmental management, institutional integration, and community engagement.

The findings reveal that while Saudi universities have initiated several sustainability-oriented projects, these efforts often lack cohesive policy frameworks, dedicated governance structures, and performance monitoring systems. In contrast, international case studies demonstrate how sustainability can be embedded across campus operations, academic curricula, and community partnerships through well-established institutional mechanisms and accountability tools. To bridge this gap, Saudi universities must develop localized sustainability assessment frameworks, establish permanent sustainability offices, and promote inclusive stakeholder engagement.

This paper emphasizes that transforming Saudi campuses into sustainable environments requires more than technical upgrades—it demands a systemic shift toward integrated, data-driven, and participatory sustainability governance. Aligning green campus strategies with Vision 2030 and national climate commitments offers a timely opportunity for Saudi universities to lead in environmental innovation, educational transformation, and societal impact at regional and global levels.

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Optimizing Fenestration Strategies for Residential Energy Reduction: A Comparative Study of Five Climatic Zones

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Keywords: Window-to-Wall Ratio, Energy-Efficient Housing, Hot-Arid Climate Design, Building Energy Simulation, Fenestration Performance

Abstract. This study investigates the impact of window design parameters—specifically window-to-wall ratio (WWR), orientation, and glazing performance—on the annual energy consumption of residential buildings across five climatic regions, focusing on Saudi Arabia's hot-arid environment. A parametric analysis was conducted using COMFEN 5.0.33 simulation software to evaluate cooling and lighting energy demands under varying WWR configurations (25%, 50%, and 75%) and four cardinal orientations. Results indicate that increasing the WWR to 75% in Riyadh led to a 42% rise in annual energy use, predominantly due to increased cooling loads. Tehran showed dual seasonal sensitivity, while tropical locations such as Singapore exhibited consistently high cooling demand across all orientations. The findings emphasize the need for region-specific, performance-based window design strategies to optimize thermal performance and visual comfort. This research supports energy efficiency targets outlined in Saudi Vision 2030 and highlights simulation as a critical tool for sustainable housing design in climate-sensitive regions.

1. Introduction

The transition toward energy-efficient and green smart buildings has become a critical global priority, particularly as the building sector continues to be one of the most resource-intensive industries worldwide [1]. According to recent estimates from the International Energy Agency, buildings account for approximately 36% of global final energy consumption and nearly 39% of carbon dioxide emissions [2]. Within this context, operational energy, particularly required for cooling, heating, and lighting, represents the most extensive energy use in residential and commercial buildings [3]. In hot-arid regions such as the Kingdom of Saudi Arabia, cooling alone constitutes up to 70% of total residential electricity demand, driven mainly by extreme summer temperatures that frequently exceed 45°C [4].

Among building envelope components, window systems are especially influential in energy performance [5]. While windows contribute significantly to indoor environmental quality by enabling natural daylight, ventilation, and visual transparency, their thermal insulation properties are considerably inferior, estimated to be five times lower than those of insulated opaque walls [6]. Consequently, between 20% and 40% of a building's total energy loss is attributed to window

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systems, making their design and specification a central focus of energy-efficient building strategies [7]. In hot climates, high solar heat gain through poorly performing windows directly exacerbates cooling loads and peak energy demand, emphasizing the importance of optimizing fenestration systems as part of a broader low-energy design approach [8].

On a global scale, the 2013 UN-Habitat report emphasized the intensifying demand for urban-scale housing, particularly in regions undergoing post-conflict reconstruction or rapid economic growth [9]. The urgency lies in the sheer volume of housing required in emerging economies. In contrast, in developed or politically stable nations, the emphasis has shifted toward integrating low-energy performance standards into new residential developments [10]. Saudi Arabia finds itself at the intersection of these two trajectories [11]. With a young and growing population, rapid urbanization, and a national push toward sustainable development under Vision 2030 and the Green Saudi Initiative, there is a pressing need to supply large volumes of urban housing that are not only affordable but also energy efficient [12].

Accordingly, this study aims to explore the applicability of low-energy housing models in the Saudi Arabian context through simulation-based analysis of window design strategies. This research investigates the potential for reducing cooling energy demand while maintaining visual comfort and indoor environmental quality by assessing the impact of glazing performance, orientation, and design variation across different climatic zones. The simulation framework enables a comparative evaluation across multiple scenarios, offering empirical data to support evidence-based design and policy recommendations tailored to hot-arid urban environments.

2. Simulation Input Data

To evaluate the impact of window design on thermal energy demand in hot-arid regions, a simulation-based energy analysis was conducted using a standardized building module, regional climate datasets, and multiple façade design scenarios [13]. The parameters were selected to represent typical residential developments in Saudi Arabia and to allow comparison across diverse climatic zones [14]. The study employs a parametric modeling approach to assess the interaction between window-to-wall ratio, solar orientation, and glazing performance, using COMFEN 5.0.33 developed by Lawrence Berkeley National Laboratory (LBNL).

2.1. Building Configuration and Envelope Specifications

The base model was configured as a single-zone space with dimensions of 4.57 meters in depth, 6.10 meters in width, and a floor-to-ceiling height of 3.05 meters [15]. These proportions align with standard unit modules used in mid-rise residential projects across Saudi cities such as Riyadh, Dammam, and Jeddah [16]. The envelope performance was modeled using thermal transmittance (U-values) derived from SBC 601 and 602, reflecting local code requirements post-2018 revisions for energy efficiency [17].

The external wall assembly was assigned a U-value of 0.26 W/m²·K, the roof 0.15 W/m²·K, and the floor slab 0.20 W/m²·K, consistent with insulation levels recommended under the Saudi Energy Efficiency Program [18]. Fenestration systems were modeled with a U-value of 0.85 W/m²·K, a solar heat gain coefficient (SHGC) of 0.46, and visible light transmittance (Tvis) of 0.62, reflecting double-glazed low-e coated units commonly deployed in new Saudi housing. The glazing model enables daylight penetration while limiting solar radiation, thus addressing dual objectives of energy conservation and occupant visual comfort.

2.2. Climate Data Input for Multi-Regional Analysis

To position the findings within a broader global context, the simulation incorporated climate data from five countries: Saudi Arabia (Riyadh), Sri Lanka (Colombo), Venezuela (Caracas), Singapore, and Iran (Tehran). These sites represent a spectrum of Köppen climate types, ranging from arid desert (BWh) to tropical rainforest (Af) and semi-arid steppe (BSk), enabling

comparative assessment of window performance under diverse temperature and humidity conditions [19].

The EnergyPlus Weather (EPW) file for Riyadh indicates annual solar radiation levels exceeding 2,200 kWh/m², extreme summer temperatures often above 45°C, and a prolonged cooling season lasting over 8 months [20]. These climatic extremes amplify the relevance of façade strategies, especially fenestration design, in reducing internal heat gains [21]. The imported EPW files were sourced from the U.S. Department of Energy and validated against local meteorological data to ensure consistency [22]. Temperature distributions, solar angles, and humidity variations across all sites were analyzed, and a comparative climate chart is presented in Table 1 and visualized in Figure 1.

Table 1. Analysis of Input Climate Data

Parameter	Saudi Arabia (Riyadh)	Sri Lanka (Colombo)	Venezuela (Caracas)	Singapore	Iran (Tehran)
Köppen Classification	BWh (Hot Desert)	Af (Tropical Rainforest)	Aw (Tropical Savanna)	Af (Tropical Rainforest)	BSk (Cold Semi-Arid)
Longitude	46.6753° E	79.8612° E	-66.9036° W	103.8198° E	51.3890° E
Latitude	24.7136° N	6.9271° N	10.4806° N	1.3521° N	35.6892° N
Yearly Direct Solar Radiation (Wh/m²)	2,200,000	1,530,000	1,610,000	1,580,000	1,950,000

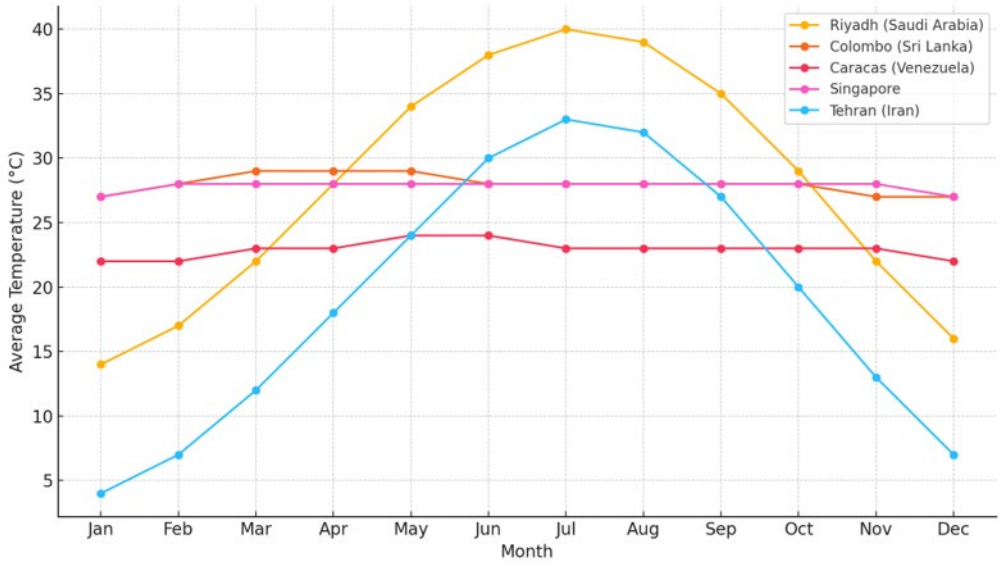


Figure 1. Principles of Solar Control Window Films

2.3. Parametric Simulation: Window-to-Wall Ratio and Orientation Variables

The simulation assessed three window-to-wall ratio (WWR) levels—25%, 50%, and 75%—to evaluate how variations in glazing area affect energy consumption [23]. A 25% WWR was selected as the baseline, reflecting typical practice in Saudi apartment developments, while 50% and 75% were tested as high-exposure configurations to capture performance extremes. These variations simulate architectural decisions significantly influencing cooling loads and daylight availability [24].

Four façade orientations—north, south, east, and west—were analyzed independently to evaluate directional sensitivity [25]. In the Riyadh climate, east and west façades typically experience higher solar exposure during morning and late afternoon hours, leading to increased

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cooling loads [26]. South-facing windows may benefit from overhang shading strategies due to the high solar altitude, while north-facing windows, though thermally less exposed, still contribute to daylighting performance. COMFEN was used as the simulation engine due to its façade-specific modeling capabilities, energy balance analysis functions, and compatibility with DOE-2 and EnergyPlus engines. The software enables performance comparison across glazing options, solar control measures, and shading devices.

The simulation outputs included annual cooling energy demand (kWh/m²), solar heat gain, daylight availability metrics, and indoor operative temperature fluctuations [27]. These outputs were synthesized to identify optimal configurations for minimizing cooling loads while maximizing visual comfort in Saudi Arabia's climate. The findings from this parametric analysis serve as a basis for practical window design guidelines and input parameters for further dynamic whole-building simulations in future studies.

3. Methodology

This study employed simulation-based analysis to evaluate the impact of window design on energy consumption across five climate zones, focusing on Saudi Arabia's hot-arid context. A standardized residential unit model (4.57 m × 6.10 m × 3.05 m) was developed to reflect typical Saudi apartment layouts. Envelope thermal properties were set according to Saudi Building Code SBC 601/602, including U-values of 0.26 W/m²·K for walls, 0.15 for roofs, 0.20 for floors, and 0.85 for windows (SHGC: 0.46; Tvis: 0.62).

Climatic data were sourced from EnergyPlus weather files for Riyadh, Colombo, Caracas, Singapore, and Tehran. Window-to-wall ratios of 25%, 50%, and 75% were tested, with façades oriented in four cardinal directions. The simulations used COMFEN 5.0.33, focusing on annual cooling demand and solar heat gain. The methodology enables comparative energy performance analysis to inform optimal window design for sustainable housing in Saudi Arabia and similar climates.

4. Analysis

4.1. Building Energy Consumption Analysis

To assess the performance impact of fenestration design on building energy consumption, a dynamic simulation analysis was conducted for five climatically diverse locations: Riyadh (Saudi Arabia), Tehran (Iran), Colombo (Sri Lanka), Caracas (Venezuela), and Singapore. The analysis was based on a parametric variation of window-to-wall ratios (25%, 50%, and 75%) and four façade orientations (north, east, south, and west), utilizing COMFEN 5.0.33 to model the annual energy demands for cooling, heating, and lighting. These simulations reflect the interplay between glazing configuration and climatic load profiles, producing region-specific performance benchmarks for design decision-making.

In Saudi Arabia (Riyadh), where a hot desert climate (BWh) dominates, the simulation confirmed that cooling energy accounts for the overwhelming majority—over 80%—of total annual building energy consumption. The simulation showed that as the window-to-wall ratio increased from 25% to 75%, total energy use rose by 42%, particularly in east- and west-facing façades that receive intense solar exposure during morning and afternoon hours. This sharp increase is attributed to high direct solar radiation levels exceeding 2,200 kWh/m² per year and prolonged summer seasons extending over eight months. Notably, the baseline 25% WWR model outperformed others in all orientations, confirming that restrained window sizing coupled with spectrally selective glazing offers the most thermally efficient envelope strategy for Saudi residential typologies. These findings emphasize the importance of fenestration control in the early design stages of apartment housing, especially in achieving compliance with SBC 602 energy performance requirements and reducing cooling-related peak loads on the national grid.

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The simulation in Iran (Tehran), classified under a cold semi-arid climate (BSk), indicated the highest variability in total building energy use across window-to-wall ratios. Glazing increased from 25% to 75%, and annual energy consumption nearly doubled, with heating and cooling loads affected. While cooling dominates in the hotter months, there was also a noticeable heating demand—approximately 3% of the annual load—during winter. This bimodal load profile requires that window systems in Tehran be designed not only for solar rejection in summer but also for insulation during winter. The energy-sensitive nature of the window area in Tehran suggests that dynamic glazing technologies or seasonal shading systems could be especially beneficial in transitional climate zones.

For Venezuela (Caracas), located in a tropical savanna climate (Aw), the influence of window size on energy use was significant, particularly for cooling. As in Sri Lanka and Singapore, the variation in cooling load across different window-to-wall ratios was substantial, though not as extreme as in Riyadh or Tehran. The energy model showed that as glazing increased, cooling loads rose consistently, while lighting energy showed minimal fluctuation due to abundant natural daylight throughout the year. These trends reflect the challenge of thermal comfort management in humid tropical climates, where high latent heat from humidity compounds the impact of direct solar gain. While reducing window size helps moderate cooling loads, such a strategy must be balanced with daylighting and natural ventilation goals, particularly in housing projects targeting passive design strategies.

The simulation revealed more balanced directional performance in Sri Lanka (Colombo), which has a tropical rainforest climate (Af). North and south orientations exhibited slightly lower energy demands than east and west façades, but overall, the difference in annual energy use by orientation was modest. Cooling remained the dominant energy use category, although at a lower intensity than in Riyadh or Singapore. Importantly, Colombo's performance suggests that reducing glazing on east and west orientations—where solar gain is more intense—can produce measurable savings while maintaining daylighting quality. Designers in tropical zones may benefit from optimizing orientation and shading devices more than radically altering glazing ratios, which can compromise visual comfort.

The simulation reported the highest total annual energy consumption in Singapore among the five locations, despite a relatively constant temperature profile throughout the year. Cooling accounted for more than 85% of energy use, and larger glazing areas translated directly into higher internal gains and mechanical cooling loads. With window-to-wall ratios of 75%, buildings experienced a significant rise in peak cooling demand, highlighting the critical need for high-performance glazing and external shading strategies in equatorial regions. Due to consistently high humidity and solar exposure, design strategies focused solely on minimizing window area may be insufficient. Instead, integrated solutions such as low-SHGC glazing, insulated spandrel panels, and vertical shading fins become essential to mitigate solar heat gain without compromising indoor environmental quality.

Across all five regions, the results reinforce that window design—specifically size, orientation, and thermal properties—plays a critical role in building energy performance. In Saudi Arabia, minimizing glazing on solar-exposed façades and using advanced window systems can significantly lower cooling loads, helping to meet Vision 2030 objectives for reduced building energy intensity and improved environmental sustainability. The findings also suggest that a one-size-fits-all glazing solution is inadequate across regions. Instead, localized climate-responsive design must guide fenestration decisions to balance energy efficiency, daylighting, and occupant comfort.

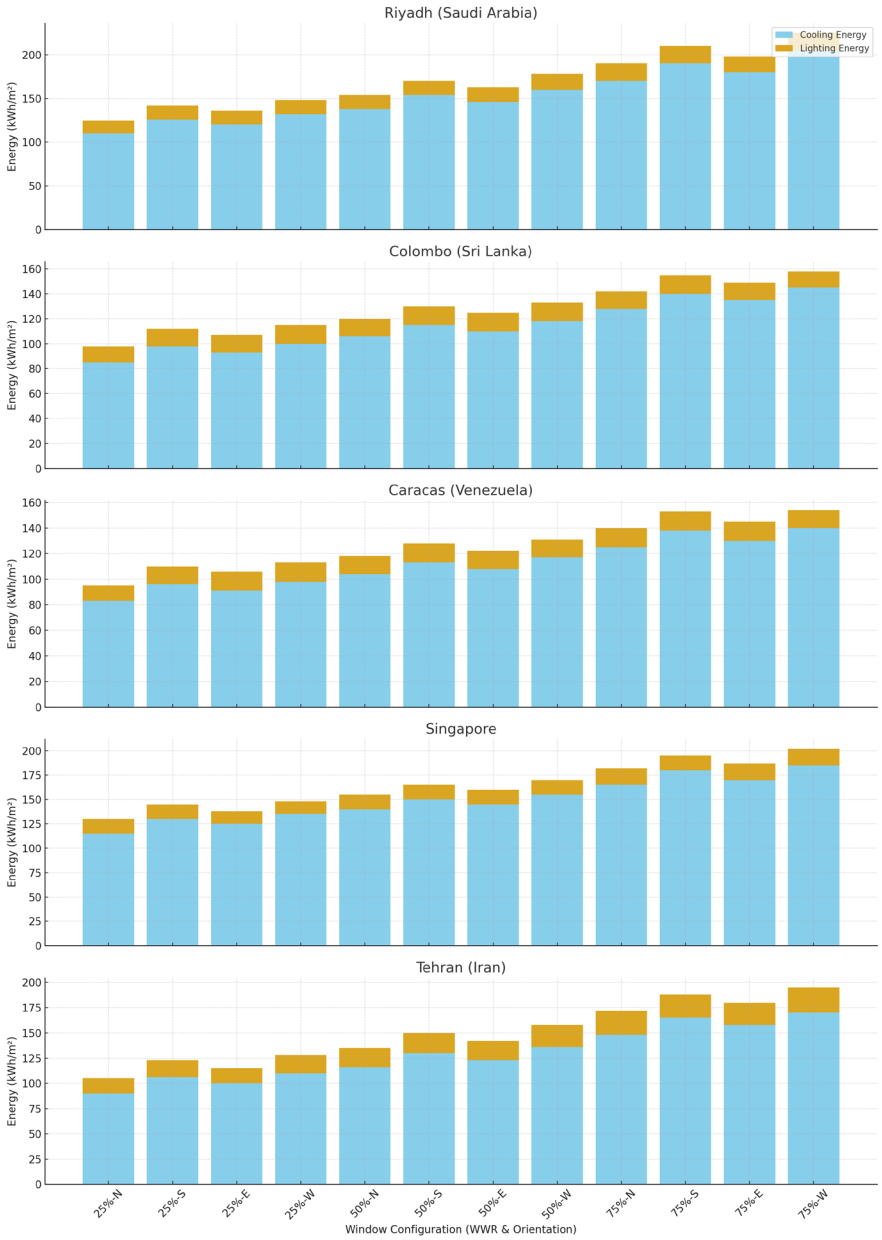


Figure 2. Comparison of annual building energy consumption by input variables

5. Discussion

This study demonstrates that building energy consumption is highly sensitive to window-to-wall ratio (WWR) variations, orientation, and glazing performance, especially in hot-arid climates like Saudi Arabia. In Riyadh, increasing the WWR from 25% to 75% resulted in a 42% rise in annual energy use, primarily driven by cooling loads, which account for over 80% of total energy consumption. East and west façades showed the highest solar exposure, emphasizing the need for selective glazing and optimized orientation in the design of residential units. These findings directly support Saudi Arabia's Vision 2030 objectives by highlighting passive design strategies that reduce peak energy demand.

In contrast, cities like Tehran showed dual seasonal loads—cooling in summer and moderate heating in winter—where higher WWR nearly doubled total energy use, suggesting that adaptable or insulated glazing solutions are more appropriate. Meanwhile, tropical cities such as Singapore and Colombo exhibited consistently high cooling loads with less orientation sensitivity, indicating

that window design should focus on thermal rejection and integration with shading systems rather than size alone. Overall, the results confirm that region-specific, performance-based window strategies are essential to improve building energy efficiency across diverse climates.

6. Conclusion

This study explored the impact of window design variables—specifically window-to-wall ratio (WWR), orientation, and glazing performance—on the energy performance of residential buildings in five climatically diverse regions, with a primary focus on Saudi Arabia's hot-arid context. Using simulation-based analysis with COMFEN 5.0.33, the results demonstrated that increases in WWR significantly raise annual cooling energy demand, particularly in solar-exposed façades. In Riyadh, the 75% WWR configuration resulted in a 42% increase in energy consumption compared to the baseline, highlighting the need for optimized fenestration strategies in hot climates.

Findings indicate that region-specific glazing solutions are essential, as climatic sensitivity varies across locations. While Riyadh and Singapore require maximum solar control due to year-round cooling demands, Tehran's dual-season load profile suggests the importance of insulation and shading. The study confirms that performance-based window design—tailored to climate and orientation—is critical for achieving energy efficiency goals, supporting sustainable housing initiatives under Saudi Vision 2030, and meeting global building decarbonization targets.

In future applications, integrating dynamic glazing technologies and responsive façade systems may optimize energy performance, particularly in climates with fluctuating thermal loads. Moreover, embedding simulation-based evaluation into the early stages of design can enhance decision-making and promote code-compliant, low-energy architecture. These findings support building-level improvements and inform broader retrofit strategies and national energy efficiency policies.

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Revisiting Sustainable Neighborhood Research: A Critical Mapping of Recent Literature Against UN-Habitat's Five Design Objectives

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Keywords: Housing, Sustainable Development; Neighborhood, UN-Habitat, Urban Design

Abstract. This paper conducted a systematic literature review of sustainable neighborhood design considering the UN-Habitat's sustainable neighborhood objectives. These objectives are compactness, connectivity, inclusiveness, vibrance, and resilience. Using Scopus database and PRISMA procedures, the study identified and analyzed 46 eligible peer reviewed articles in this regard. The papers were coded and analyzed based on the UN-Habitat's sustainable neighborhood design objectives they cover. The findings revealed that the literature on sustainable neighborhoods primarily concentrates on connectivity and compactness, while vibrance, inclusivity and resilience received less attention. Most studies emphasized physical and spatial design strategies, particularly walkability, street networks, and mixed land use, whereas themes such as barrier-free environments, safe and affordable housing, and climate-responsive design were less frequently addressed. This shows a clear tendency towards spatial planning approaches, with limited engagement in social, economic, and institutional dimensions. By reclassifying existing studies according to the five UN-Habitat sustainable neighborhood objectives, this research makes these gaps visible and clarifies where the UN-Habitat agenda is being advanced and where it remains only partially addressed.

Introduction

Neighborhood is a common framework of urban development, where built form, services, and social relations shape people's well-being. It combines spatial and social dimensions, to enable everyday interaction and access to services [1]. This makes neighborhood scale a viable platform for advancing urban sustainability initiatives targeting sustainable land use, mobility, public space, and social infrastructure [2]. Sustainable neighborhoods are districts whose physical form and systems reduce resource use and emissions while enabling health, equity, and economic opportunity [3].Rating systems like LEED for Neighborhood Development and BREEAM Communities operationalize this by evaluating site selection, connectivity, transit access, land use mix, green infrastructure, energy, and community processes, moving beyond single buildings to district-scale outcomes [4]. UN-Habitat's "MY Neighborhood" initiative offers design recommendations for sustainable neighborhoods under five objectives: compact, connected, inclusive, vibrant, and resilient. Using these five objectives to guide neighborhood design should be done in an integrative way across the different sectors and scales [5]. This means creating compact form with adequate density and land use mix, connected multimodal networks, inclusive access, vibrant public spaces and urban life, and resilient systems that prepare for and adapt to shocks and stresses [6]. Similarly, the Our City Plans toolbox reinforces this integrative logic by requiring neighborhood designs and directives to explicitly reference the five objectives, thereby

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facilitating alignment with Sustainable Development Goal (SDG) 11. This framing connects neighborhood-scale interventions to citywide visions to achieve the targets of SDG 11 and enable decision makers to prioritize investments [5].

Accordingly, this study conducts a systematic literature review of sustainable neighborhood design through the lens of the five UN-Habitat' sustainable neighborhood design objectives and strategies *Fig.1* to identify which are most frequently addressed and to map and synthesize the key neighborhood-scale design strategies associated with each, offering guidance for future research and practice. To achieve this aim, this study employed a systematic literature review to answer the following research questions:

Which of the five objectives (compact, connected, inclusive, vibrant, resilient) and their related design strategies are most frequently addressed in neighborhood design studies?

What are the current research gaps that require more future attention?

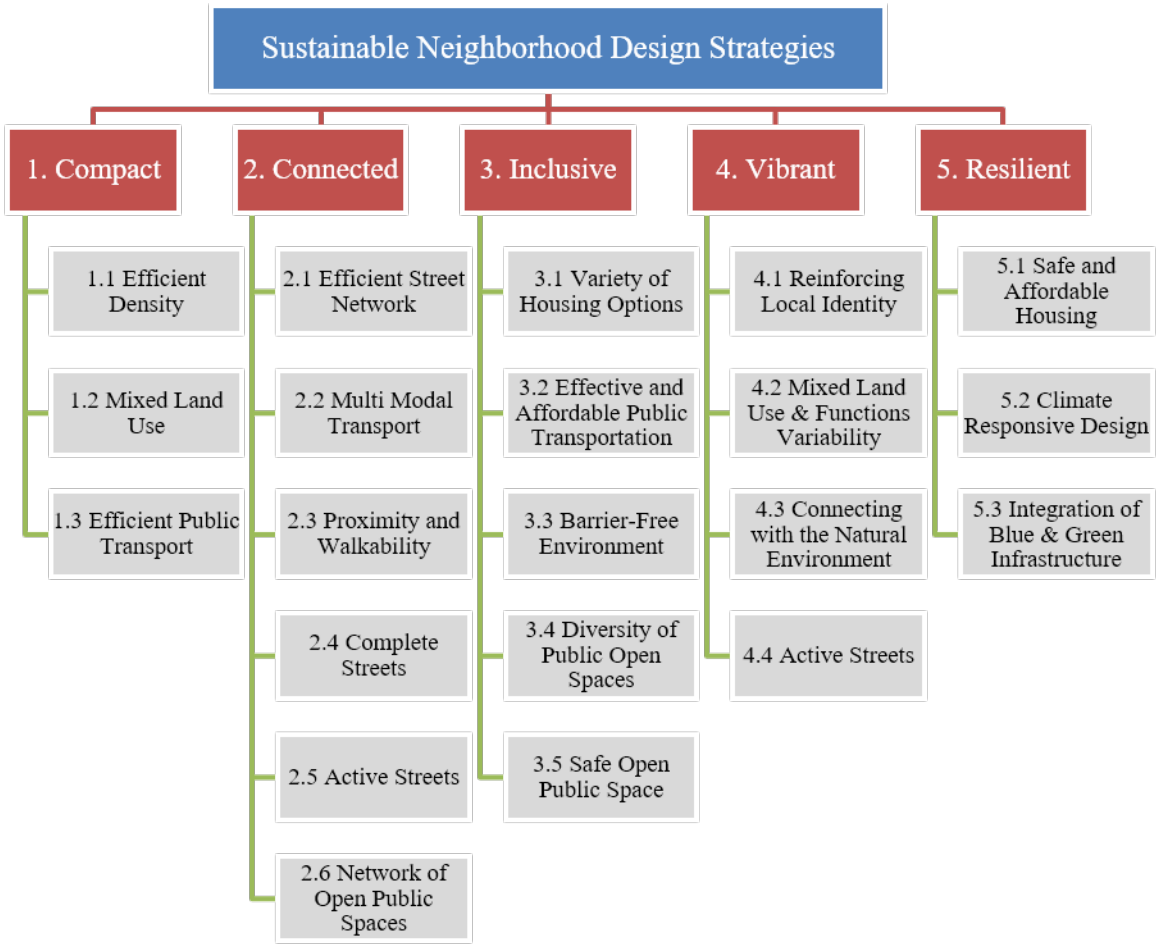


Fig. 1: Sustainable neighborhood design strategies, reproduced from [5].

Materials and Methods

This systematic review utilized the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta Analysis) methodology to gather the scholarly sources related to the UN-Habitat objectives of sustainable neighborhood design. Scopus was selected as the primary search database because of its broad coverage of peer-reviewed journals in planning, architecture, and environmental studies. The search targeted titles, abstracts, and keywords using a two-step Boolean strategy, as shown in Table 1. The combined search initially returned 4013 documents. Results were then refined using Scopus filters to keep only studies relevant to sustainable neighborhood and urban design. The search was limited to the last 10 years (2016–2025) and to

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journal articles and review papers in English. Subject areas were restricted to engineering, social sciences, and environmental science. Additional refinement was carried out using indexed keywords such as neighborhood, neighbourhood, urban planning, urban design, sustainable development, neighborhood design, neighborhood planning, urban growth, urban development, urban area, resilience, and urban renewal. After applying all filters, 483 journal papers remained for screening.

Table 1: Scopus research strings used in this study

1.	Primary Search strings	TITLE-ABS-KEY (neighborhood design OR "neighbourhood design" OR "neighborhood planning" OR "neighbourhood planning" OR "district design" OR "community design")
2.	Secondary Search Strings	TITLE-ABS-KEY (UN-Habitat OR "Our City Plans" OR "My Neighbourhood" OR "My Neighborhood" OR "five city objectives" OR "compact city" OR "compact neighborhood" OR "compact neighbourhood" OR "connected city" OR "connected neighborhood" OR "connected neighbourhood" OR "inclusive city" OR "inclusive neighborhood" OR "inclusive neighbourhood" OR "vibrant city" OR "vibrant neighborhood" OR "vibrant neighbourhood" OR "resilient city" OR "resilient neighborhood" OR "resilient neighbourhood")

The Screening process was conducted in two stages. Firstly, titles and abstracts of the 483 papers were screened to assess their relevance to sustainable neighborhoods and the UN-Habitat sustainable neighborhood design objectives. At this stage, irrelevant papers were excluded. This step reduced the set to 65 papers for full text review. In the second stage, full texts of the 65 short-listed papers were examined. Papers were included if they address neighborhood-scale or district-scale design or planning, focus on sustainable neighborhoods or sustainable urban development, and discuss at least one of the UN-Habitat's sustainable neighborhood design strategies. Papers were excluded if they were out of the selected subject areas, did not discuss sustainable neighborhoods or urban design, did not engage with any of the five UN-Habitat's sustainable neighborhood design strategies, or had inaccessible full text. This process led to the exclusion of 22 papers, resulting in a final sample of 43 peer-reviewed studies. The overall selection process is illustrated in Fig. 2, and the final set of reviewed studies is listed in Table 2.

Findings

Research trends. The co-occurrence map *Fig.3* highlights the terms that appear most often across the 46 reviewed papers. The largest nodes "accessibility," "urban planning," "mixed use," "school," and "green space" show that the literature is dominated by classic built-environment research problems including how people reach everyday destinations and how land use is mixed or distributed. Another cluster linking "physical activity," "social capital," and "neighborhood attachment," indicates a strong health and community strand, while a separate chain around "policy" and "association" points to institutional and governance concerns. As for year of publication, *Fig.4* shows that research on sustainable neighborhoods and the UN-Habitat city objectives fluctuates between 7% and 16% from 2016 to 2025. After 2020, the percentages stabilized around 8% through 2025. Regarding geographical distribution, nearly one-fifth of the studies were conducted in the United States (21%), followed by China (12%) and Australia (12%), indicating that the literature is concentrated in high-income or rapidly urbanizing countries. Methodologically, about half of the studies adopted quantitative approaches (53%), while 28% used mixed methods and only 19% were purely qualitative.

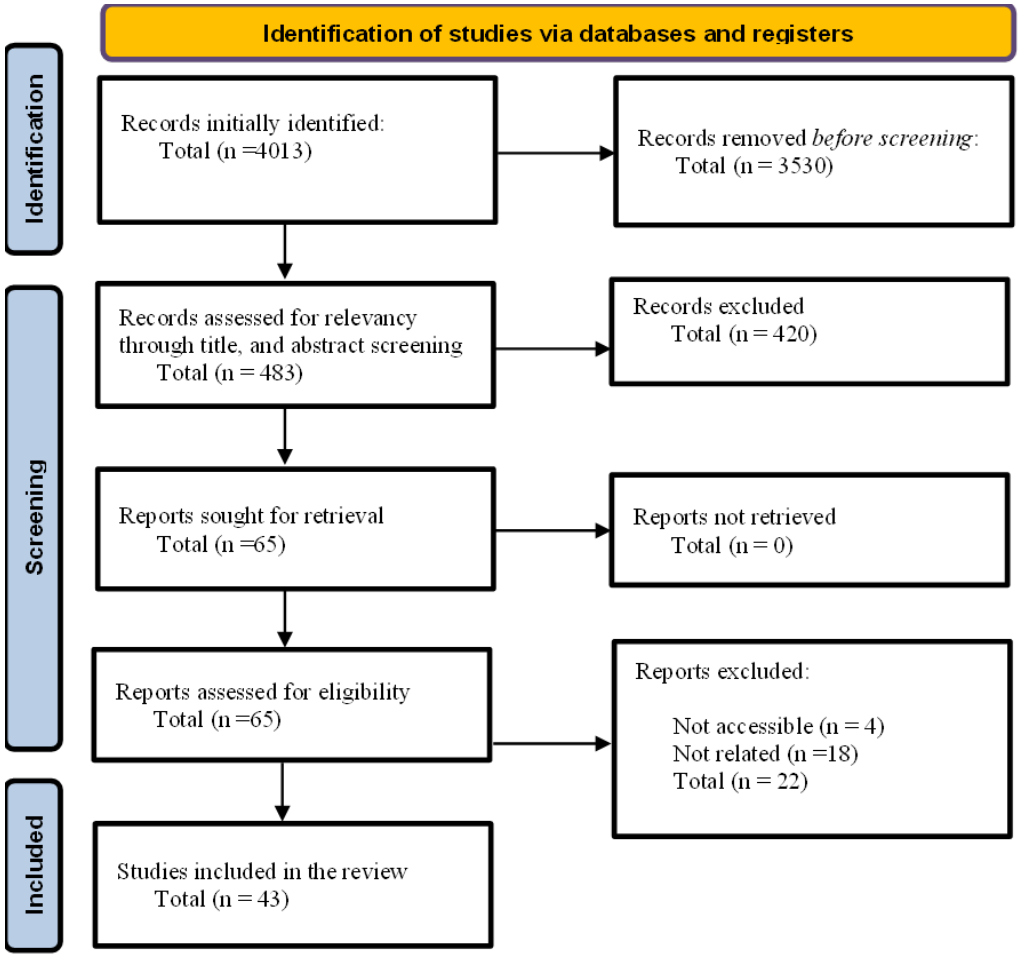


Fig.2: PRISMA Framework

Table 2: A list of the reviewed papers

No	Author(s)	Year	Country	Scope of the Study
1.	Anguelovski	2016	USA	Evolution of environmental justice activism and 'green LULUs'.
2.	Szibbo	2016	USA	Livability assessment of LEED-ND neighborhoods (Pacific Northwest).
3.	Wei et al.	2016	USA	Land use, transport accessibility and physical activity (Utah).
4.	Wang et al.	2016	NA	Review of built-environment effects on walking and cycling.
5.	Stollmann	2016	Germany	Neighborhood resilience and co-production in mass housing.
6.	Foster et al.	2016	Australia	Livable Neighborhoods policy and crime outcomes.
7.	Zuniga-Teran et al.	2016	USA	Evaluation and enhancement of LEED-ND walkability criteria.
8.	Yue et al.	2017	China	POI-based mixed-use index development (Shenzhen).
9.	Satu & Chiu	2017	Bangladesh	Livability comparison in dense Dhaka neighborhoods.
10.	Park	2017	USA	Green-space connectivity and resident perceptions (Phoenix).

11.	Abass & Tucker	2018	Australia	Neighborhood physical characteristics and attachment (suburbs).
12.	Chhipi-Shrestha et al.	2018	Canada	Multi-criteria framework for optimal residential density.
13.	Lo & Houston	2018	USA	Regional accessibility, walkability and couples' activity spaces (California).
14.	Zhang & Chen	2018	Singapore	Inclusive sharing economy model translated into neighborhood design.
15.	Garnier	2019	NA	Historical perspectives on risk, vulnerability and resilience.
16.	Scoppa et al.	2019	UAE	Connectivity performance of superblock designs (Abu Dhabi).
17.	Abass et al.	2019	Australia	Urban design era and neighborhood social activity (Australia).
18.	Hachem-Vermette & Grewal	2019	Canada	Mixed-use, density and neighborhood-scale energy/GHG optimization.
19.	Stanislav & Chin	2019	USA	Perceptions of sustainable design in New Urbanist vs suburb developments.
20.	Ibrahim et al.	2020	Qatar	Land-use change dynamics in downtown Doha neighborhoods.
21.	Ibrahim et al.	2020	Qatar	Downtown land-use dynamics prototype (emerging cities).
22.	Pfeiffer et al.	2020	USA	Walkability, transit, parks and life satisfaction (Phoenix).
23.	Herrmann-Lunecke et al.	2020	Chile	National review of walking as dominant mobility mode (Chile).
24.	Zhang et al.	2020	China	15-minute accessibility comparison using survey and big data (Beijing).
25.	Hooper et al.	2020	Australia	Longitudinal evaluation of Livable Neighborhoods policy impacts (Perth).
26.	Alawadi et al.	2021	UAE	Accessibility of nonresidential land uses in Abu Dhabi using centrality analysis.
27.	Ahmed & Alipour	2021	UAE	Urban morphology, land use and walkability (Emirati neighborhoods).
28.	Pinto & Akhavan	2021	Italy	Review of 15-minute city and related planning models.
29.	Kashef	2022	UAE	Land-use mix, density and street configuration vs pedestrian vitality (Abu Dhabi).
30.	Masoud et al.	2022	Canada	Agent-based model linking neighborhood design and mode choice.
31.	Ashik et al.	2022	Bangladesh	TOD vs non-TOD neighborhoods and transport CO_2 emissions (Dhaka).
32.	Singhal	2022	India	Density, parks, connectivity and walkability perceptions (Amritsar).
33.	Lee et al.	2023	USA	Built environment and correlates of walking vs biking to school (children).
34.	Kashef	2023	KSA	Synthesis of mixed land use and street-network design impacts on pedestrian vitality.

35.	Naseri et al.	2023	Australia	Built environment and cycling behavior during COVID lockdowns (Melbourne).
36.	Kweon et al.	2023	USA	School walk-zone design and children's active travel.
37.	Rui & Li	2024	China	City-wide vitality comparison: formal vs urban villages (Shenzhen).
38.	Choi	2024	France	Sustainable neighborhood design model and prototype.
39.	Wang et al.	2024	Singapore	Qualitative study of pedestrian inclusiveness (Singapore).
40.	Ali Komak et al.	2024	Malaysia	Neighborhood design quality and life satisfaction (international residents).
41.	Sallam & Al-Kazee	2025	Oman	Framework to monitor deviations from neighborhood planning under rapid urbanization (Gulf cities).
42.	Wu	2025	China	Built-environment effects on physical-activity facility use (Xiamen).
43.	Gao et al.	2025	China	Built environment, elderly physical activity and social capital (Shenzhen).

Most quantitative research relied on surveys, GIS-based indicators, and statistical modeling to examine the relationship between neighborhood form and outcomes such as walking, safety, or resident satisfaction. Although these studies are valuable for assessing the effectiveness of specific UN-Habitat strategies, they often provide limited insight into why residents experience places in particular ways. In contrast, the smaller body of qualitative research offers deeper understanding through interviews, go-along walks, and document analysis.

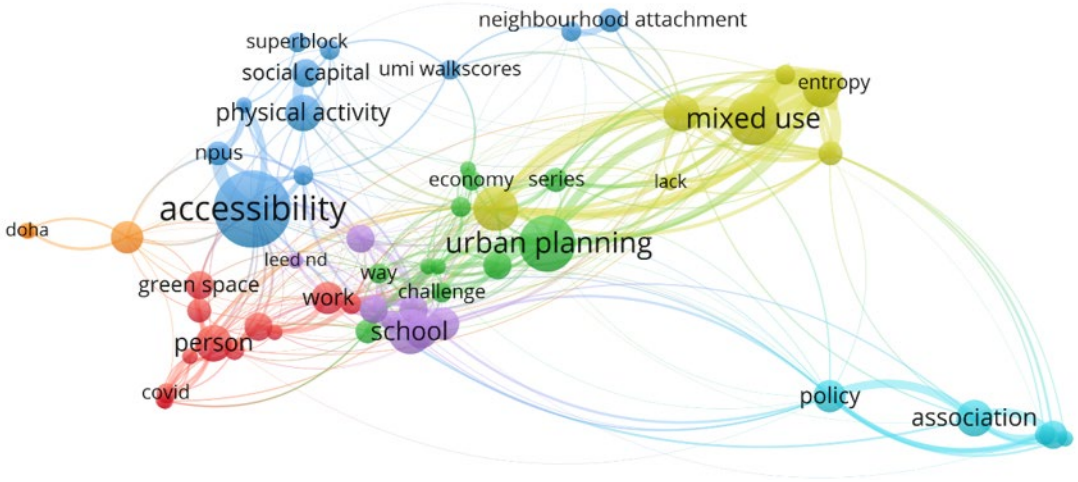


Fig. 3 : Co-occurrence map of the reviewed studies.

Thematic Analysis of UN-Habitat's Sustainable Neighborhood Objectives. *Fig.5* shows that the connectivity objective was the most extensively investigated theme in the reviewed literature, where its related strategies appeared 86 times in the analyzed papers. This was followed by neighborhood compactness, where its related strategies appeared 43 times. Vibrance and inclusiveness came next, followed by resilience, which was significantly the least examined objective. These findings suggest that researchers tend to prioritize tangible and measurable strategies such as mobility, accessibility, land-use mix, and urban form. Overall, the literature demonstrates a stronger emphasis on the physical and functional dimensions of sustainable neighborhoods, while social inclusion and long-term resilience receive comparatively less systematic and sustained attention.

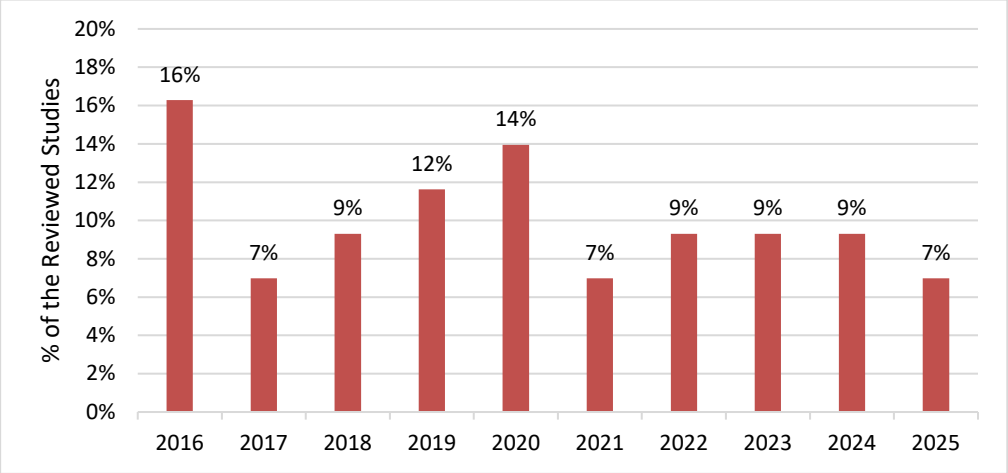


Fig. 4 : Year of publication of the reviewed studies

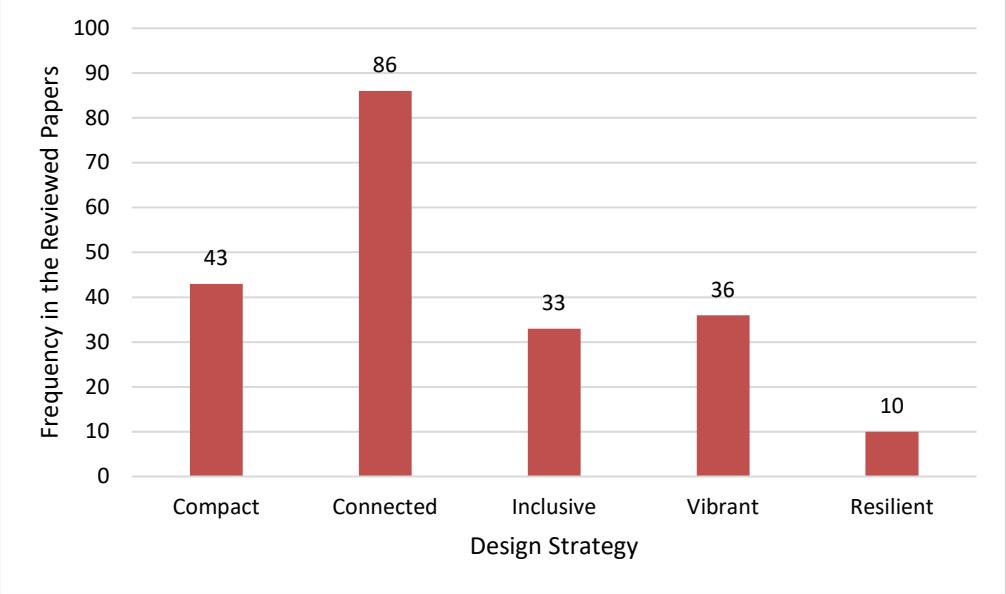


Fig. 5: Coverage of UN-Habitat's sustainable neighborhood objectives in the reviewed literature

On a detailed level, *Fig. 6* shows coverage of UN-Habitat's sustainable neighborhood detailed strategies to achieve each of the five objectives discussed above. As for the first objective, compactness is consistently associated with efficient density, mixed land use, and efficient public transport. The emphasis in this regard varies among sources to ensure shorter trips, infrastructure efficiency, and containment of urban sprawl [7]. UN-Habitat emphasized this through recommending several design strategies including efficient density, mixed land use, and efficient public transport, which were considerably cited in the reviewed studies as shown in *Fig. 6.* The second objective is connectivity, which is commonly quantified using multiple indicators such as distance, directness, and route diversity. This metric-driven perspective is commonly associated with reduced travel distances, improved walking and cycling conditions, expanded access to services and employment, and distributed traffic flows [8]. UN-Habitat adopted a holistic approach for connectivity that encompasses multiple design strategies that are directly linked to people's daily life activities. These strategies include efficient street network, multi modal transport, proximity and walkability, complete streets, active streets, and network of open public spaces. Among these strategies, proximity and walkability emerged as the most frequently addressed themes, followed by efficient street networks and mixed land use. Multi-modal transport and

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networked public spaces also received substantial attention, reinforcing the strong focus on mobility, accessibility, and spatial structure. Inclusion and vibrance come next in terms of their frequency in the reviewed literature. As for inclusion, it should be realized beyond physical accessibility toward broader concerns of equity and participation [9]. This includes housing, mobility, public space, and governance, which foregrounds rights and social justice. Compared to compactness and connectivity, which are often defined through measurable spatial indicators, inclusion is framed more normatively and socially. This was emphasized by UN-Habitat through

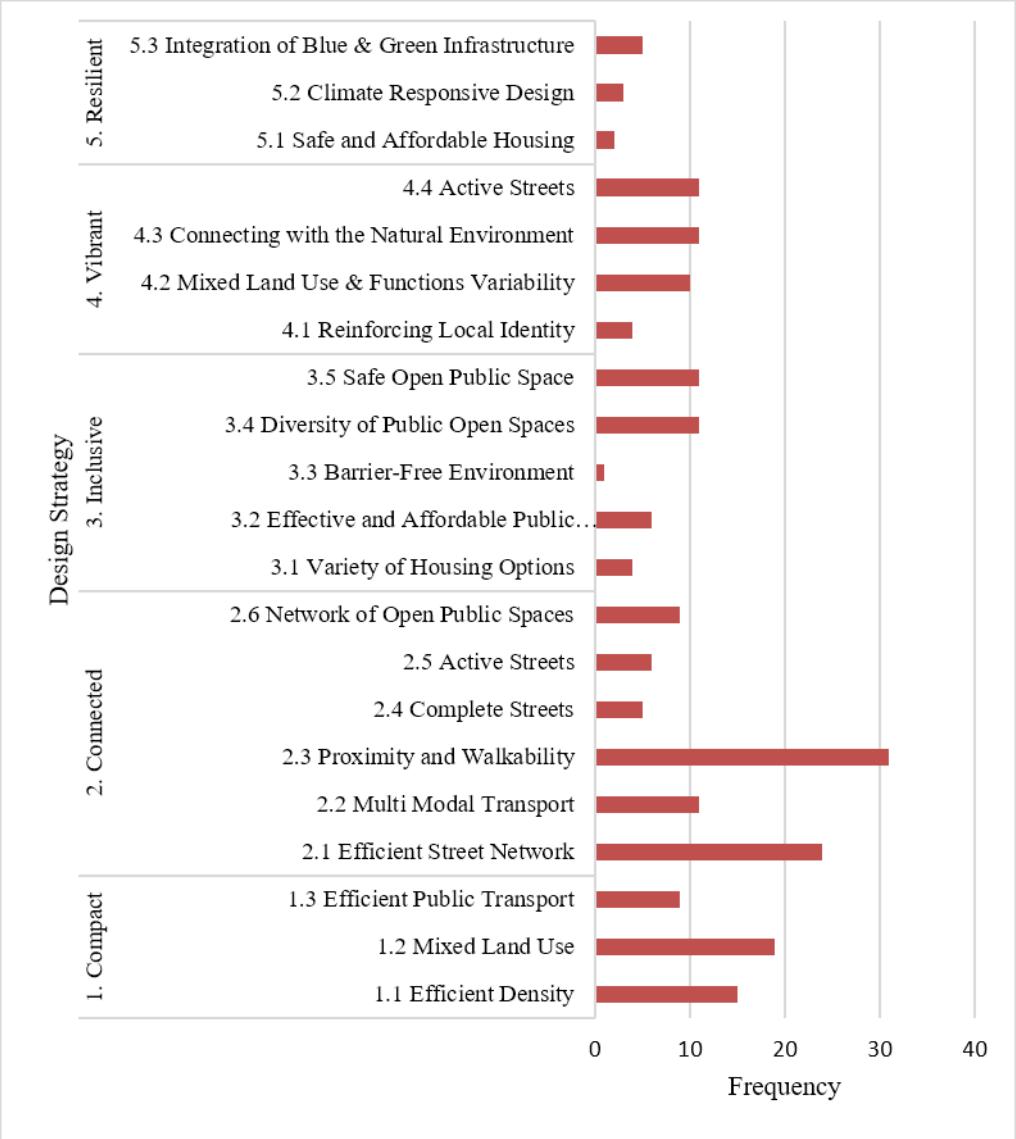


Fig. 6: Coverage of UN-Habitat's sustainable neighborhood detailed strategies in the reviewed literature

multiple designs strategies including variety of housing options, effective and affordable public transportation, barrier-free environment, diversity of public open spaces, and safe open public space. Vibrancy, on the other hand, is defined primarily through the presence and intensity of human activity and observable street life. UN-Habitat recommended multiple design strategies for vibrant neighborhoods including mixed land use and functions variability, connecting with the natural environment, and active streets, and reinforcing local identity, which received the least attention among these strategies. Resilience is the fifth and least-cited objective in the reviewed

literature. Resilience is commonly seen as the capacity of places and systems to absorb, adapt, and recover from disasters and hardships. At a neighborhood scale, resilience should consider sensitive land use, nature-based solutions, permeable surfaces, stormwater detention, and preparedness into everyday design and governance [6]. UN-Habitat recommended multiple strategies to improve neighborhood resilience including safe and affordable housing, climate responsive design, and integration of blue and green infrastructure. This re-introduces resilience as both a physical and governance-oriented concept, extending beyond spatial design to encompass institutional preparedness and long-term adaptive capacity. This holistic approach is needed since the reviewed literature prioritizes physical planning and mobility-related strategies, whereas social equity and long-term environmental resilience are comparatively underexplored.

Conclusion

UN-Habitat's "My Neighborhood" approach consolidates design guidance to ensure that each neighborhood plan advances all five objectives simultaneously rather than in isolation. This review examined how the five UN-Habitat's sustainable neighborhood design objectives are investigated in neighborhood-scale studies. In this context, the study reviewed 46 articles, published between 2015 and 2025 mainly in developed countries' contexts. Findings showed a clear focus on neighborhood connectivity and compactness, while inclusivity, vibrance and resilience attracted less attention. In this regard, the dominant design strategies investigated were walkability, street networks, and mixed land use. In contrast, strategies concerned with inclusiveness and resilience, such as barrier-free environments, safe and affordable housing, and climate-responsive design, appeared less frequently. Keyword and co-occurrence analysis revealed several research gaps, where sustainable neighborhoods are predominantly framed as a technical and design-oriented challenge, rather than as part of the broader, integrated, and people-centered agenda. This showed more tendency towards spatial design strategies, and a limited engagement with social, economic and institutional dimensions. By re-classifying the existing literature through the five UN-Habitat's sustainable neighborhood design objectives, this research makes those gaps visible and highlights where the UN-Habitat agenda is being advanced and where it remains only partially addressed. Future work is recommended to address these gaps and link them with the SDGs in order to comprehensively structure research questions in the field of sustainable neighborhood research. More attention is needed to discuss the different trade-offs in this regard to bring the UN-Habitat framework from concept to practice and support more balanced progress across environmental, social and economic pillars of sustainable neighborhoods.

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Adaptive Façade System for Hot Arid Climates: Material and Cultural Integration for Madinah

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Keywords: Adaptive Façade Systems, Dynamic Façades, Cultural Integration, Madinah Architecture

Abstract. Adaptive façade systems have recently gained increased attention as a sustainable approach to reduce building energy consumption and counter overheating problems. Despite this, most smart systems focus mainly on static solutions rather than dynamic ones that adapt to changing environmental conditions. A study is initiated to investigate alternatives for dynamic façade systems suitable for hot arid climate in Saudi Arabia. In the current study, available adaptive façade technologies are explored and assessed in light of architectural and material constraints. Findings are expected to guide the development of a movable façade system prototype.

Introduction

With the increasing awareness of global energy consumption challenges, finding energy efficient solutions has become a critical trend for energy-efficient buildings. Recent trends such as smart facades are becoming increasingly popular ways to reach optimal solutions. A significant component of energy efficient facades is the integration of smart materials [1]. These materials allow for reduced energy loads by regulating indoor thermal conditions based on the external environment, reducing the need for active cooling methods [2]. Some common adoptions include thermochromic materials, that change their properties in response to temperature changes and phase change materials (PCMs), that store and release thermal energy allowing for passive thermal efficiency [3].

While passive materials contribute to energy efficiency, their limitations in responding to extreme weather changes necessitated finding alternative solutions. Among such innovations are automated façade systems equipped with motor-driven panels that adapt to variations in solar radiation, temperature, and daylight levels [4]. Hosseini et al. [5] evaluated the daylight performance and visual comfort of interactive kinetic façades with two-dimensional (2D) and three-dimensional (3D) movement configurations achieving useful daylight illuminance (UDI) percentages of 67–82%. Akimov et al. [6] developed a simulation-based dynamic façade system optimized for daylight performance and evaluated different movement typologies with combined in-plane and out-of-plane rotations. Results indicated a 43% improvement in daylighting performance. Panya et al. (2020) employed simulation-based method for designing dynamic motion façades using hybrid parametric strategies that integrate rotational and translational movements optimized through real-time environmental data [7]. Results revealed that the proposed dynamic louver system significantly improved solar shading, daylight autonomy, and visual comfort compared to static façades, while enhancing the realism and efficiency of the design process. Dynamic façade systems can be categorized into adaptive, kinetic, bio-mimetic, and passive types [4]. In all these systems, integrating light, low-mass materials into the façade elements enables rapid responsiveness to solar and thermal loads especially in complex architectures [8], [9], [10], [11]. It is noted that the above studies were conducted in climatic

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conditions substantially different from that of Madinah, which is characterized by an arid desert climate with extremely high summer temperatures, intense solar radiation, low annual rainfall, and significant diurnal temperature variations. These conditions impose distinct thermal and solar loads on building envelopes, potentially altering the performance, control strategies, and energy-saving potential of dynamic façade systems. Therefore, direct extrapolation of previously reported daylighting and thermal efficiency outcomes to Madinah's context may not be reliable, underscoring the need for climate-specific evaluation and optimization of smart façade technologies tailored to hot-arid environments. The current research is an early-stage framework that aims to evaluate and optimize dynamic smart façade systems specifically for Madinah's hot-arid climate by integrating climate-responsive design strategies, material selection, and adaptive control mechanisms to enhance thermal performance, daylight efficiency, and overall energy savings. Different constraints related to construction and architectural considerations are explored with the aim of developing a dynamic façade system suitable for conditions in Madinah.

Material Exploration for Adaptive Façade Systems

Material selection for dynamic facades is crucial for determining its adaptability and sustainability to the surrounding environment. Materials do not only influence the mechanical characteristics but also the thermal response, energy utilization, and overall building visual aspects [12]. In hot arid climatic conditions such as Madinah, façade material has to withstand heat and cooling loads, while also having a lightweight nature to be able to move and transform to changing environmental conditions [13].

Previous case studies show that material choice has a direct influence on the environmental performance of the façade. For example, Al Bahar Towers in UAE employs Glass Fiber Reinforced Polymer (GFRP) kinetic modules that open and close depending on the solar direction, lowering heat gain by nearly 50% [14]. Similarly, Institute du Monde Arabe in Paris utilizes aluminum diaphragms to control the natural light, while the Media-TIC Building in Barcelona use ETFE cushions to regulate for thermal control [15]. Wood has also been used as an adaptive material, particularly through humidity-driven wooden panels capable of natural actuation [16].
Several types of adaptive façade material, including Glass Reinforced Concrete (GRC), GFRP, Aluminum (Al), Wood (Douglas Fir), and Foam Concrete (FC), are evaluated based on the thermal conductivity, weight, structural strength, and local availability. These criteria directly influence the facades' ability to perform under arid climates while remaining appropriate for construction. Table 1 Summarizes the key material properties used in comparison based on industrial and local specifications [17], [18], [19].

Table 1. Comparison of selected façade materials

Material	Density (kg/m^3)	Thermal Conductivity (W/m·K)	Compressive strength (MPa)	Fire Resistance
GRC	1800-2100	0.9–1.5	40-80	Non-combustible
GFRP	1714-1922	0.58	206	Poor
Al	2700	167	250-300	Non-combustible (loses strength when heated)
Wood	480	0.12	35-50	Combustible
FC	600-1800	0.10-0.62	2.0-15	Non-combustible

As the values show, FC provides the best compromise between different features for dynamic façade designs in hot arid environments. Compared with all the materials investigated, FC has the

lowest thermal conductivity of all the evaluated materials, which is the most effective in regard to heat transfer and reduction of cooling loads vital for façade systems facing extreme temperatures in Madinah. Its low density further reduces the load on actuators, joints, and supporting frames critical for moving or transformable façade modules. In contrast, materials including GRC, GFRP, and aluminum show significantly higher density, increasing mechanical demand and energy needed for kinetic activity. Also, FC is a non-combustible and inorganic material, which provides superior fire safety properties than GFRP and untreated wood. Although FC shows inferior compressive strength to structural materials, adaptive façade panels are considered as non-load-bearing components with their behavior determined mainly by insulation, weight, and fire behavior rather than any structural capacity. FC material's high porosity contributes to enhanced thermal resistance and sound insulation, making it suitable for energy-efficient façade envelopes and retrofit panels. In static façade systems, foam concrete can be cast into precast sandwich panels with integrated insulation cores, reducing thermal improving fire resistance compared to polymer-based insulations. For movable façades, the reduced weight of foam concrete will enable integration with mechanical systems while minimizing structural demand on frames and actuators. In addition, pigeon droppings pose a significant problem to building facades in Madinah considering the highly corrosive uric acid in their guano is highly corrosive. Hence, the best material to resist this form of chemical and biological degradation possesses low porosity, high surface durability, and strong chemical resistance. Taken together, FC displays the strongest alignment with the environmental, performance, and safety considerations of the proposed adaptive façade system. Table 2 presents additional geometric and material properties of FC as per local specifications [19].

Table 2. Geometric and material properties of FC [19]

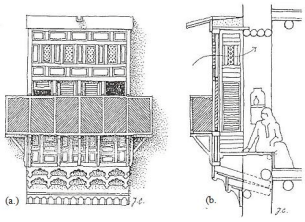
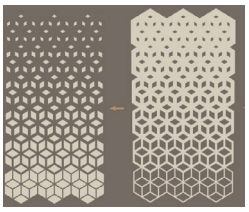
Property	Min. Value	Max. Value
Water Absorption (%)	High	Very high if untreated
Porosity	High	-
Workability	High flowability	Self-flowing
Shrinkage	Requires curing	-
Acoustic Performance	Good absorption	-
Thermal Mass	low	-
Typical Uses	Insulation, void filling	Non-load-bearing walls, finishes

Cultural Identity in Façade Design in Madinah

The adoption of adaptive façade systems in Madinah to achieve energy-efficacy and successful contextual integration requires moving beyond purely technical considerations [20]. In this section, use of local vernacular heritage in climate-adaptive solutions is explored. The wooden lattice window, known as Rāwshan or Mashrabiya, is considered as a leading precedent for passive climate control and a key marker of architectural cultural identity in Hijaz region. Fathy [21] identified five functional dimensions of Rāwshan: (1) passage of light; (2) control of airflow; (3) reduction of temperature; (4) privacy; and (5) increased humidity. Table 3 shows a functional and form-function analysis considering three categories: climate responsiveness, culture; and aesthetics for better contextual integration. Madinah Regional Municipality sets guidelines for façade design originating from traditional heritage practices in Madinah. These guidelines include openings' dimensions, typical architectural patterns, a palette of locally- appropriate materials, and rules for color and shading elements. For instance, a specific engineering pattern is set for each main road in Madinah. Table 3 shows an example pattern for King Abdullah Road.

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Table 3. Rāwshan Functional Analysis and Form-Function Derivation

Climate Responsiveness	Culture	Aesthetics
	Values	
Passage of light Control of airflow Reduction of temperature	Privacy	Architectural Aesthetics
	Form-Function Analysis	
		
The façade projection (Bay) and double-skin effect create a permanent self-shaded cavity; significantly reducing direct solar heat gain, thus reducing the overall ambient temperature. Additionally, the Projection help promote air flow into the building. The complex latticework diffuses harsh sunlight, minimizing glare while allowing a controlled air flow [22].	The Dense, Angled Lattice achieves unilateral visual permeability. This ensures visual seclusion and provide privacy to the occupants while maintaining light and air access [22].	Rāwshan display complex Islamic geometric patterns. These patterns are not merely decorative; they act as visual language that reflects regional identity [22]. An example of an engineering pattern for King Abdullah Road is set by Madinah Regional Municipality

Considering the above, the proposed design translates the functional logic of the Rāwshan into a contemporary façade system by reinterpreting its projecting geometry and parametrically controlled lattice patterns to create a responsive envelope that simultaneously enhances thermal performance, regulates daylight and airflow, and embeds culturally rooted geometric expression, thereby achieving a balanced integration of climatic efficiency with the architectural identity of Madinah. A vertical movement is adopted similar to the traditional operable components of the Rāwshan, where adjustable wooden elements respond to environmental conditions, allowing the façade system to modulate solar exposure, airflow, and privacy while maintaining the characteristic layered depth and cultural expression of the original vernacular design.

Construction Considerations

Designing a façade system from a structural engineering perspective requires considering several issues including safety, performance, and durability [23]. The structural design must account for different loads including self-weight of panels, wind pressure and suction, seismic forces on non-structural elements [24], and thermal loads caused by expansion and contraction [25]. The façade must safely transfer these loads into the primary structural frame via well-designed connections that also allow for differential movement without overstressing the envelope. Thermal expansion and building inter-story movements must be accommodated to avoid stress concentrations.

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Material selection is also crucial to balance strength, stiffness, and durability. On the other hand, architectural requirements are fulfilled based on analysis in Section 3.

The proposed façade panel has a dimension of 3.0 m, 1.8 m, and 0.05 m in length, width, and thickness, respectively. These dimensions were selected to comply with building requirements and regulations set by Madinah Region Development Authority [26]. Additionally, based on the density of FC, the mass of a single panel ranges from 125 kg to 376 kg. This weight range maintains, in proportion, a lightweight system that allows for smooth motion and reduces required energy as a fin rotating vertical shading system. According to several studies, vertical shading systems clearly show higher effectiveness in controlling low-angle solar exposure due to their ability to block direct sunlight while maintaining adequate daylight [27]. Therefore, we have chosen to design the panel as a vertical element to align with the advantages of this performance. Fig.s 1 and 2 show a schematic view of the panels and steps to validate the design.

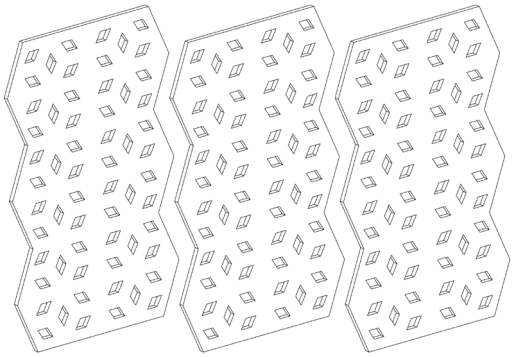


Fig. 1. Schematic View of Proposed Façade System

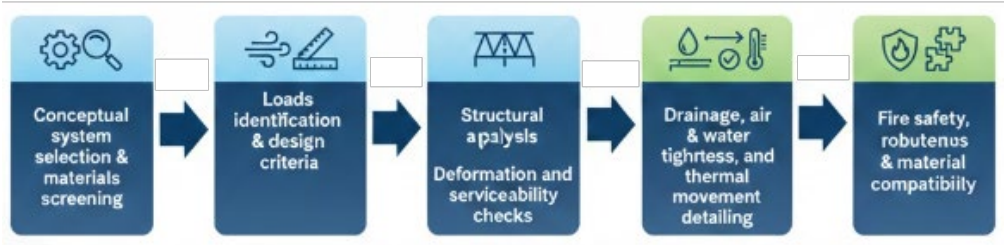


Fig. 2. Building Envelope Design Flowchart

Performance Potential

The proposed adaptive façade system has strong potential for improving thermal performance, daylight regulation, and overall building energy efficiency in hot-arid climates. From a thermal perspective, the integration of low-conductivity materials such as foam concrete (FC), combined with a double-skin configuration inspired by the Rāwshan, is expected to significantly reduce heat transfer through the building envelope. Previous studies indicate that façade material selection plays a critical role in reducing cooling loads by limiting conductive and radiative heat gains [2], [12]. Furthermore, dynamic façade systems have been shown to reduce solar heat gain by up to 50% when responsive shading strategies are applied, as demonstrated in precedent projects such as Al Bahar Towers [14]. The proposed vertical rotating panels enhance this effect by minimizing direct solar exposure during peak hours, particularly for low-angle solar radiation, which is dominant in desert climates [27]. Studies on kinetic façades report useful daylight illuminance (UDI) levels ranging between 67% and 82%, indicating substantial improvements in visual comfort and reduced reliance on artificial lighting [5]. Similarly, adaptive motion-based façade systems have demonstrated up to 43% enhancement in daylighting performance compared to static

systems [6]. The proposed system adopts similar adaptive principles, allowing controlled diffusion of daylight while reducing glare through patterned shading elements derived from traditional Rāwshan geometry [22].

From an energy perspective, the combined thermal and daylighting improvements directly contribute to lowering building operational energy demand. By reducing cooling loads and minimizing artificial lighting requirements, adaptive façades are recognized as key contributors to achieving energy-efficient and near-zero energy buildings [4]. The lightweight nature of FC panels further enhances energy efficiency by reducing the operational energy required for façade movement, improving the overall system responsiveness [8 and 9]. Additionally, the integration of passive design principles with active control strategies aligns with recent trends in smart façade technologies that emphasize hybrid solutions for enhanced performance under variable environmental conditions [7].

Conclusion

This study examined initial steps for the development of an adaptive façade system suitable for hot arid climates, with a specific focus on environmental and cultural context of Madinah. The review of smart material trends demonstrated that while passive systems enhance energy performance, they remain limited in addressing rapid or extreme climatic fluctuations. Consequently, dynamic and kinetic façade systems have emerged as effective alternatives capable of optimizing daylight, shading, and visual comfort through controlled motion-based responses to solar and thermal conditions. Through comparative material evaluation, Foam Concrete (FC) was identified as the most appropriate panel material for the proposed façade configuration considering its low density and resistance to chemical erosion. The material's lightweight characteristics are especially critical for kinetic systems, reducing load demands on actuators while maintaining sufficient performance for non-structural façade applications. The study also explored the cultural identity required for contemporary façade design. Finally, structural considerations were considered to ensure that the proposed system meets essential requirements for safety, durability, and performance under expected loads. By selecting panel dimensions compliant with local regulatory guidelines and adopting a vertical rotating shading configuration, the proposed façade system will be analysed to assess environmental efficiency, structural practicality, and aesthetic relevance.

Acknowledgement

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Cluster Morphology as a Determinant of Outdoor Thermal Stress in Container-Based Temporary Worker Housing: A Comparative Simulation Study in a Hot-Arid Climate

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Keywords: Temporary Worker Housing, Cluster Morphology, Outdoor Thermal Stress, Universal Thermal Climate Index (UTCI), Solar Radiation, Hot–Arid Climate, Microclimate Simulation, Ladybug Tools

Abstract. Rapid infrastructure development in Gulf desert regions has led to the proliferation of container-based temporary worker settlements, yet the microclimatic performance of their spatial configurations remains largely unexplored. In hot–arid environments, outdoor spaces within such settlements often experience severe thermal stress due to high solar exposure and limited shading. This study investigates the influence of cluster morphology on outdoor thermal stress in container-based temporary worker housing. Four representative spatial configurations—linear, staggered, courtyard, and double-row—were identified from satellite imagery and analyzed through simulation-based environmental modelling. Standardized settlement models were developed and evaluated using Ladybug Tools within the Grasshopper environment. Solar radiation was simulated for June 21 (representing peak summer conditions) between 06:00 and 18:00, and outdoor thermal stress was assessed using the Universal Thermal Climate Index (UTCI) at 14:00 to represent peak daytime heat stress conditions. The results indicate that settlement morphology significantly influences solar exposure and pedestrian-level thermal stress. The double-row configuration demonstrated the lowest average UTCI and solar radiation values due to improved shading continuity, while staggered and courtyard layouts exhibited higher thermal stress associated with reduced enclosure and increased sky exposure. The findings highlight the importance of spatial configuration in the planning of temporary worker settlements and suggest that compact building arrangements can improve outdoor thermal conditions in hot–arid climates.

1. Introduction

Over the past two decades, rapid infrastructural expansion and mega-development projects across Gulf desert regions have generated unprecedented demand for construction labour and associated temporary accommodation. Large-scale industrial zones, transport corridors, and urban megaprojects have led to the establishment of extensive worker settlements in peripheral desert locations. Labour camps across GCC countries are frequently situated outside urban centres and characterised by high-density accommodation patterns and spatial isolation[1]. These settlements are typically composed of modular or container-based housing units arranged in repetitive geometric clusters and constructed within compressed timeframes to meet urgent labour demands. While such developments are essential to supporting regional economic growth, their environmental performance—particularly under extreme hot–arid climatic conditions—remains insufficiently examined.

Hot–arid desert climates are characterised by intense solar radiation, high air temperatures, low relative humidity, and pronounced diurnal variation. In these contexts, outdoor spaces between housing units frequently experience severe heat stress, posing risks to thermal safety, occupational health, and overall well-being. Outdoor thermal comfort (OTC) in such environments is governed

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by complex interactions between air temperature, wind speed, relative humidity, and mean radiant temperature (MRT), with MRT often emerging as the dominant contributor to perceived thermal stress under high solar exposure [2]. Composite thermal indices such as the Universal Thermal Climate Index (UTCI) and Physiological Equivalent Temperature (PET) are therefore widely adopted to quantify pedestrian-level heat stress in hot climates [3].

A substantial body of literature demonstrates that urban morphology plays a decisive role in shaping microclimatic conditions. Key parameters include building density, height-to-width ratios, street orientation, sky view factor, and spatial compactness, all of which influence solar access, radiative exchange, and wind flow patterns.[4]. Studies conducted in hot–arid regions confirm that compact urban fabrics can significantly mitigate heat stress by reducing direct solar exposure and enhancing shading performance [5].

Beyond pedestrian comfort alone, recent research emphasises the interdependence between morphological characteristics, microclimate regulation, and building energy demand. Variations in urban density and typological arrangement influence both outdoor thermal conditions and indoor cooling loads, often revealing trade-offs between thermal comfort optimisation and energy efficiency[6]. Integrated analytical frameworks have been proposed to standardise the evaluation of urban form, microclimate, and energy performance in hot climate cities such as Dubai, Jeddah, and Abu Dhabi [7]. These studies collectively underscore the importance of geometry-driven microclimatic assessment in climate-responsive urban design.

However, despite the depth of research on permanent residential neighbourhoods, traditional compact settlements, and high-rise developments, significantly less attention has been directed toward temporary or modular housing clusters. The spatial organisation of temporary housing has been shown to influence wind flow and summer thermal conditions in post-disaster contexts[8], yet such investigations are predominantly situated in temperate or humid climates. There remains a distinct lack of systematic analysis addressing large-scale temporary worker settlements located in hot–arid desert environments.

This omission is critical. Temporary worker accommodations in desert regions often consist of highly repetitive, grid-based layouts with limited vegetation, high surface exposure, and minimal climatic modulation. Unlike traditional urban fabrics, these settlements are frequently designed with logistical efficiency rather than environmental performance as the primary objective. Consequently, the microclimatic implications of their cluster morphology remain largely unexplored in the literature, despite the significant number of inhabitants exposed to extreme thermal conditions.

In response to this gap, the study is guided by the following research question: “Which settlement morphology minimizes peak outdoor thermal stress under controlled hot–arid conditions?” By abstracting representative settlement typologies derived from settlements observed in Saudi Arabia**,** used here as representative cases for broader Gulf desert contexts**,** and evaluating them using UTCI-based microclimatic simulation, the study examines how geometric configuration, spatial density, and layout orientation influence pedestrian-level thermal stress. This investigation extends morphology-based thermal stress research into the domain of temporary worker settlements and contributes to the development of thermally resilient design strategies for rapidly expanding desert housing environments.

2. Literature Review

2.1 Outdoor Thermal Stress in Hot–Arid Climates

Hot–arid climates are characterized by extreme solar radiation, prolonged high air temperatures, low relative humidity, and pronounced diurnal temperature variation. In such environments, outdoor thermal stress is primarily governed by radiative heat exchange rather than air temperature alone. Mean radiant temperature (MRT), wind speed, and solar exposure often dominate the

human heat balance equation, making pedestrian-level conditions highly sensitive to spatial configuration.

Recent investigations in Upper Egypt demonstrate that morphological adjustments alone can significantly reduce pedestrian thermal stress during extreme summer periods. However, these contexts differ from temporary worker settlements in terms of spatial regularity, modular repetition, and limited enclosure, which may result in different microclimatic responses. For instance, densification processes that reduce sky exposure have been shown to lower PET values by up to 5.5°C at specific locations under hot–arid conditions[9]. This indicates that outdoor thermal stress in desert environments is not purely a climatic inevitability but can be spatially mediated.

Similarly, cluster-scale analysis in Baghdad's hot–arid climate reveals that grouping patterns, building height, and contiguity significantly affect pedestrian thermal comfort indices [10]. Although PMV was used in that study, the findings reinforce that solar access control and airflow modulation through morphology are decisive factors in mitigating outdoor heat stress.

At a regional scale, the severity of heat stress across desert urban centers is intensifying due to climate change. Longitudinal assessments of the Arabian Peninsula show increasing frequency and magnitude of heat stress events, directly impacting outdoor labour productivity and human health[11]. Complementary analyses of Gulf urban cores document amplified thermal discomfort due to urban density and surface hardening [12]. These findings contextualize the urgency of microclimatic regulation strategies in desert-built environments, particularly for populations exposed to prolonged outdoor conditions.

Despite these advances, most research concentrates on permanent residential districts or urban cores. Temporary settlements, often located in exposed desert peripheries, have received comparatively limited attention in outdoor thermal stress analysis.

2.2 Urban Morphology as a Microclimatic Regulator

Urban morphology plays a central role in shaping microclimatic conditions through its influence on shading, radiative exchange, wind corridors, and sky view factor (SVF). The theoretical foundation linking urban form and climate responsiveness emphasizes that spatial configuration must be climate-specific [13]. In hot–dry regions, compact and clustered arrangements historically functioned as passive cooling strategies by minimizing sky exposure and enhancing mutual shading. A comprehensive synthesis of block-scale research confirms that urban geometry influences microclimatic performance. Key parameters such as height-to-width ratio, density, and orientation affect solar access, ventilation, and thermal conditions at the neighbourhood scale[14]. This body of work establishes that buildings cannot be thermally evaluated in isolation; rather, their collective arrangement determines microclimatic behaviour. More recent investigations extend these principles through simulation-based analyses of clustered housing in arid climates. In Egyptian desert contexts, courtyard-based cluster integrated with vegetation formations were found to reduce peak-time heat gain by approximately 24.66% compared to parcel-based layouts [15]. The study further emphasized that PET should be complemented with solar radiant exposure metrics to fully represent outdoor thermal conditions. Cluster-scale optimization research reinforces that spatial layout can produce measurable shifts in UTCI values across seasonal scenarios [16] . Importantly, this work demonstrates that layout-level interventions at the building cluster scale may exert greater influence on outdoor thermal environment than facade-level adjustments alone.

Across the literature, several morphological parameters consistently emerge as critical regulators of microclimate in hot–arid environments. Sky View Factor (SVF) plays a decisive role in controlling radiative heat exchange, as reduced sky exposure typically lowers mean radiant temperature during peak daytime periods. Building height and enclosure ratios influence shading

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depth and airflow modulation, thereby affecting both solar access and wind penetration at pedestrian level. Cluster contiguity and compactness determine the extent of mutual shading between units and shape the thermal behaviour of shared open spaces. Orientation relative to the solar path and prevailing wind directions further governs diurnal heat gain and ventilation efficiency. In addition, spatial density and ground coverage influence surface heat accumulation and long-wave radiation exchange within settlement fabrics. In this study, these morphological parameters are implicitly represented through variations in cluster layout, including differences in alignment, enclosure, spacing, and continuity across the selected typologies.

While these morphological principles are well-established in studies of permanent urban neighbourhoods, their systematic application to temporary and modular settlements remains largely underexplored.

2.3 Simulation-Based Evaluation of Thermal Comfort

Advancements in computational environmental modelling have significantly enhanced the capacity to evaluate pedestrian-level thermal stress in hot–arid climates. High-resolution simulation studies demonstrate that outdoor thermal comfort cannot be adequately assessed using air temperature alone; instead, it requires integrated analysis of mean radiant temperature (MRT), wind speed, humidity, and solar exposure [9] . Such investigations confirm that spatial configuration directly alters radiative exchange and airflow patterns, thereby shaping human thermal perception at ground level. Increasingly, the Universal Thermal Climate Index (UTCI) has been adopted as a comprehensive indicator of outdoor thermal stress. While indices such as PET and PMV are widely used, UTCI is adopted in this study due to its ability to integrate multiple climatic variables and provide a physiologically relevant assessment of heat stress under extreme outdoor conditions**.** UTCI integrates air temperature, wind velocity, humidity, and mean radiant temperature into physiologically meaningful stress categories. Cluster-scale optimization research shows that UTCI-based evaluation captures both seasonal and diurnal variability in microclimate, offering a robust framework for morphology-driven environmental assessment [16].

Recent methodological developments extend beyond stand-alone urban microclimate platforms to parametric environmental simulation frameworks integrated within computational design environments. Tools such as Ladybug and Honeybee enable climate-responsive modelling by extracting EPW-based weather data and computing solar radiation, mean radiant temperature, and UTCI within a flexible parametric workflow. Such platforms are particularly suitable for comparative morphological investigations, where spatial density, orientation, enclosure ratio, and layout typology are systematically varied under controlled climatic boundary conditions. By allowing direct integration of solar radiation analysis, thermal comfort indices, and geometry manipulation within a single parametric environment, these tools facilitate precise evaluation of how cluster-scale design decisions influence outdoor thermal exposure.

Integrated approaches that combine radiative metrics with thermal comfort indices provide a more complete representation of environmental performance in arid climates [15]. This is particularly critical in desert contexts, where radiant heat often dominates thermal stress. However, simulation-based investigations in temporary settlements largely emphasize indoor envelope performance rather than outdoor spatial configuration. As a result, the microclimatic implications of cluster morphology in modular worker accommodations remain insufficiently examined. Given the exposure patterns typical of such settlements, where circulation, social interaction, and rest frequently occur outdoors, there is a clear need for morphology-focused thermal evaluation using comprehensive outdoor stress metrics.

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2.4 Temporary and Modular Settlements: Existing Approaches and Limitations

Temporary settlements, including refugee camps, disaster-relief housing, and migrant worker accommodations, are typically characterized by modular repetition, lightweight construction, and rapid deployment. Research in desert refugee camps highlights significant thermal vulnerability in such environments, where inadequate insulation and high exposure contribute to overheating risks [17]. While these investigations provide insight into material and envelope performance, they seldom evaluate settlement-scale spatial configuration. Post-disaster housing studies further emphasize the rapid thermal response of lightweight structures in extreme climates, showing elevated temperature rise rates and heavy dependence on mechanical cooling. Although advanced modelling techniques have been applied to evaluate envelope optimization, outdoor spatial morphology is rarely examined.

Socio-spatial analyses of labour camps in Gulf countries describe grid-based layouts, repetitive container units, and hierarchical zoning strategies [18]. These works document spatial organization and living conditions but do not quantify microclimatic performance.

Consequently, temporary worker settlements in desert regions are frequently characterized by high sky exposure, limited built or vegetative shading, minimal landscape integration, and poorly defined wind corridors. Their spatial organization is typically governed by construction speed, modular repetition, and logistical efficiency rather than climatic responsiveness, resulting in repetitive grid-based layouts with low enclosure ratios and extensive radiative exposure. Socio-spatial analyses of labour accommodations in Gulf countries indicate that such settlements are often planned with standardized modular units arranged for operational convenience, with limited consideration of environmental performance [18]. Similarly, investigations of temporary housing typologies highlight the predominance of functional and economic priorities over microclimatic adaptation in rapidly deployed settlements[17]. Despite accommodating populations that are particularly vulnerable to prolonged heat exposure, especially during outdoor rest periods, circulation between units, and communal activities - these environments remain underrepresented in morphology-based thermal stress investigations.

2.5 Identified Research Gap

The existing literature provides substantial evidence that urban morphology plays a significant role in regulating outdoor thermal stress in permanent residential neighbourhoods in hot–arid climates. It also highlights increasing concern over intensifying desert heat and the growing use of simulation-based methods to evaluate pedestrian-level thermal comfort. However, research on temporary settlements has largely focused on envelope performance or socio-spatial organization, with limited attention to cluster-scale microclimatic conditions.

The key research gap lies in applying morphology–microclimate principles to container-based or modular temporary worker housing in extreme desert environments, particularly through comprehensive outdoor thermal indices such as the Universal Thermal Climate Index (UTCI). Given the rapid expansion of desert mega-projects and associated worker accommodations, understanding how settlement geometry influences outdoor thermal exposure is increasingly important. By employing controlled typology abstraction and simulation-based evaluation, this study directly addresses this gap by isolating the impact of spatial configuration on outdoor thermal stress.

3. Methodology

3.1 Research Design

This study adopts a comparative simulation-based approach to examine how different spatial configurations of container-based temporary worker housing influence outdoor thermal stress in a hot–arid desert environment. Instead of generating hypothetical layouts, the research draws on

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spatial patterns observed in existing worker settlements identified through satellite imagery of large-scale labour accommodations in Saudi Arabia. A preliminary review of multiple worker settlements was conducted to identify recurring spatial patterns. The selected four typologies represent the most commonly observed layout configurations across these settlements, rather than isolated or atypical cases.

The aim is to evaluate how variations in cluster morphology affect solar exposure and pedestrian-level thermal conditions while maintaining consistent physical and environmental parameters across all scenarios. To enable a controlled comparison, all typologies were standardized to identical plot dimensions, module sizes, building heights, and overall density. By controlling these variables, differences in thermal performance can be attributed primarily to the spatial arrangement of housing units rather than variations in scale or material properties.

3.2 Identification and Abstraction of Settlement Morphologies

Satellite imagery analysis revealed several recurring spatial arrangements within container-based worker settlements. From these observations, four typologies were selected for analysis: linear arrangement, staggered configuration, courtyard cluster, and double-row configuration.

Each typology was simplified into an abstract geometric model that preserved the core spatial characteristics of the settlement layout, including module orientation, spacing between units, and circulation corridors. This abstraction allowed the study to focus specifically on the microclimatic implications of cluster morphology while eliminating irregular contextual influences. The abstraction process retained key spatial characteristics such as module orientation, relative spacing, and circulation paths, while removing irregularities and contextual variations such as terrain, auxiliary structures, and landscape elements. Spacing proportions between units were normalized to enable consistent comparison across typologies.



Figure 1: Satellite imagery extracts of selected settlements

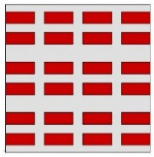
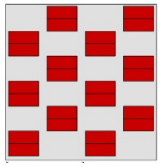
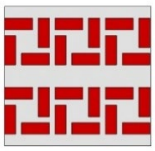
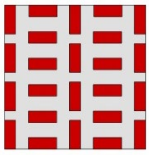
3.3 Simulation Setup and Parameters

Environmental simulations were conducted using Ladybug Tools within the Grasshopper environment for Rhino**.** Weather data was derived from an EPW file corresponding to a representative hot–arid location in Saudi Arabia. A uniform analysis grid was applied at pedestrian level to ensure consistent spatial resolution across all simulations. Ground surfaces were assumed to be hard, unshaded materials typical of desert worker settlements. Wind conditions were incorporated through EPW weather file inputs as part of the UTCI calculation. To ensure comparability between scenarios, several parameters were standardized across all typologies, including a plot area of 2500 m²**,** 24 housing modules**,** and module dimensions of 4 m × 10 m × 3 m**.** All units were assumed to be constructed using prefabricated steel modular structures with insulated sandwich panels**,** representing typical container-based worker housing. Two height scenarios were analysed to reflect common variations in such settlements: a single-storey configuration (G) with a building height of 3 m and a double-storey configuration (G+1) with a height of 6 m**.** Solar radiation simulations were conducted for 21 June (representing peak summer conditions) between 06:00 and 18:00 to evaluate cumulative solar exposure. Outdoor thermal stress was assessed using the Universal Thermal Climate Index (UTCI) at 14:00, representing peak

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daytime heat stress conditions in hot–arid climates. The simulations produced spatial distribution maps for both solar radiation and UTCI, from which average and maximum UTCI values, along with radiation levels, were extracted to enable quantitative comparison between the different settlement configurations.

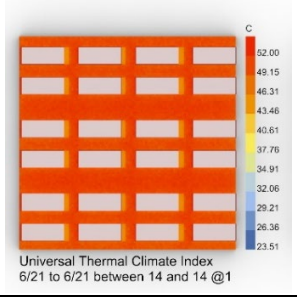
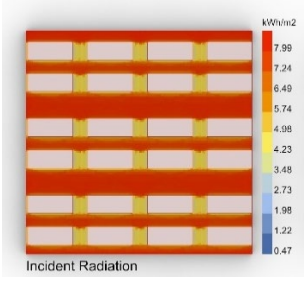
Table 1: Attributes of selected typologies

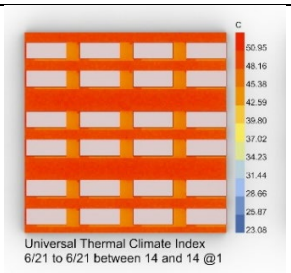
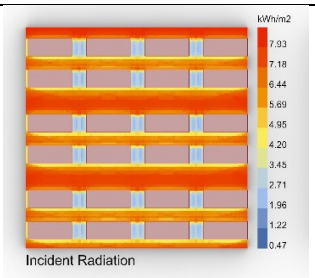
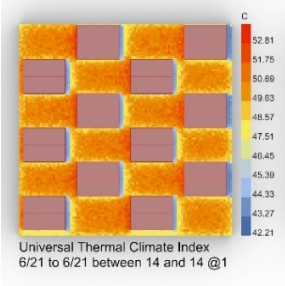
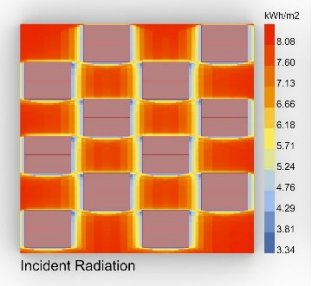
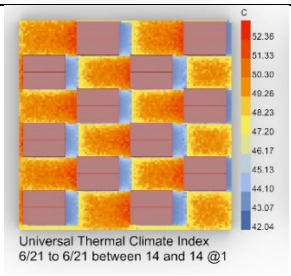
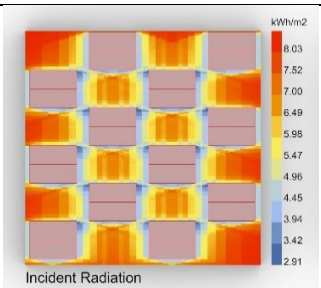
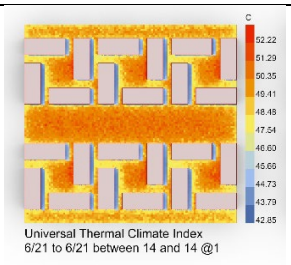
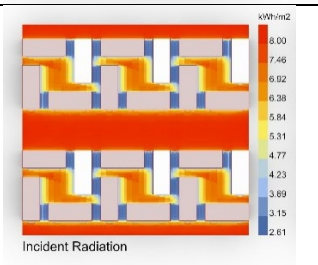
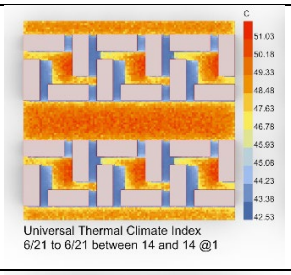
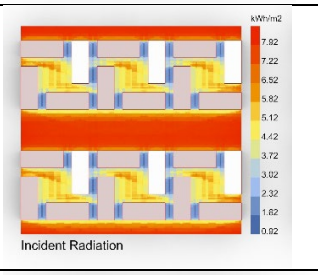
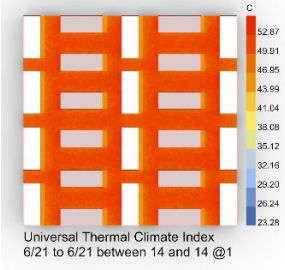
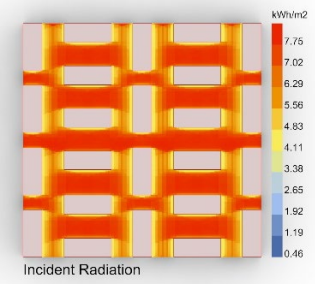
Pattern type	Grouping Pattern	Floors	Surface area (sqm)	Height (m)	Site Area (sqm)	Floor area ratio (FAR)	Material
	Type A – Linear Pattern	G G+1	2976 5912	3 6	2500 2500	0.384 0.768	Prefabricated steel modular unit with insulated sandwich panels
	Type B- Staggered Pattern	G G+1	2976 5912	3 6	2500 2500	0.384 0.768	Prefabricated steel modular unit with insulated sandwich panels
	Type C- Courtyard Pattern	G G+1	2976 5912	3 6	2500 2500	0.384 0.768	Prefabricated steel modular unit with insulated sandwich panels
	Type D – Double Row Pattern	G G+1	2976 5912	3 6	2500 2500	0.384 0.768	Prefabricated steel modular unit with insulated sandwich panels

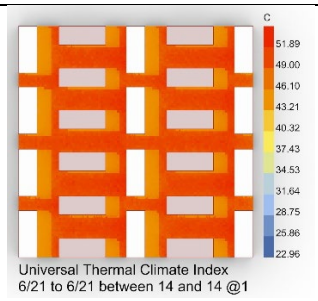
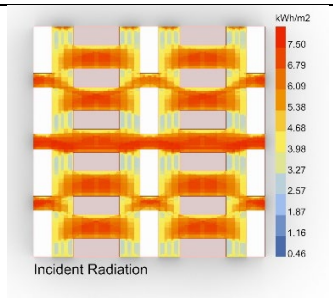
4. Results

From the simulations, key performance indicators including average and maximum UTCI values, as well as average and maximum solar radiation values, were extracted to enable quantitative comparison between the different settlement configurations. The results of these simulations are summarized in Table 2

Table 2: Result of cluster simulations using Honeybee and Ladybug

Typology	UTCI Map	UTCI Statistics (°C)	Solar Radiation Map	Radiation Statistics (kWh/m²)
Linear G		Average- 47.74 Max- 52 Min – 23.52		Average- 3.35 Max- 7.99 Min – 0.49

Linear G+1		Average- 42.81 Max- 50.94 Min – 23.08		Average- 2.99 Max- 7.92 Min – 0.47
Staggered G		Average- 48.94 Max- 52.81 Min – 42.21		Average- 6.67 Max- 8.07 Min – 3.341
Staggered G+1		Average- 47.87 Max- 52.36 Min – 42.03		Average- 5.82 Max- 8.03 Min – 2.91
Courtyard G		Average- 48.40 Max- 52.22 Min – 42.85		Average- 6.27 Max- 8.00 Min – 2.61
Courtyard G+1		Average- 47.08 Max- 51.03 Min – 42.52		Average- 5.36 Max- 7.91 Min – 0.90
Double Row G		Average- 44.01 Max- 52.80 Min – 23.00		Average- 3.30 Max- 7.75 Min – 0.46

Double Row G+1		Average- 42.9 Max- 51.88 Min – 22.96		Average- 2.80 Max- 7.50 Min – 0.46

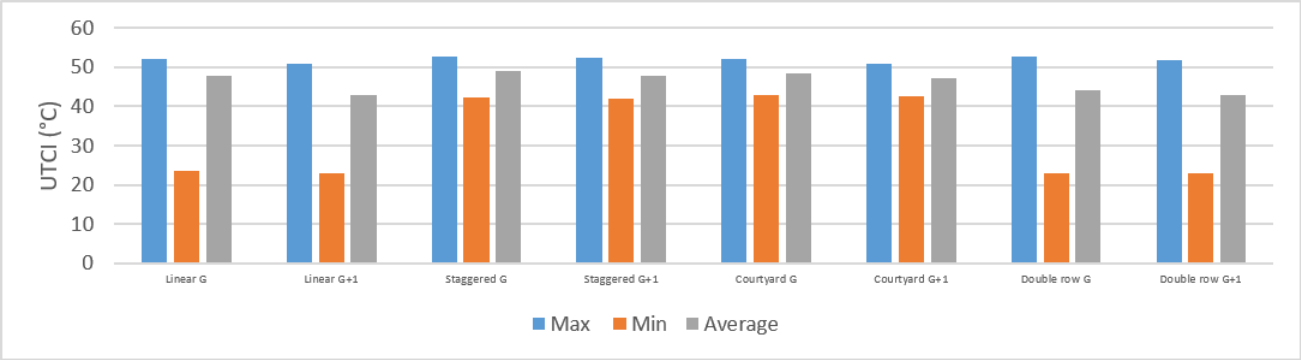


Figure 2: UTCI across various typologies

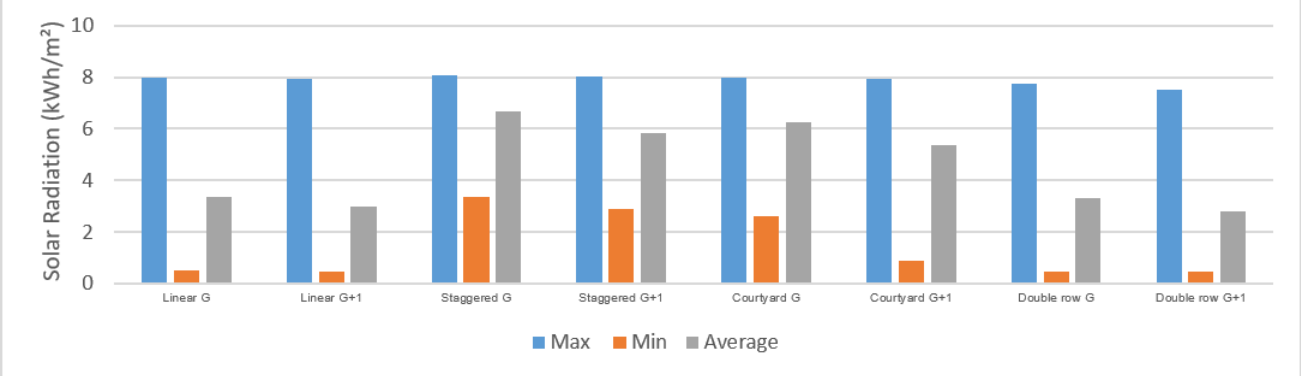


Figure 3: Radiation across various typologies

Simulation results reveal that settlement morphology significantly influences outdoor thermal conditions within container-based housing clusters.

Across all typologies, increasing building height from G to G+1 resulted in lower average UTCI values. The additional height enhances mutual shading between modules, which reduces direct solar exposure and lowers mean radiant temperature within pedestrian spaces.

Among the four configurations, the double-row typology exhibited the lowest average UTCI values (approximately 42.9°C), which is about 4°C lower than the staggered configuration, the latter recording the highest thermal stress**,** indicating comparatively lower levels of outdoor thermal stress. The parallel alignment of building rows creates continuous shaded corridors that limit solar penetration into circulation areas.

In contrast, the staggered configuration recorded the highest UTCI and solar radiation values**.** The offset arrangement increases sky exposure and disrupts shading continuity, resulting in greater solar radiation reaching ground surfaces.

The courtyard typology demonstrated moderate performance. Although the central courtyard provides some internal shading, the relatively open geometry still allows significant solar exposure during peak hours.

The linear configuration also showed intermediate performance, performing better than the staggered layout but less effectively than the compact double-row arrangement.

Solar radiation patterns closely correspond to the observed UTCI trends. Typologies with greater enclosure and shading continuity generally exhibited lower cumulative radiation levels, while layouts with higher sky exposure recorded increased solar gain.

Overall, the results demonstrate that compact and continuous building arrangements can substantially reduce outdoor thermal stress in container-based housing settlements located in hot–arid environments.

Conclusion

This study examined the influence of settlement morphology on outdoor thermal stress in container-based temporary worker housing located in hot–arid desert environments. Four common spatial configurations—linear, staggered, courtyard, and double-row—were derived from satellite imagery and evaluated through simulation to assess their impact on solar radiation exposure and pedestrian-level thermal comfort. The results demonstrate that cluster layout significantly affects both solar radiation distribution and UTCI values. Among the examined typologies, the double-row configuration showed the lowest average UTCI and solar radiation values, indicating improved shading continuity and reduced thermal stress. In contrast, the staggered and courtyard layouts exhibited higher thermal stress due to greater sky exposure and fragmented shading patterns. Increasing building height from G to G+1 further reduced UTCI values across all configurations by enhancing mutual shading between modules. These findings highlight the importance of spatial configuration in the planning of temporary worker settlements in desert climates and suggest that compact and continuous building arrangements can improve outdoor thermal conditions in such environments.

Limitations

This study has several limitations. First, the settlement morphologies were simplified from satellite imagery to allow controlled comparison between typologies. In practice, additional elements such as vegetation, shading devices, and variations in surface materials may influence microclimatic conditions.

Second, the simulations were conducted for a representative peak summer day (21 June) and a single peak hour for UTCI analysis. While this captures extreme heat conditions, it does not represent seasonal or full diurnal variations.

Finally, the analysis primarily focused on solar radiation and UTCI. Other factors such as wind flow, surface material properties, and human activity patterns were not explicitly considered and could be explored in future studies.

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Integrating BIM, Virtual Reality, and Material Passports for Early-Stage Circular and Low-Carbon Material Selection

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Keywords: Building Information Modelling (BIM), Virtual Reality (VR), Material Passports, Circular Construction, Embodied Carbon, Early-Stage Design, Design Science Research, Decision Support System, Sustainable Material Selection

Abstract. The construction sector requires decision-support workflows that address embodied carbon and circularity before detailed design constrains material choices. Although material passports, Building Information Modelling (BIM), and Virtual Reality (VR) each offer partial support, an integrated early-stage workflow for material selection remains underdeveloped. This study proposes a BIM-integrated, VR-enabled material-passport framework for comparing low-carbon and circular material alternatives in context. Using a design science research approach, the study develops a four-layer framework comprising a data layer, passport layer, interaction layer, and decision layer, and implements it as a proof-of-concept prototype in a bounded classroom fit-out case. BIM objects are linked to passport records containing identity, embodied carbon, reuse and recovery potential, disassembly logic, lifespan, and end-of-life information, which are visualized through an immersive comparison interface. The prototype is evaluated against a conventional BIM-based workflow using decision time, decision confidence, perceived understanding, usability, and benchmarked selection quality, while expert and user reflections are used to identify implementation barriers. Initial findings suggest that the integrated workflow is technically feasible, improves in-context accessibility of sustainability information, and supports clearer comparison-oriented reasoning, although gains in decision speed remain sensitive to onboarding time and data quality. Persistent barriers include interoperability, data consistency, standardization, and stakeholder ownership. The study contributes an integrated framework, a prototype workflow, and implementation priorities for more decision-ready circular construction.

Introduction and problem framing

The construction sector is central to climate mitigation because it consumes large quantities of virgin resources, generates major waste streams, and locks environmental impacts into projects at the design stage. Circular-economy research therefore argues for a shift from linear material practices toward reuse, recovery, long life, and better lifecycle transparency, while embodied-carbon research shows that these concerns must be addressed early, when material alternatives are still flexible [1,2,3,4].

Within this transition, material passports have emerged as structured records for documenting composition, provenance, disassembly, recycling pathways, and residual value, BIM has matured as the main structured environment for project information, and VR has shown growing value for spatial understanding and collaborative review. Yet these streams are still weakly connected. Material-passport studies report fragmented data models and weak interoperability; BIM-based carbon workflows often remain assessment-oriented rather than decision-oriented; and VR studies rarely connect immersive review to structured circularity intelligence for measurable material-selection tasks [5,6,7,8,9].

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Accordingly, this paper addresses three linked questions: how a BIM-integrated, VR-enabled material-passport framework can be designed for early-stage low-carbon and circular material selection; whether such a workflow can improve decision quality, speed, confidence, and understanding when compared with a conventional BIM workflow; and which interoperability, information-sharing, and adoption barriers shape practical implementation. The study responds through design science research, a bounded classroom fit-out case, a comparative proof-of-concept evaluation, and barrier analysis.

The contribution is threefold. First, the paper integrates BIM, VR, and material-passport intelligence into a single early-stage decision-support logic. Second, it translates that logic into a lightweight prototype architecture linking BIM objects, passport attributes, and immersive comparison functions. Third, it identifies the technical and organizational conditions required for broader adoption in circular construction practice.

Focused literature background and gap synthesis

Material-passport research establishes the importance of lifecycle traceability, reuse potential, and structured component-level datasets, but it also shows that passport methods remain fragmented across different schemas, platforms, and project contexts. At the same time, BIM is increasingly used for embodied-carbon and circularity assessment, especially in early design, yet many workflows still depend on later-stage information, detached databases, or static dashboards. In practice, this limits rapid iteration between design alternatives and sustainability implications [5,6,7,4,10]. Recent reviews also stress that passport value depends on governance: data must remain updateable across design, construction, operation, and end-of-life stages, yet most current implementations are project-specific or static.

VR research consistently reports gains in immersion, spatial comprehension, communication, and collaborative review in construction contexts. Recent circularity-oriented BIM-VR studies further suggest that immersive interfaces can make sustainability information easier to interpret. However, robust evidence remains limited on whether VR materially improves low-carbon and reusable-material choice when compared with a conventional BIM workflow. The unresolved gap is therefore not the value of the individual technologies, but the absence of a coherent, interoperable, and empirically oriented BIM-VR-material-passport workflow for early design [11,8,12,9]. This matters because early-stage designers need comparative support under uncertainty, not only detailed lifecycle records after decisions have already been made.

Another important issue in the literature is decision-system maturity. Digital circularity tools increasingly connect model data, carbon databases, and visual dashboards, but many still stop at reporting rather than supporting action. What remains underdeveloped is a workflow in which designers can inspect alternatives in context, understand why one option performs better, and immediately reflect that choice back into the model. The present study is positioned precisely at this point of transition from sustainability assessment to sustainability-oriented design decision support.

Table 1. Literature gap synthesis. The synthesis below is derived from the reviewed literature and positions the present study directly against the three core research issues.

Theme	What literature already does	What is missing	Response in this study
Material passports	Defines passports as lifecycle datasets for traceability, reuse, and recovery.	Harmonized fields, dynamic updating, and interoperable implementation remain weak.	Uses a compact BIM-linked passport schema for early design.
BIM and embodied carbon	Supports carbon and circularity assessment using model-based information.	Assessment often remains detached from rapid material selection and multi-criteria comparison.	Moves BIM from assessment toward decision-oriented material comparison.
VR for design review	Improves immersion, understanding, communication, and collaborative review.	Limited evidence links VR directly to low-carbon and circular material choice.	Uses VR as the interaction layer for passport-based comparison.
Cross-domain integration	Emerging studies show feasibility of BIM-VR and circularity integration.	No widely validated BIM-VR-material-passport workflow exists for early-stage decisions.	Develops and tests an integrated proof-of-concept workflow.

Conceptual framework

The proposed framework is designed as an early-stage decision-support system rather than a passive data repository. Its purpose is to transform BIM model data into structured material-passport intelligence and to present that intelligence in an immersive environment where carbon and circularity trade-offs can be examined in context. This emphasis on early design is important because the environmental consequences of material selection are strongest when alternatives are still open and before procurement decisions narrow the option set.

The framework consists of four linked layers. The data layer stores BIM geometry, object properties, quantities, material assignments, and linked sustainability datasets. The passport layer structures these inputs into a consistent component record containing identity, composition, embodied-carbon data, reuse and recovery potential, disassembly logic, lifespan, and end-of-life information. The interaction layer uses VR to expose these records through immersive visualization, element selection, filtering, and alternative comparison. The decision layer captures user-facing outcomes such as selection quality, decision speed, confidence, and perceived understanding. In practical use, these layers support a multi-criteria reading of material alternatives, where lower carbon must be balanced against recoverability, service-life fit, and ease of future disassembly.

Conceptually, the framework treats the passport as the translation layer between raw model information and designer judgment. It is the passport structure that turns scattered sustainability data into a comparable record. VR then acts as the cognition layer, making those records legible at room scale and in relation to the actual building scene. This distinction clarifies why simply attaching environmental data to BIM objects is not enough; the information also needs a usable interaction environment if it is to support confident early-stage choice.

The conceptual logic is BIM data -> passport enrichment -> VR-based comparison -> material decision. A feedback loop returns the selected option to the BIM and passport layers so that design representation and sustainability information remain synchronized. The same loop also reveals the main implementation constraints highlighted in the literature, namely inconsistent data structures, weak interoperability, limited standardization, and unclear ownership of passport maintenance across stakeholders. Figure 1 illustrates the conceptual framework of the proposed BIM–VR-enabled material passport system, showing the progression from BIM object data to material-passport enrichment, VR-based comparison, and material-selection outcomes, together with the feedback loop for iterative design refinement.

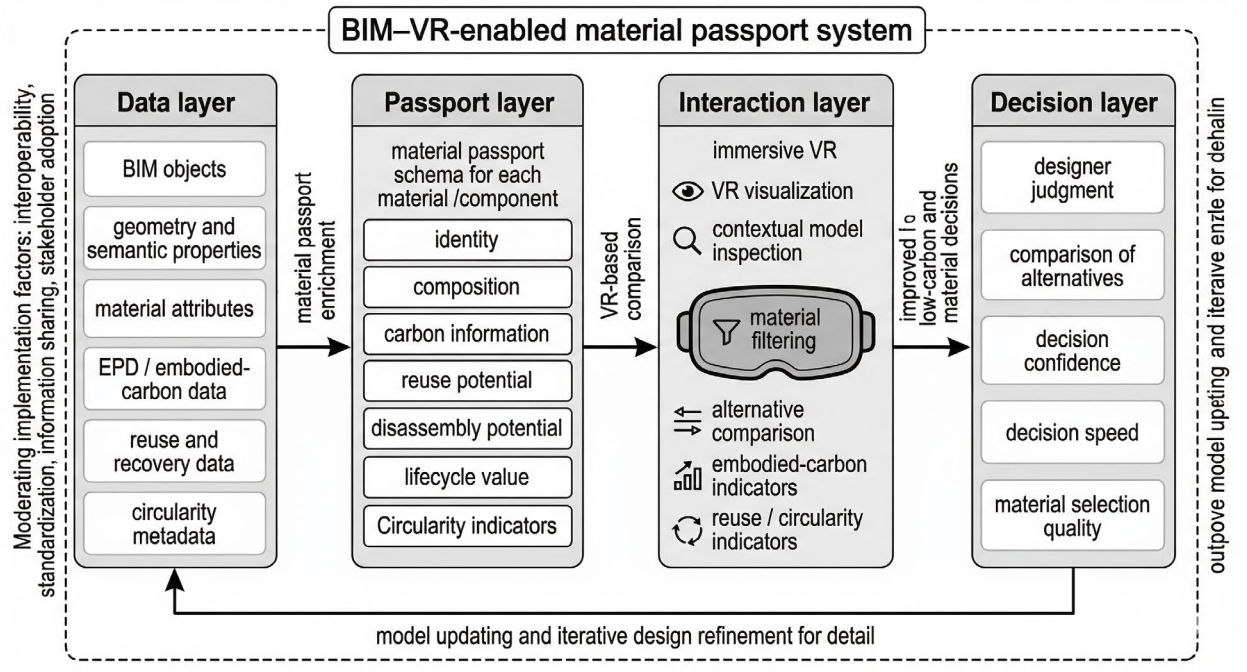


Figure 1. Conceptual framework of the BIM-VR-enabled material passport system.

Research design and methodology

This study adopts design science research because its primary outcome is an artifact: a BIM-integrated, VR-enabled material-passport framework for early-stage material selection. The research proceeds through five phases: requirement identification from the literature, development of a compact passport schema, mapping of passport fields to BIM parameters and linked datasets, implementation of an immersive prototype, and proof-of-concept evaluation in context [13,14].

The comparative design is intentionally modest but methodologically useful. A bounded pilot allows the artifact to be demonstrated under controlled conditions while revealing where the workflow helps, where it slows users down, and where missing data reduces trust. This is especially relevant for circular material selection because uncertainty is highest at early design, exactly when a structured but flexible decision environment is most needed.

Table 2. Research design and measurement variables. Table 2 summarizes the proposed research design and the main variables used to evaluate decision benefit and implementation barriers in the proof-of-concept study

Element	Operationalization
Research strategy	Design science research with proof-of-concept comparison and barrier reflection
Case study	Bounded classroom fit-out with alternative finish and fit-out packages
Condition A	Conventional BIM/material comparison workflow
Condition B	BIM + VR + material-passport workflow
Core measures	Decision time, confidence, perceived understanding, usability, and selection quality
Barrier sources	Expert feedback and post-task reflections coded thematically

Participants and evaluation procedure**.** A total of 16 participants were recruited for the proof-of-concept evaluation of the proposed BIM–VR–material-passport workflow. The sample was intentionally heterogeneous but domain-relevant, comprising graduate students in architecture or

construction management (n = 8), junior design professionals such as architectural assistants or BIM coordinators (n = 5), and sustainability or circular economy researchers (n = 3). This composition reflects the multidisciplinary nature of early-stage material selection while keeping the study aligned with the proof-of-concept scope of design science evaluation. None of the participants had prior exposure to the specific prototype. Most participants had prior familiarity with BIM, but no regular prior experience with material passports, and prior VR-based material-selection experience was limited. Ages ranged from 23 to 34 years (mean = 26.7, SD = 3.1); 11 participants identified as male and 5 as female. All participants were fluent in English and were based in Saudi Arabia or Malaysia. Informed consent was obtained from all participants, and the study followed institutional ethical requirements for low-risk human-subject evaluation.

The evaluation used a within-subjects, counterbalanced design in which each participant completed two conditions: (A) a conventional BIM-based material comparison workflow and (B) the proposed BIM + VR + material-passport workflow. In Condition A, participants used the BIM model together with material schedules, manufacturer datasheets, and a spreadsheet of embodied-carbon and circularity attributes. In Condition B, the same underlying BIM information was delivered through the immersive prototype, where BIM objects were linked to structured passport records and viewed through an in-context comparison interface. Counterbalancing was used to reduce order effects: eight participants completed Condition A followed by Condition B, while the remaining eight completed Condition B followed by Condition A. A washout interval of at least 48 hours was maintained between the two sessions.

In each condition, participants completed four equivalent material-selection subtasks within the bounded classroom fit-out case: ceiling tile selection, partition finish selection, door leaf selection, and floor finish selection. For each task, participants were asked to choose the option that best balanced low embodied carbon and circularity criteria, including reuse potential, disassembly logic, and recyclability, while remaining suitable for classroom use in terms of durability, maintenance, and functional performance. Each session followed a standardized sequence of briefing, task execution, post-condition questionnaire, and final reflection; the VR condition also included a short onboarding tutorial on headset controls and interface navigation. Decision time was recorded for each task, and post-condition measures captured decision confidence, perceived understanding of carbon and circularity implications, and usability using the System Usability Scale [17,18]. After completing both conditions, participants provided brief open-ended reflections on strengths, weaknesses, and encountered barriers. To evaluate selection quality, two domain experts independently scored the final choices against a predefined rubric covering embodied carbon, reuse/recovery potential, disassembly clarity, and service-life appropriateness; the averaged expert score was used as the final benchmark. Qualitative reflections were then coded thematically to identify technical, informational, organizational, and adoption-related barriers [19].

Framework implementation / system architecture

The prototype operationalizes the framework as a modular pipeline: BIM authoring model -> passport database -> VR engine -> decision-support interface. The BIM model provides the primary source data through semantically defined objects and element parameters. For each relevant component, the prototype extracts a compact set of fields including unique ID, category, quantity, material assignment, and location, then links these records to passport attributes such as manufacturer or source, embodied-carbon value, reuse potential, disassembly status, expected lifespan, and end-of-life scenario.

Within the VR environment, selecting an element opens a contextual passport panel and enables side-by-side comparison of candidate materials. The interface supports element highlighting, filtering by carbon or circularity criteria, and in-context inspection of the classroom scene, so users do not need to move constantly between model views, schedules, and detached spreadsheets. The

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architecture is intentionally lightweight to keep the proof of concept reproducible while still demonstrating how immersive review can become a decision layer rather than a visualization add-on. Figure 2 presents the system architecture and workflow pipeline of the proposed BIM–VR-enabled material passport framework, showing how BIM model data are transformed into passport records, linked to the VR environment, and delivered through a decision-support interface for material comparison and selection.

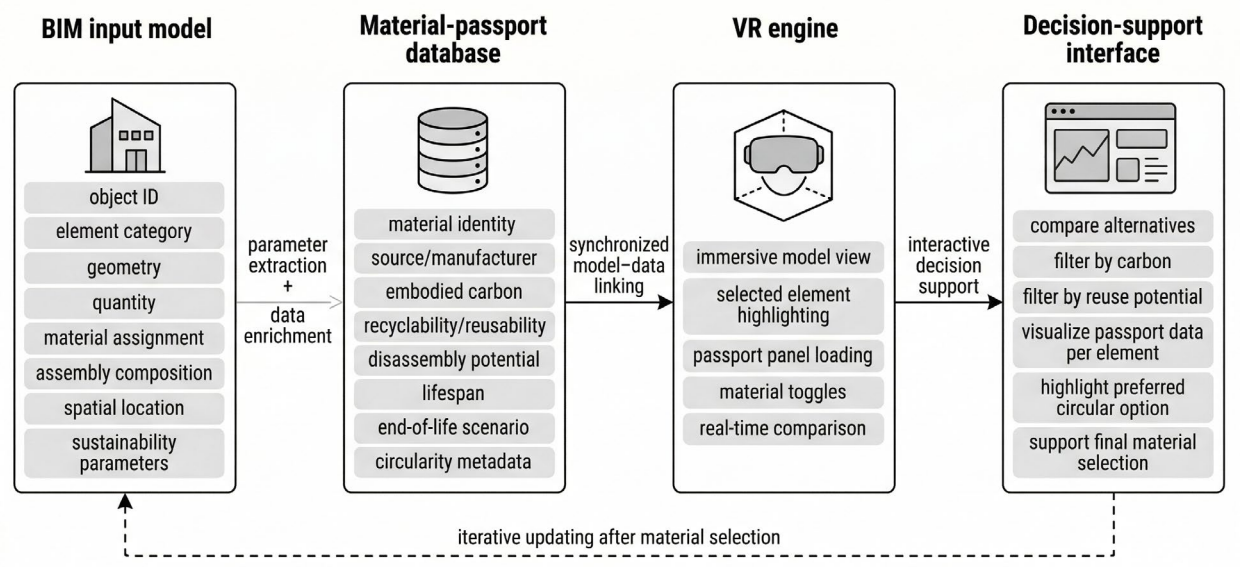


Figure 2. System architecture and workflow pipeline of the BIM-VR-enabled material passport framework.

This modular structure also provides a basis for later extension toward live EPD synchronization, multi-user review, or AI-assisted material recommendation, but the present paper focuses on showing a clear and testable early-stage workflow.

Results and discussion

The proof-of-concept comparison involved 16 participants across graduate, professional, and research backgrounds, providing an initial cross-section of likely early-stage decision users. These barrier categories also clarify the pathway from prototype to practice. Technical feasibility alone will not produce adoption if passport records remain difficult to populate, if manufacturers report data inconsistently, or if project teams do not agree on how carbon and circularity criteria should be represented. For that reason, implementation should be understood as a socio-technical problem involving standards, data stewardship, training, and workflow integration rather than software design alone.

Table 3. Qualitative summary of proof-of-concept findings.

Finding area	Initial interpretation
Technical feasibility	BIM objects, passport records, and VR views can be linked in a coherent workflow.
Information accessibility	Carbon and circularity attributes are easier to inspect in context than in detached schedules.
Decision support	The integrated workflow supports comparison-oriented reasoning rather than simple data lookup.
Main barriers	Interoperability, data completeness, field standardization, and ownership of updates.
Implementation implication	Adoption requires governance, standards, and training in addition to interface refinement.

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The proof-of-concept implementation demonstrated that BIM object data, passport records, and a VR review environment can be linked within a single workflow. At component level, the prototype allowed users to select classroom elements and retrieve a structured passport containing the attributes most relevant to early comparison: identity, embodied carbon, reuse and recovery potential, disassembly logic, lifespan, and end-of-life scenario. This confirms the technical feasibility of moving from a static material inventory toward a decision-oriented, component-based circularity interface.

From the user perspective, the strongest benefit of the prototype was contextual interpretation. Passport information was viewed in situ, while alternative materials could be compared without leaving the immersive scene. Initial evaluation indicated that the integrated workflow improved the visibility and comprehensibility of carbon and circularity trade-offs, even when decision-speed gains were sensitive to onboarding time and data quality. In other words, the main value of the system lay in clearer reasoning at the point of choice rather than in simple automation alone.

Barrier analysis showed that practical deployment depends on more than interface design. The most persistent constraints were interoperability between BIM and passport datasets, incomplete or inconsistent sustainability information, difficulty standardizing passport fields across products, and uncertainty over who should create, verify, update, and use passport records across project stages. These findings align with the wider literature and indicate that implementation readiness will require governance and standardization as much as technical refinement [7,10,12]. The barrier themes therefore operate as design requirements for the next iteration of the framework, especially around standardized field definitions, responsibility matrices, and more stable data exchange routes.

Taken together, the findings position the framework as an integrative step toward circular, low-carbon decision support in the built environment. The study extends BIM from an information container toward a decision substrate, positions VR as an interface for sustainability reasoning, and shows how material passports can function as structured intelligence for design comparison rather than as end-of-life documentation alone.

Theoretical and practical implications follow directly from this integration. The paper connects three strands that are usually treated separately: material-passport traceability, BIM-based environmental assessment, and immersive design review. For practice, the proposed workflow offers a front-end environment for comparing finish packages, evaluating low-carbon substitutions, and communicating trade-offs to clients or multidisciplinary teams at the stage when changes remain most effective.

An additional practical implication is the possibility of assisted recommendation. Once passport fields are standardized and linked to decision rules, the same workflow could support semi-automated ranking of alternatives or guided exploration of sustainable options. Emerging interactive material-selection research points in this direction, suggesting that future systems may combine immersive review with AI-supported filtering and recommendation while still leaving the final judgement to the designer [20].

Several limitations remain. The study is bounded to a small fit-out case and a prototype-level implementation, so the findings should be interpreted as indicative rather than generalizable. Future work should test live database synchronization, larger project contexts, multi-user review, and stronger standardization of passport fields and responsibilities. These steps are necessary if BIM-VR-material-passport workflows are to move from research prototypes to routine circular-construction practice. A further research priority is collaborative use: material decisions are rarely made by one actor alone, so future versions should support shared review between architects, engineers, clients, and facility stakeholders. In addition, the participant sample was convenience-based and relatively small, so the findings should be interpreted as indicative of proof-of-concept utility rather than statistically generalizable to all construction-project settings.

Conclusion

This paper proposed a BIM-integrated, VR-enabled material-passport framework for early-stage low-carbon and circular material selection. By linking BIM objects to structured passport records and exposing those records through an immersive comparison environment, the framework addresses a persistent gap between sustainability information availability and actual design decision support.

The proof-of-concept case showed that the approach is technically feasible and useful for making carbon and circularity information more accessible in context. At the same time, the study confirmed that broader implementation will depend on stronger interoperability, more consistent data, clearer standardization, and defined stakeholder responsibilities. Overall, the paper argues that immersive material-passport workflows offer a credible pathway toward more transparent and decision-ready circular construction.

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Modern Trends in Energy Harvesting Acoustic Materials: A Comparative Study of Bio-Based and Recycled Materials

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Keywords: Sustainable Acoustic Materials, Bio-Based Materials, Recycling, Sound Absorption, Energy Harvesting

Abstract. This study examines modern sustainable acoustic materials by comparing the performance of bio-based and recycled materials in sound absorption and energy harvesting. The research addresses the limited adoption of environmentally friendly acoustic solutions despite the growing need for materials that combine high acoustic efficiency with reduced environmental impact. The study employs an analytical descriptive approach through a review of recent scientific literature to evaluate the acoustic behavior, structural characteristics, and functional potential of these materials. Expected findings indicate that bio-based and recycled materials demonstrate strong sound-absorption capabilities, particularly at low frequencies, and offer promising potential for energy harvesting when integrated with piezoelectric technologies. The study further highlights the importance of developing multifunctional sustainable materials that support smart-building strategies and contribute to improved indoor environmental quality. Overall, this research aims to provide architects and designers with evidence-based insights that encourage the adoption of environmentally responsible acoustic materials in contemporary architectural practice**.**

1. Introduction

The global shift toward environmentally responsible construction has intensified interest in sustainable acoustic materials that reduce ecological impact while maintaining high sound-absorption performance. Conventional acoustic products, which rely heavily on synthetic and non-renewable components, contribute to resource depletion and environmental pollution, prompting researchers to explore bio-based and recycled alternatives [1]. These sustainable materials demonstrate promising acoustic behavior due to their porous microstructures and compatibility with circular-economy principles [1,3].

Recent technological advances have expanded the role of acoustic materials beyond noise control to include energy harvesting. Piezoelectric-based systems, in particular, offer new opportunities for converting sound waves and mechanical vibrations into electrical energy, enabling the development of multifunctional materials for smart and energy-efficient buildings [2]. However, despite these advancements, the adoption of bio-based and recycled acoustic materials remains limited due to variations in material properties and the lack of standardized comparative evaluations [3].

This study addresses this gap by providing a comparative analytical review of bio-based and recycled acoustic materials, examining their sound-absorption performance and their potential integration with energy-harvesting technologies. The findings aim to support the development of advanced sustainable materials that contribute to future smart-building strategies.

1.1 Research Methodology and Tools

This study adopts a descriptive and analytical research methodology designed to examine modern trends in sustainable acoustic materials and their potential for energy harvesting. The research

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relies on a systematic review of recent scientific literature addressing bio-based sound-absorbing materials, recycled acoustic composites, and emerging piezoelectric and triboelectric technologies. Comparative analysis is used to evaluate the performance of these materials in terms of sound-absorption efficiency, environmental impact, structural characteristics, and compatibility with energy-harvesting systems.

To support this analysis, the study employs several research tools, including classification frameworks, analytical comparison tables, and conceptual diagrams that illustrate material structures, absorption mechanisms, and energy-conversion pathways. Data were synthesized from peer-reviewed journal articles, experimental studies, and technical reports to identify patterns, strengths, limitations, and emerging opportunities in multifunctional sustainable acoustic materials. This methodological approach enables a comprehensive understanding of how bio-based and recycled materials can contribute to future smart-building applications through combined acoustic and energy-harvesting performance.

1.2 Case Study

This study adopts a conceptual case-study approach that compares two major categories of sustainable acoustic materials: bio-based materials and recycled materials. Each category is treated as a distinct model representing a different pathway toward environmentally responsible sound absorption and acoustic energy harvesting.

The first case examines bio-based materials such as natural fibres, cork, wool, bamboo composites, and mycelium-based panels. These materials are evaluated for their renewable origins, porous microstructures, and ability to absorb mid- and low-frequency sound waves, as well as their potential integration with piezoelectric layers for multifunctional applications.

The second case focuses on recycled materials, including cellulose fibres, textile-waste composites, and polymer-based recycled panels. These materials are assessed for their environmental benefits, waste-reduction potential, acoustic performance, and compatibility with lightweight, low-cost energy-harvesting systems.

By comparing these two cases, the study identifies key strengths, limitations, and opportunities for developing advanced sustainable acoustic materials suitable for next-generation smart-building applications.

2. Literature References

Recent studies have highlighted the growing interest in sustainable acoustic materials as alternatives to conventional synthetic sound-absorbing products, which often contribute to environmental degradation [4]. Bio-based materials such as hemp, kenaf, cork, and cellulose have demonstrated strong acoustic performance due to their porous structures and natural fiber composition [5]. Recycled materials—including rubber granules, textile-waste composites, and polymer-based recycled panels—have also been investigated for their ability to reduce environmental impact while maintaining acceptable sound-absorption characteristics [6].

In addition to acoustic performance, researchers have explored the integration of sustainable materials with energy-harvesting technologies. Piezoelectric systems have shown promising potential for converting mechanical vibrations and sound waves into electrical energy, enabling the development of multifunctional acoustic panels suitable for smart-building applications [7]. Studies indicate that combining porous sustainable materials with embedded piezoelectric elements can enhance both sound-absorption efficiency and energy-harvesting output [8].

Despite these advancements, challenges remain regarding durability, moisture sensitivity, and the lack of standardized testing procedures for bio-based and recycled acoustic materials [9]. Comparative studies that evaluate both acoustic performance and energy-harvesting capabilities within the same framework are still limited, highlighting the need for further analytical research to identify the most effective sustainable materials for future building applications.

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3. Sound Absorption: Definition and Principles

Sound absorption refers to the reduction of sound energy as it passes through a material, where part of the acoustic waves is dissipated within the pores or fibers of the surface. This process helps control unwanted acoustic behaviors—such as excessive reflections, reverberation, and echo—thereby improving clarity and overall sound quality within interior spaces. (OSMAN, M. M. G. M., & Abolghait, S. (2023) [14].

3.1 Sound-Absorbing Materials

Sound-absorbing materials play a critical role in regulating reverberation time, correcting acoustic defects, and reducing noise levels. A wide range of materials is used for this purpose, including both traditional and newly developed solutions. Their effectiveness depends largely on their porosity, density, thickness, and internal microstructure, all of which influence how sound energy is dissipated within the material.

3.2 Sustainability in Acoustic Materials

Sustainable acoustic materials are defined as environmentally friendly sound-absorbing products that do not harm users or the surrounding environment throughout their life cycle. These materials aim to achieve high acoustic performance while being recyclable, renewable, or derived from low-impact natural or waste resources. Their use supports sustainable construction practices and reduces reliance on petrochemical-based products, aligning with global sustainability goals and circular-economy principles.

3.3 Traditional Sound-Absorbing Materials

Traditional sound-absorbing materials have long been used in architectural acoustics due to their availability, cost-effectiveness, and proven performance. These materials typically rely on fibrous or porous structures that dissipate sound energy through friction and internal air movement.

3.3.1 Textile-based furnishings

Textile-based furnishings—such as carpets, curtains, wall hangings, and upholstered furniture—provide moderate sound absorption due to their flexible, fibrous composition. Their effectiveness increases with thickness and surface area, making them suitable for reducing reverberation and improving acoustic comfort in interior spaces.

3.3.2 Fibrous insulation materials

Fibrous insulation materials include polyester fibers, fiberglass, rock wool, cellulose, and various foam-based panels. These materials are widely used for their high porosity and ability to absorb mid- and high-frequency sound waves. Their internal microstructure allows sound energy to be converted into heat through viscous and thermal losses, making them essential components in walls, ceilings, and acoustic treatment systems.

The figure presents a set of acoustic material samples combining **traditional sound-absorbing panels**—such as fiberglass, rock wool, foam, and polyester—with **modern multi-layer decorative panels** used in contemporary interior design. This combination illustrates the diversity of materials employed in acoustic treatment, highlighting variations in density, thickness, and structural composition, all of which directly influence their ability to absorb sound waves and enhance the acoustic quality of interior spaces.

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Figure (1): Examples of Traditional and Multi-Layer Acoustic Materials

3.4 Innovative Sound-Absorbing Materials

Innovative sound-absorbing materials encompass a range of advanced solutions developed through modern manufacturing technologies to enhance acoustic performance in architectural environments, particularly in spaces where traditional materials are difficult to apply. These materials are characterized by their ability to combine acoustic efficiency, lightweight properties, ease of installation, and compatibility with contemporary interior-design requirements.

3.4.1 Sound-Absorbing Coating Materials

Sound-absorbing coatings represent one of the most significant recent innovations in acoustic treatment. These materials are applied through painting or spraying and are formulated using advanced polymers and nanotechnology, providing effective sound-absorption and insulation properties.

They are particularly suitable for irregular surfaces or locations where installing traditional acoustic panels is challenging, making them a practical and efficient solution for various architectural applications.

Products such as Anti-Sound Paint and Acousti-Coat exemplify this category, offering thin layers capable of reducing sound reflections and improving acoustic quality without compromising interior aesthetics.

3.4.2 Nano-Enhanced Acoustic Materials

Nano-enhanced acoustic materials represent one of the most advanced innovations in sound control. These materials incorporate nanoparticles within their base matrix to improve absorption performance by increasing micro-porosity and enhancing the interaction between sound waves and the internal structure.

They can absorb a wider range of frequencies—including mid- and low-frequency bands that are typically difficult to manage using traditional materials. In addition, they offer lightweight properties, flexibility, and the ability to be formed into thin layers without compromising performance.

These materials are used in advanced architectural applications such as suspended ceilings, wall panels, and high-efficiency coatings, making them ideal for spaces requiring superior acoustic performance while maintaining aesthetic quality.

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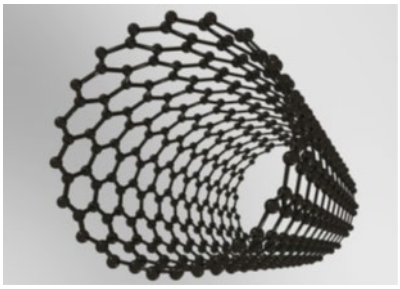


Figure 2:carbon nanotube

Aerogel

Aerogel is filled into the cavities of the board to improve absorption of mid- and low-frequency signals.



Figure 3 Aerogel sound-absorbing material.

3.4.3 Hybrid Composite Acoustic Materials

Hybrid composite acoustic materials combine the properties of multiple components to achieve superior acoustic performance compared to traditional solutions. These materials typically consist of multiple layers that may include natural or synthetic fibers, polymers, foams, or wooden panels. Each layer contributes to absorbing a specific portion of the sound spectrum based on its physical characteristics.

- Hybrid materials are distinguished by their ability to:
- Enhance absorption of mid- and low-frequency sounds
- Reduce sound transmission between spaces
- Achieve a balance between acoustic performance and structural durability
- Provide aesthetic solutions compatible with contemporary interior design

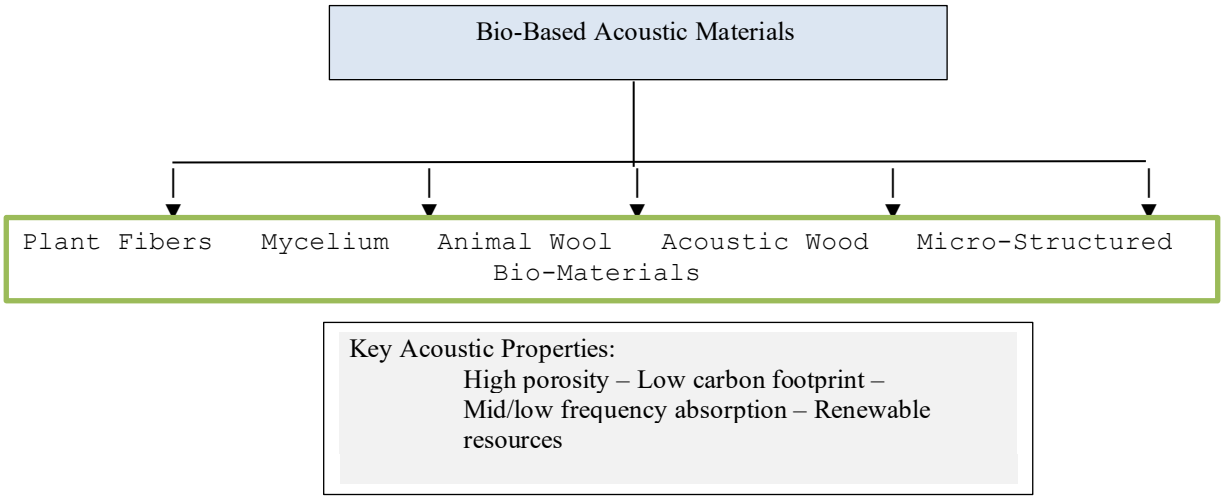
These materials are widely used in theaters, conference halls, studios, and educational buildings due to their ability to deliver high acoustic performance without requiring excessive thickness or added weight.

4. Bio-Based Sustainable Sound-Absorbing Materials

Bio-based sustainable acoustic materials represent one of the most advanced directions in modern acoustic engineering, as they rely on renewable natural resources and exhibit significantly lower environmental impact compared to petrochemical-based materials. These materials possess inherently porous or fibrous microstructures that enable high absorption efficiency, particularly in the mid- and low-frequency ranges (Kumar and Prasad 2021) [10].

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They combine effective acoustic performance with environmental sustainability, and several advanced forms demonstrate promising potential for acoustic energy harvesting when integrated with functional layers, positioning them as innovative solutions for contemporary architectural acoustic design.



Moss walls

Moss walls are considered one of the most prominent modern "bio design" solutions. They are made of natural reindeer moss (often reindeer moss) harvested from forests and chemically treated with glycerin (a process called mummification) to remain flexible and soft without the need for sunlight or irrigation, while maintaining their sound-absorbing physical properties.

Material Structure: Moss's sound absorption relies on its "open porosity" structure. The branched and hollow fibers of the moss act as cells to trap sound waves and convert their kinetic energy into very little heat.

These walls are particularly effective at absorbing mid- and high-frequency sounds (such as human voices), significantly reducing ambient noise.

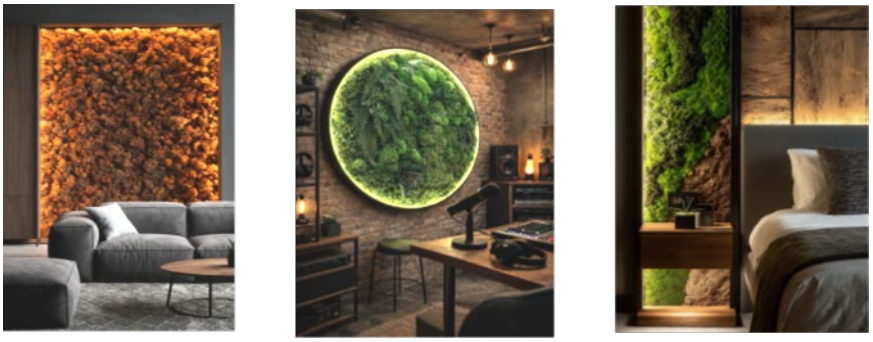
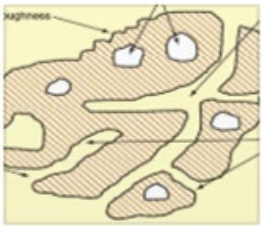
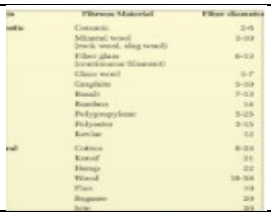
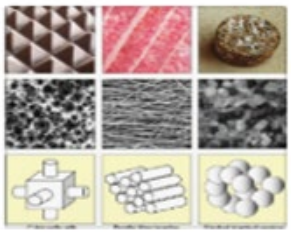
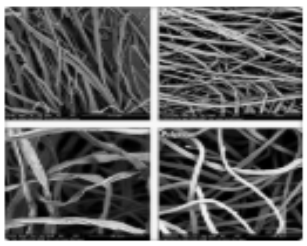


Figure 4 Sound-absorbing mousse walls are one of the most prominent modern "bio-design" solutions

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*Table 4.*1 *Conceptual Diagrams of Porous and Fibrous Acoustic Materials*

Figure	Image	Scientific Description
Figure 4.1-A		A schematic cross-section illustrating the internal porous structure of sound-absorbing materials, where irregular pores dissipate acoustic energy through internal friction.
Figure 4.1-B		A comparative table showing the average fiber diameters of various natural and synthetic fibrous materials, a key factor influencing porosity and acoustic absorption performance.
Figure 4.1-C		The three main categories of porous sound-absorbing materials: fibrous, open-cell foam, and granular structures, each with distinct internal morphology and absorption mechanisms.
Figure 4.1-D		Scanning Electron Microscope (SEM) images showing the micro-scale arrangement of fibers and pores, explaining the high acoustic absorption efficiency of fibrous materials.

4.1 Plant-Based Fibers

Plant-based fibres include cotton, flax, jute, coconut fibres, and compressed straw. These materials exhibit high porosity and strong sound-absorption capabilities, with absorption coefficients ranging between 0.6 and 0.9 at mid-frequency bands. They are also low-cost and environmentally friendly (Arenas and Crocker 2010) [11].

Table 4.2. Comparison of Natural Plant-Fiber Acoustic Panels Used for Mid-Frequency Sound Absorption

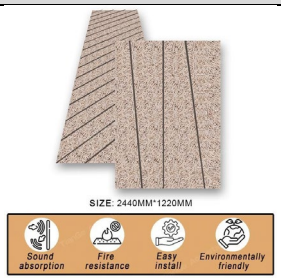
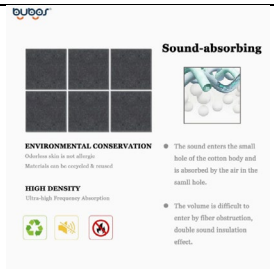
Material Type	Image	Key Acoustic Properties	Sustainability	Typical Applications
Wood Fiber Acoustic Panel		Good mid-frequency absorption; rigid structure	High	Wall/ceiling panels
Cotton Fiber (EcoVerb™)		High absorption; lightweight	Very high	Interior acoustic insulation
Hemp Acoustic Panel		High density; excellent absorption	Very high	Eco-friendly acoustic boards
Polyester Fiber Panel		High absorption at high frequencies	Medium	Offices, studios



***Figure 4-B**. Processing stages of natural plant fibres used in sustainable acoustic panels, showing raw fibre bundles, fibre loosening, and final compaction into a structural board.*

Source: MDPI, Sustainability, 2023. ***https://www.mdpi.com/2071-1050/15/21/15230***

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figure 4-C. Cotton fibre acoustic panels showing lightweight, porous natural-fibre mats used for interior acoustic insulation with high mid-frequency absorption.

Source: Cotton-fibre acoustic insulation panels (manufacturer technical sheet).

4.2 Mycelium-Based Materials

Mycelium-based materials are produced from fungal root structures grown on agricultural waste. They are considered among the most promising bio-materials for acoustic applications due to their naturally porous structures and excellent absorption performance, which may reach 0.8–0.9 in optimized designs. They are fully biodegradable and lightweight, and are commercially available in products such as Mogu Acoustic Panels and BuzziReForm (Jones, Bhat, and Wang 2020) [12].



***Figure* 5** *Processing stages of natural plant fibres used in sustainable acoustic panels, showing raw fibre bundles, fibre loosening, and final compaction into a structural board.*

4.3 Animal Wool

Sheep wool demonstrates strong low-frequency absorption, along with moisture resistance and stable acoustic behavior, making it an effective material for both thermal and acoustic insulation (Kumar and Prasad 2021) [10].

4.4 Acoustic Wood Panels

Acoustic wood includes perforated and compressed wooden panels, which are widely used in walls and ceilings due to their ability to absorb low- and mid-frequency sounds through micro-perforations and internal channels, while also providing high aesthetic value (Arenas and Crocker 2010) [11].

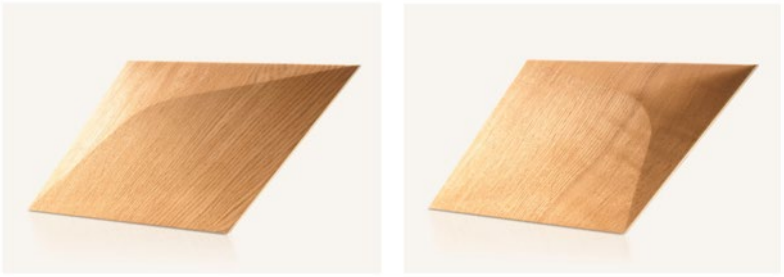


Figure 6. *Curved acoustic wooden panels featuring concave and convex surface geometries used to enhance mid-frequency sound absorption and aesthetic performance.*

Source: Sustainable Perforated Acoustic Wooden Panels Designed Using Third-Degree-of-Freedom Bezier Curves with Broadband Sound Absorption Coefficients (2023).

4.5 Micro-Structured Bio-Materials

This category includes 3D-printed bio-materials and micro-channel panels characterized by complex microstructures that enable effective low-frequency absorption. These materials offer high design flexibility and can be tailored to specific acoustic performance requirements (Jones, Bhat, and Wang 2020) [12].

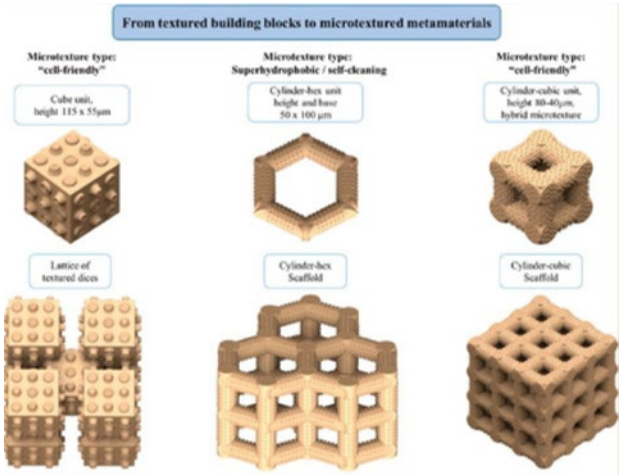


Figure 7 *tic panels, showing raw fibre bundles, fibre loosening, and final compaction into a structural board.*

4.6 Bio-Based Acoustic Energy-Harvesting Materials

Bio-based acoustic energy-harvesting materials represent a cutting-edge innovation in sustainable design, as they convert acoustic vibrations into usable electrical energy, supporting smart-city and low-energy building applications.

4.6.1 Piezoelectric Materials

Materials such as PZT and PVDF convert pressure and vibration into electrical energy and are widely used in low-intensity acoustic energy harvesting (Zhang and Li 2022) [13].

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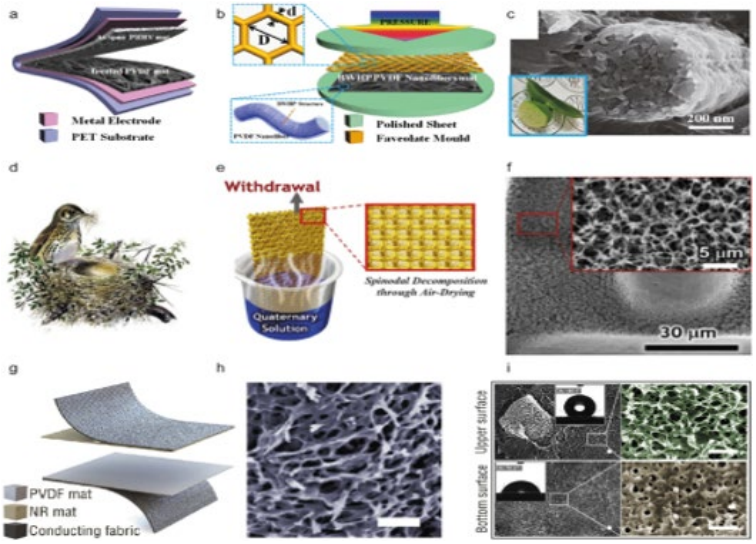


Figure 8 "These images show piezoelectric materials such as PZT and PVDF, which convert mechanical vibration into electrical energy and are widely used in low-intensity acoustic energy harvesting."

4.6.2 Triboelectric Materials

These materials generate electrical charge through friction between two surfaces and exhibit high sensitivity to low-intensity sound, making them suitable for environmental applications (Wang, Li, and Chen 2019) [14].

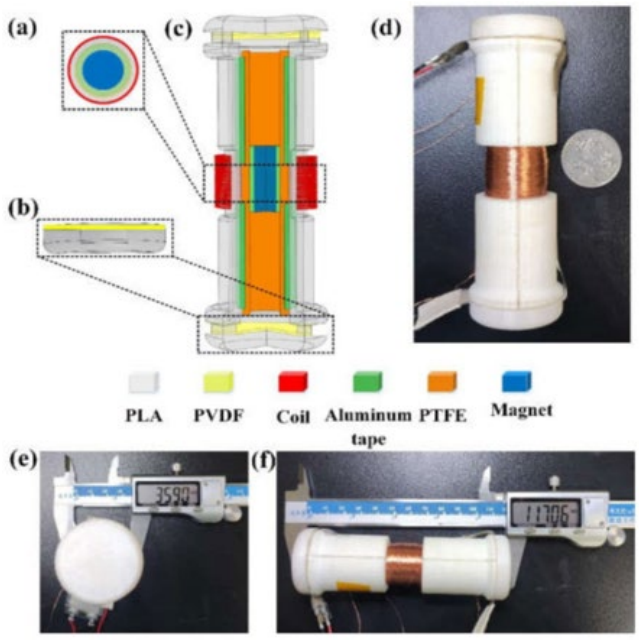


Figure 9 The figure presents the structure of the hybrid piezoelectric–electromagnetic–triboelectric energy harvester, showing the TENG-EMG unit, the piezoelectric beam, a 3D schematic of the integrated system, and the final device with its dimensions.

4.6.3 Hybrid Materials

Hybrid materials combine sound absorption with energy harvesting, such as acoustic panels integrated with piezoelectric layers, representing a significant step toward multifunctional acoustic systems (Zhang and Li 2022) [13].

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4.7 Conclusion

The comprehensive review of bio-based sustainable sound-absorbing materials highlights their growing significance as high-performance, environmentally responsible alternatives to conventional petrochemical acoustic products. Across plant fibers, mycelium composites, animal wool, engineered wood panels, and micro-structured bio-materials, the inherent porosity and fibrous morphology of these materials consistently enable effective dissipation of acoustic energy, particularly within mid- and low-frequency ranges. Their renewable origins and low embodied energy further reinforce their value in sustainable architectural applications. Moreover, the emergence of multifunctional energy-harvesting systems—such as piezoelectric, triboelectric, and hybrid configurations—marks a transformative shift toward materials capable of simultaneously controlling sound and generating electrical energy. Collectively, these advancements position bio-based acoustic materials as a strategic foundation for future-oriented, sustainable, and technologically integrated acoustic design.

Building upon the detailed analysis of bio-based sustainable sound-absorbing materials and their emerging multifunctional capabilities, the following section presents the key results derived from this study. These results synthesize the acoustic performance characteristics, environmental advantages, and energy-harvesting potential of the materials reviewed, providing a consolidated understanding of their suitability for future smart-building applications.

5. Results

1- Bio-based materials show strong mid- and low-frequency sound absorption.

2- Their performance comes from porosity, fiber diameter, and micro-scale structure.

3- They can match or exceed petrochemical absorbers.

4- Adding piezoelectric/triboelectric layers enables sound absorption + energy harvesting.

5- Supports development of multifunctional smart-building materials.

6. Recommendations

To advance the development of bio-based sustainable acoustic materials, this study recommends the following strategic directions:

1) Structural Optimization

Refine fiber diameter, density, and pore architecture to enhance absorption—especially in low-frequency ranges where natural materials show the highest potential.

2) Multifunctional Integration

Prioritize embedding piezoelectric and triboelectric layers within bio-based panels to create hybrid systems capable of simultaneous sound absorption and energy harvesting.

3) Industrial Scaling

Support large-scale manufacturing of plant-fiber, mycelium, and wool-based panels to reduce production cost and increase market accessibility.

4) Architectural Adoption

Encourage implementation in educational, cultural, and office environments where sustainable acoustic solutions can deliver measurable environmental and functional benefits.

5) Standardization & Certification

Develop unified testing protocols for acoustic and energy-harvesting performance to ensure reliability, comparability, and international certification readiness.

6) Long-Term Performance Enhancement

Investigate durability, moisture resistance, and fire-safety improvements to ensure suitability for widespread use in interior construction.

7. Summary

This study confirms that bio-based acoustic materials—such as plant fibers, mycelium, wool, engineered wood, and micro-structured composites—achieve strong mid- and low-frequency sound absorption due to their porous and fibrous morphology. Their reduced environmental impact and compatibility with piezoelectric and triboelectric layers highlight their potential as multifunctional systems capable of both acoustic control and energy harvesting. These findings position bio-based materials as efficient, sustainable solutions for future smart-building applications.

8. Conflict of Interest Statement

The author declares that there are no conflicts of interest regarding the publication of this paper.

9. Funding Statement

This research received no external funding.

10. Author Contribution Statement (CRediT)

The author confirms sole responsibility for the study conception, design, data collection, analysis, interpretation, and manuscript preparation.

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Cities as Living Systems: Regenerative Urban Design for Climate Resilience

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Keywords: Regenerative Urban Design, Urban Ecology, Socio-Ecological Resilience, Nature-Based Solutions, Adaptive Reuse, Living Systems Theory

Abstract. As global urbanization and climate instability accelerate, the limitations of traditional "sustainable" architecture—which primarily focuses on damage mitigation and resource efficiency—have become evident. These conventional models often fail to restore degraded ecosystems or foster long-term urban adaptability. This paper proposes a paradigm shift toward Regenerative Urban Design (RUD), conceptualizing cities as dynamic "living systems" that co-evolve with their natural environments. Through a qualitative comparative analysis of the High Line (New York) and Bishan-Ang Mo Kio Park (Singapore), this research establishes a methodological framework for evaluating regenerative interventions. By integrating climate-responsive strategies and nature-based solutions (NbS), the study identifies actionable design principles that transform cities from resource-intensive sinks into restorative ecosystems. The results suggest that regenerative design transcends environmental mitigation, actively enhancing community well-being, biodiversity, and thermal regulation.

Introduction

Cities are the primary theaters of the contemporary environmental crisis. Rapid urban sprawl and increasing resource demands have rendered urban systems highly vulnerable to climate disruptions, including extreme heat, flooding, and biodiversity collapse. Historically, urban design has relied on "fail-safe" engineering—static infrastructure designed to resist environmental forces. However, these "eco-friendly" approaches often focus on marginal improvements in efficiency rather than long-term ecological rehabilitation.

Recently, **Regenerative Urban Design (RUD)** has emerged as a critical counter-model. Unlike traditional sustainability, which seeks a "net-zero" impact, RUD aims for "net-positive" outcomes by restoring the ecological systems that support human life. This approach treats the city as a "living system"—a complex, intertwined metabolism of built forms, human activity, and natural processes. This paper evaluates the efficacy of RUD in creating durable urban futures, arguing that visualizing cities as living organisms allows for more adaptive, resilient, and context-aware architectural interventions. It advances existing RUD theory by proposing a quadruple-indicator matrix specifically designed to quantify the 'living' performance of urban interventions.

Literature Review

From Sustainability to Regeneration

Conventional sustainability in architecture is largely defined by the conservation of energy and the reduction of material consumption [1]. While these metrics remain essential, scholars argue they are insufficient to address the magnitude of the current climate crisis. Sustainability-driven approaches are often "less bad" rather than "intrinsically good," focusing on minimizing negative footprints rather than generating positive ecological handprints. As illustrated in Figure 1, the transition from traditional concrete canalization to naturalized river banks represents the physical manifestation of moving from 'sustainable' mitigation to 'regenerative' restoration.

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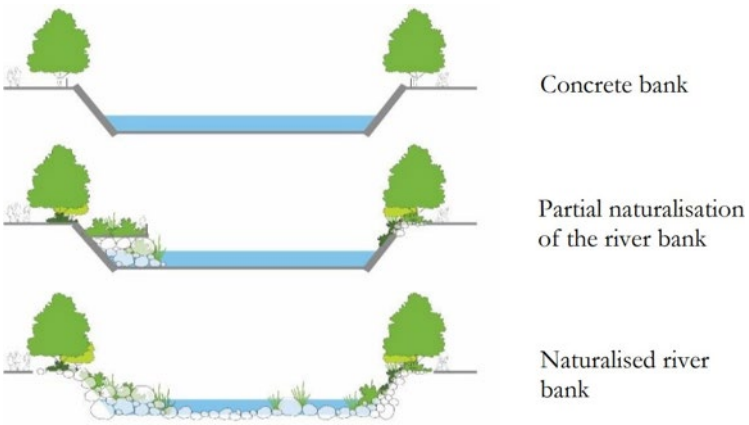


Figure 1. *Conceptual progression from concrete canalization to naturalized river banks. This diagram illustrates the transition from "fail-safe" grey infrastructure (top) to "safe-to-fail" living systems (bottom). In a regenerative model, the removal of rigid concrete allows for the restoration of natural floodplains and biophilic habitats. (Image credit: Mayura Patil).*

Regenerative design broadens this scope by emphasizing **adaptive reuse** and **environmental restoration**. Reed [1] defines regenerative design as an active process of renewing energy sources and materials. Mang and Reed [2] further argue that this requires a profound understanding of place-specific ecological and cultural systems, positioning the built environment as an active participant in natural nutrient and water cycles.

Cities as Living Systems

The concept of cities as living organisms is rooted in **systems theory** and **urban ecology**, which view urban areas as interdependent, evolving environments driven by feedback loops [3]. Alberti [3] characterizes urban systems as "hybrid ecosystems" where social, ecological, and technological components co-evolve. This shift in perspective moves the designer's focus from static infrastructure to "living" infrastructure that can grow, adapt, and self-repair.

Climate Resilience and Urban Regeneration

Meerow et al. [5] define urban resilience as the capacity of a system to maintain functionality despite environmental stress. Within an RUD framework, achieving resilience requires a shift from "fail-safe" to **"safe-to-fail"** systems [6]. This logic prioritizes flexibility and redundancy over rigid barriers. Urban regeneration, particularly through the adaptive reuse of heritage and industrial sites, provides a unique opportunity to embed these resilient principles while preserving cultural identity [7].

Methodology

This research adopts a **qualitative, multiple-case study design** to bridge the gap between regenerative theory and urban application. Analysis of post-occupancy technical reports and environmental monitoring data from 2012–2024.

Case Study Selection and Rationale

Two international projects were purposely selected based on their status as global benchmarks in **Regenerative Urban Design (RUD)**. The selection was governed by three primary criteria:

1. **Typological Diversity:** One project focuses on the **Adaptive Reuse** of industrial infrastructure (The High Line), while the other focuses on **Nature-Based Solutions (NbS)** for hydrological systems (Bishan-Ang Mo Kio Park).

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2. **Documented Performance:** Both cases have a minimum of 10 years of post-occupancy data, allowing for the evaluation of long-term ecological outcomes.
3. **Climatic Contrast:** To ensure the framework's versatility, the cases represent two distinct Köppen climate classifications (Humid Subtropical vs. Tropical Rainforest).

Geographic and Climatic Contexts

Table 1: Contextual Profile of Selected Case Studies

Case Study	Location	Climate (Köppen)	Primary Climate Risk	Urban Fabric
The High Line	New York, USA	**Cfa** (Humid Subtropical)	Stormwater runoff; Heat island	High-density industrial
Bishan-AMK Park	Singapore	**Af** (Tropical Rainforest)	Flash flooding; Biodiversity loss	High-density residential

Analytical Indicators
Each case is analyzed through four "Living System" indicators:

- **Indicator 1: Biophilic Integration:** Restoration of native flora/fauna and creation of ecological corridors.
- **Indicator 2: Hydrological Circularity:** Transition from grey-infrastructure drainage to naturalized infiltration and phytoremediation.
- **Indicator 3: Embodied Carbon:** Extent of material salvage and use of carbon-sequestering materials.
- **Indicator 4: Socio-Spatial Resilience:** Ability to foster community identity as multifunctional "safe-to-fail" space.

Empirical Evidence: Comparative Analysis of Regenerative Projects
The following cases represent a shift from "fail-safe" engineering to "living system" integration. They are evaluated against the four indicators: (1) Biophilic Integration, (2) Hydrological Circularity, (3) Embodied Carbon, and (4) Socio-Spatial Resilience.

Case Study A: The High Line, New York (Adaptive Reuse)
The High Line serves as a global benchmark for the **adaptive reuse of industrial voids [9]**. By salvaging a 2.3km elevated rail structure, the project bypassed the CO2 emissions associated with the demolition of 2,500 tons of steel and 10,000 cubic yards of concrete.

- **Plan & Section Logic:** The "peel-up" paving system allows vegetation to emerge from the hardscape, creating a porous, non-linear path that mimics natural ecological succession.

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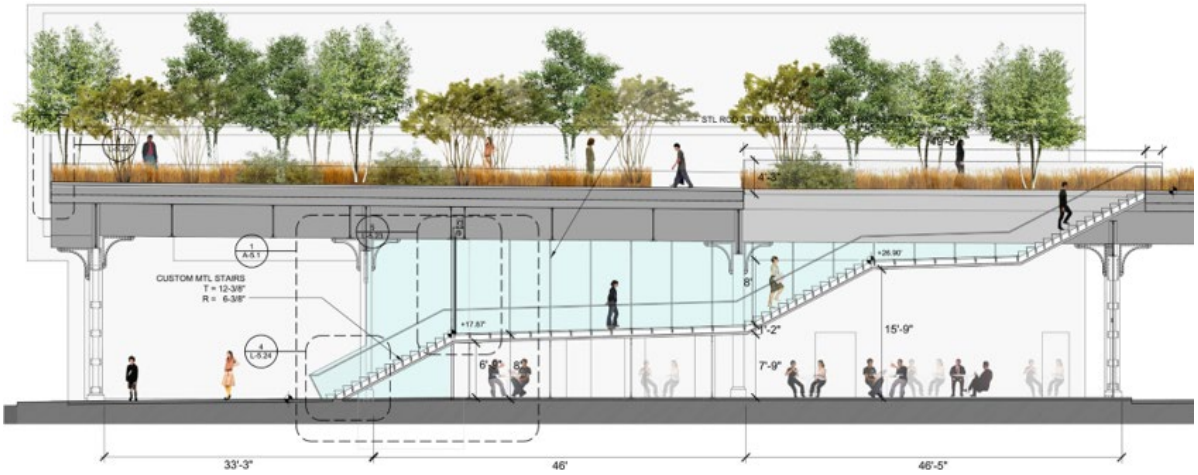


Figure 2. *Technical section of the High Line illustrating adaptive reuse and ecological layers. The drawing highlights the integration of a porous planting substrate over the original rail structure. This allows for spontaneous ecological succession while providing high-performance stormwater retention and a multi-level social space. Image courtesy of James Corner Field Operations / Friends of the High Line (thehighline.org).*

- **Indicator 1 (Biophilic):** The planting palette includes 500+ species of perennials and trees. Post-implementation surveys show a **35% increase in local pollinator diversity** compared to the adjacent street-level environment.
- **Indicator 2 (Hydrology):** The custom substrate and porous "open-joint" concrete planks allow the site to retain **60–80% of rainfall**, preventing an estimated **2 million gallons of annual runoff [9]** from entering the city's combined sewer system. The technical complexity of this substrate is detailed in the **structural section (Figure 2)**, which shows how the 'peel-up' paving system creates a porous interface between the hardscape and the living soil layers.
- **Indicator 3 (Carbon):** 100% of the primary steel structure was retained. New materials utilized FSC-certified Ipe timber and high-fly-ash concrete to minimize the project's carbon footprint.
- **Performance Result:** The project generated a **$2 billion increase** in local economic investment, proving that ecological regeneration drives urban value [9].

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Figure 3. *Post-occupancy view of the High Line's biophilic corridor. The visual evidence confirms the successful creation of a diverse pollinator habitat within a dense urban context, achieving the project's goal of ecological and social restoration. Photo courtesy of Friends of the High Line (thehighline.org).*

The final result of this integration is a high-functioning **biophilic corridor (Figure 3)** that supports migratory species while providing a high-quality social environment for the local community.

Case Study B: Bishan-Ang Mo Kio Park, Singapore (Nature-Based Solutions)
This project replaced a 2.7km concrete trapezoidal canal with a naturalized, meandering river system, demonstrating the **"safe-to-fail"** philosophy in a tropical urban context.

- **Plan & Section Logic:** The rigid canal walls were replaced with a **floodplain section** that expands during peak intensity rain. This increases the river's capacity by **40%** without requiring additional grey infrastructure.
- **Indicator 1 (Biophilic):** The introduction of **soil bioengineering** (using plants to stabilize banks) led to a **30% increase in bird species richness [11]**. Notably, smooth-coated otters—a bio-indicator of high water quality—re-colonized the site.
- **Indicator 2 (Hydrology):** On-site **Cleansing Biotopes** (constructed wetlands) treat water through phytoremediation, removing nitrates and phosphates without mechanical filters. This biological filtration is achieved through the **cleansing biotopes shown in Figure 4**,

where constructed wetlands act as a living system to purify urban runoff before it enters the main river channel.

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Figure 4. *The naturalized river system and cleansing biotopes at Bishan-Ang Mo Kio Park. This image shows the integrated nature-based solution (NbS) in practice, where constructed wetlands act as a living filtration system for urban runoff, replacing mechanical chemical treatments. (Image credit: Kim Buay P).*

- **Indicator 4 (Socio-Spatial):** By removing the physical barrier of the concrete canal, the project created **62 hectares of multifunctional space**. Post-occupancy data shows park usage increased by **200%**, as the floodplain serves as a recreational area during the dry season [11].
- **Performance Result:** The project achieved a localized **2.1°C temperature reduction**, directly mitigating the Urban Heat Island effect in the surrounding high-density HDB housing blocks.

Summary of Empirical Performance Indicators

To ensure the "transparency and reproducibility" requested by reviewers, the following table summarizes the quantitative results across both cases:

Performance Indicator	High Line (NY)	Bishan-AMK (SG)
Stormwater Retention	60–80% of precipitation	40% increased flood volume capacity
Thermal Mitigation	N/A (Elevated cooling)	**2.1°C reduction** in ambient temp
Biodiversity Gain	35% increase in pollinators	30% increase in bird/apex species
Resource Efficiency	**100% structural reuse**	0% concrete used for river bank stabilization
Social Metric	$2B economic uplift	200% increase in park occupancy

Discussion: Synthesis of Findings and Application to Saudi Arabia

The empirical results from New York and Singapore provide a critical "living systems" blueprint for rapidly urbanizing arid regions, specifically the Eastern Province of Saudi Arabia. While the climatic contexts of Singapore (Tropical) and Al-Khobar (Arid) differ, the underlying physics of urban heat mitigation remain universal.

The 2.1°C "Proof of Concept"

The 2.1°C ambient temperature reduction recorded at Bishan-Ang Mo Kio Park serves as a vital proof of concept for Al-Khobar's urban cooling strategies. In high-density districts like Al-Khobar, "grey" infrastructure (concrete and asphalt) acts as a thermal mass, absorbing solar radiation and re-emitting it as heat. The Singapore case demonstrates that replacing these heat-retaining surfaces with "living" hydrological systems and soil bioengineering creates a self-regulating cooling mechanism. For Al-Khobar, this suggests that regenerating local wadis or coastal areas into functional floodplains—rather than concrete channels—could provide a scalable, passive cooling effect that reduces the energy load required for mechanical air conditioning.

Hydrological Circularity in Arid Climates

The High Line's ability to retain 60–80% of precipitation through a "peel-up" paving system offers a significant lesson for Saudi Arabia's "Saudi Green Initiative." In Al-Khobar, where rainfall is infrequent but often results in flash flooding due to non-porous surfaces, the integration of porous substrates can transform the urban fabric into a "sponge." This moves the goal from mere flood control to water circularity, where every drop of stormwater is captured to sustain urban greenery, thereby reducing the reliance on desalinated water for irrigation.

From Infrastructure to Ecosystem

Ultimately, the findings suggest that regenerative design transitions urban elements from static, single-purpose utilities into multifunctional ecosystems. By adopting the "safe-to-fail" logic seen in Singapore's naturalized riverbanks, Saudi cities can develop infrastructure that not only manages climate risks but also restores biodiversity and provides high-quality public space. This synthesis proves that the "Cities as Living Systems" framework is not a theoretical luxury but a high-performance necessity for achieving long-term climate resilience in the Gulf region.

Conclusion

This research positions regenerative urban design as an indispensable framework for the future of climate-resilient cities. By reframing urban areas as living systems, we can transition from a model of extraction to one of restoration. The findings from the High Line and Bishan-Ang Mo Kio Park demonstrate that nature-based solutions and adaptive reuse are not merely aesthetic choices but high-performance engineering strategies. Future urban development must prioritize these regenerative principles to foster environments that are not only sustainable but actively restorative.

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Smart and Sustainable Architectural Design in KAPSARC, Riyadh, Saudi Arabia

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Keywords: Smart Architecture, Sustainable Design Climate-Responsive Architecture, KAPSARC, Zaha Hadid Architects, Saudi Arabia

Abstract. This paper investigates the integration of smart and sustainable architectural design strategies in the King Abdullah Petroleum Studies and Research Center (KAPSARC) in Riyadh, Saudi Arabia. Located in a hot arid climate, the project provides a relevant case for examining how architectural form, passive environmental strategies, and smart building systems can improve environmental performance, user comfort, and operational efficiency. The study adopts a qualitative case study methodology supported by secondary quantitative data and analyzes the project through four dimensions: geometry, climate-responsive design, smart systems, and sustainability outcomes. The findings show that KAPSARC's hexagonal modular geometry functions as a performance-driven system that enhances shading, daylight control, spatial flexibility, and circulation. Environmental strategies such as optimized orientation, compact massing, sheltered courtyards, and high-performance façades reduce solar gain and improve thermal comfort. These passive measures are supported by smart systems, including automated HVAC, lighting control, and performance monitoring. Reported data indicate a 45% reduction in energy performance compared to ASHRAE standards, with further operational reductions of 35% in energy use and 30% in water consumption. The paper argues that KAPSARC demonstrates an integrated approach where passive and smart strategies operate within a unified architectural framework. A brief comparison with Al Bahr Towers highlights that, while both projects address desert climates effectively, KAPSARC stands out through its modular campus planning and strong integration of form and function. The study concludes that the project offers a relevant model for institutional buildings in hot arid regions, while recognizing the limitations of relying on secondary data.

1. Introduction

In hot arid climates, architecture must respond to extreme temperatures, intense solar radiation, glare, and high cooling demand. Under such conditions, sustainable design is not limited to aesthetics or material selection. It requires the integration of environmental performance, climatic responsiveness, and efficient building operation. Smart architecture strengthens this approach by introducing systems that improve energy management, occupant comfort, and long-term operational performance.

In Saudi Arabia, these issues are especially important as institutional buildings are increasingly expected to combine environmental responsibility with technological efficiency. Within this context, the King Abdullah Petroleum Studies and Research Center (KAPSARC) in Riyadh stands out as a relevant architectural case. The project is widely recognized for its distinctive modular geometry, climate-responsive design approach, and integration of advanced building systems. However, many discussions of KAPSARC remain largely descriptive and focus more on its visual identity than on its architectural and environmental performance.

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This paper addresses that gap by examining KAPSARC as an integrated model of smart and sustainable architectural design. Rather than treating architectural form, passive strategies, and smart systems as separate topics, the study analyzes how these components operate together within a single design framework.

1.1 Research Aim

The aim of this paper is to analyze how KAPSARC integrates architectural form, passive environmental design, and smart building systems to improve sustainability performance in a hot arid climate.

1.2 Research Questions

This study is guided by the following questions:

1. How does KAPSARC's geometry contribute to environmental performance and spatial efficiency?
2. How do passive design strategies support thermal comfort and energy reduction?
3. How do smart systems enhance the building's environmental performance?
4. What broader lessons can KAPSARC offer for institutional architecture in hot arid regions?

1.3 Research Contribution

The contribution of this study lies in presenting KAPSARC as a performance-oriented case study rather than a purely descriptive architectural example. It connects geometry, climate response, and smart systems within one analytical framework and highlights the project's relevance to contemporary sustainable design in Saudi Arabia.

2. Research Methodology

This paper adopts a qualitative case study methodology supported by secondary quantitative performance data. The case study approach is appropriate because KAPSARC is a prominent, context-specific institutional project in a hot arid climate and allows in-depth examination of design strategies, environmental logic, and operational sustainability outcomes.

2.1 Research Approach

The study combines:

- **architectural analysis**, focusing on form, geometry, spatial organization, and environmental design;
- **document analysis**, using official project descriptions, institutional sustainability information, and certified performance references;
- **comparative analysis**, using Al Bahr Towers in Abu Dhabi as a regional benchmark for climate-responsive and technologically advanced design in a similar desert environment.

2.2 Data Sources

The analysis relies on:

- official project information published by Zaha Hadid Architects;
- institutional information published by KAPSARC;
- certification references from USGBC;
- comparative project information from AHR/Arup and supporting architectural publications for Al Bahr Towers.

2.3 Analytical Framework

The project is analyzed through four categories:

- **Geometry and spatial organization:** Examines how the hexagonal modular system shapes circulation, hierarchy, and environmental buffering.

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- **Climate-responsive environmental design:** Evaluates orientation, compactness, courtyards, shading, daylighting, and microclimatic effects.
- **Smart building systems:** Studies automation, HVAC zoning, lighting control, and building performance monitoring.
- **Quantitative sustainability outcomes:** Assesses available measurable indicators such as energy reduction, water reduction, materials sourcing, and certification results

2.4 Methodological Limitation

Because this study depends primarily on published project and institutional sources, it does not include original simulation modeling, post-occupancy measurements conducted by the author, or proprietary technical engineering datasets. Accordingly, the paper should be read as an analytically strengthened case study based on verified secondary evidence rather than a primary field-performance audit.

3. Project Overview

3.1 Location and Climatic Context

KAPSARC is in Riyadh, Saudi Arabia, which is characterized by a hot desert climate with high temperatures and intense solar exposure. These conditions require buildings to minimize heat gain, control glare, and enhance shading to improve environmental performance and reduce reliance on cooling systems.



*(**Fig. 1)** Aerial view of King Abdullah Petroleum Studies and Research Center (KAPSARC), Riyadh, Saudi Arabia.*

3.2 Function, Program, and Design Concept

KAPSARC is an independent research institution focused on energy, policy, and sustainability. The campus includes research facilities, offices, a conference and exhibition center, a library, and a prayer space. It consists of five interconnected buildings that support both research activities and collaboration.

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Architecturally, the project is based on a hexagonal modular system that creates interconnected spaces rather than a single building mass. This geometry enhances spatial flexibility and supports environmental control. The clustered form reduces exposed surfaces, while courtyards create shaded areas and improve thermal comfort. The spatial organization also enhances circulation and supports efficient functional zoning.

The internal organization of KAPSARC reflects a clear functional hierarchy, where public and semi-public spaces such as conference and exhibition areas are more accessible, while research and office spaces are more controlled. This spatial arrangement enhances circulation efficiency and supports both collaboration and privacy within the institutional environment.

3.3 Design and Completion

The project was developed in collaboration with Zaha Hadid Architects, with construction starting in 2010 and completion in 2015. It achieved LEED Platinum certification and later received multiple LEED-EBOM Platinum certifications for its operational performance.

4. Sustainable Design Strategies

KAPSARC integrates climate-responsive strategies directly into its architectural form rather than applying them as separate systems. These include compact massing to minimize solar exposure, shaded courtyards that improve microclimatic conditions, and controlled daylighting that enhances visual comfort while limiting heat gain. The building orientation and façade design further contribute to reducing environmental stress by controlling glare and solar radiation. Together, these strategies reduce overall energy demand and decrease reliance on mechanical cooling, supporting a more efficient and sustainable building performance.

Table 1. Main design strategies

Strategy	Application	Impact
Compact massing	Clustered building form	Reduces heat gain
Courtyards	Internal shaded spaces	Improves microclimate
Daylighting	Filtered openings	Reduces artificial lighting
Façade design	Shaded surfaces	Limits solar exposure

These strategies reduce environmental load and improve indoor comfort.

5. Smart Building Features

The project's sustainable design is reinforced by smart building systems that improve operational efficiency. These systems include building controls related to energy use, lighting, and indoor environmental management. Their role is not to replace passive design, but to enhance its effectiveness.

This relationship between passive and active strategies is especially important. KAPSARC works as an integrated system in which environmental design reduces building loads while smart controls help manage performance more efficiently during operation. This creates a stronger sustainability model than one based only on technology or only on form.

Smart systems also support the building's institutional function. Since the campus includes spaces with different levels of use and occupancy, operational control becomes more effective when systems can respond to changing internal conditions. This improves energy efficiency while maintaining comfort in a more targeted way.

A key analytical point in this study is that smart architecture should not be understood as a purely technical layer. In KAPSARC, intelligent systems are meaningful because they are linked to spatial organization, environmental logic, and the actual functioning of the building.

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Table 2. Relationship between design and performance

Design Element	Function	Performance Impact
Geometry	Creates shaded zones	Improves thermal comfort
Courtyards	Transitional spaces	Reduces heat stress
Daylighting	Natural light control	Reduces energy use
Smart systems	Operational control	Improves efficiency

6. Comparative Analysis

To highlight the broader relevance of KAPSARC, it can be briefly compared with Al Bahr Towers in Abu Dhabi, another project in a hot arid climate. Al Bahr Towers are known for their dynamic façade system, which reduces solar gain through a responsive shading mechanism.

Table 3. Comparative analysis: KAPSARC and Al Bahr Towers

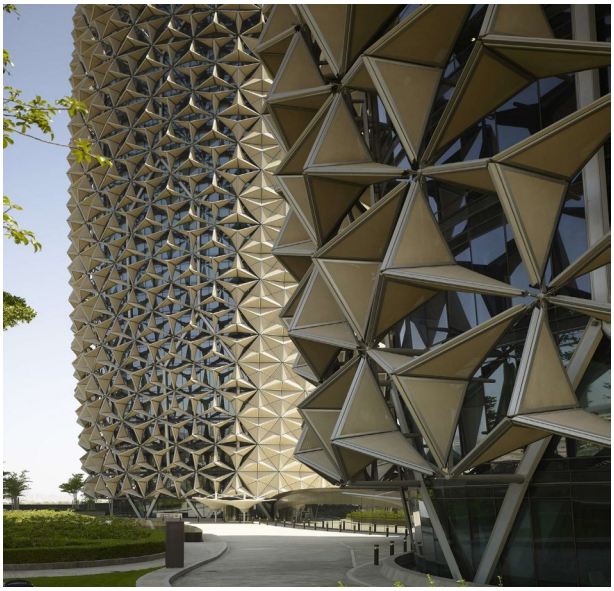
Aspect	KAPSARC	Al Bahr Towers
Building type	Institutional campus	Office towers
Design logic	Modular spatial system	Dynamic façade system
Climate strategy	Courtyards, shading, massing	Responsive façade shading
Smart systems	Integrated building systems	Façade-based control
Key strength	Integrated design approach	Advanced façade technology

KAPSARC demonstrates a more integrated approach, where environmental performance is embedded in the overall spatial and architectural system. In contrast, Al Bahr Towers rely primarily on façade technology. This suggests that KAPSARC provides a broader model for institutional buildings in hot climates.



(Fig. 2) *Exterior view of KAPSARC showing modular geometry and spatial integration.*

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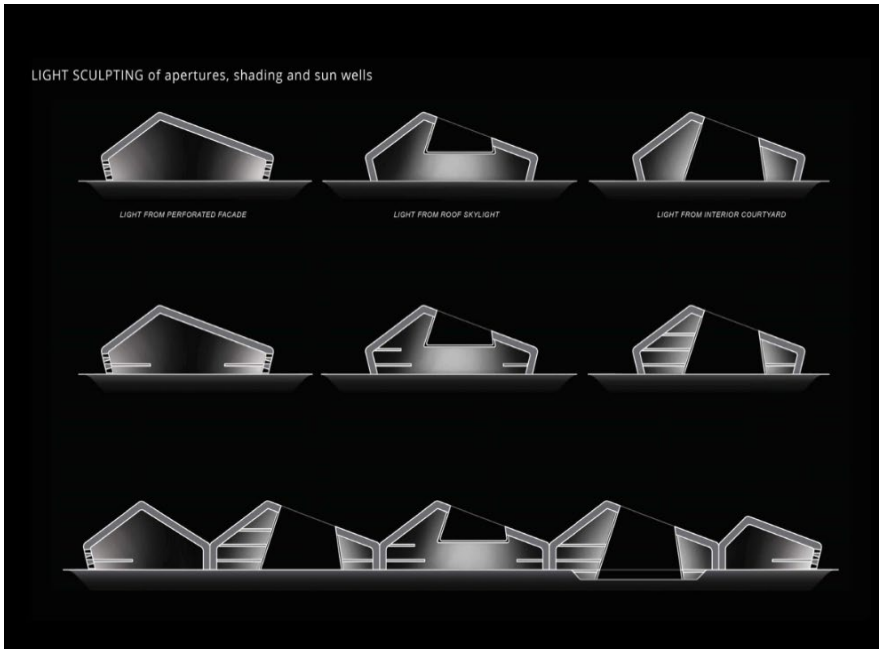


(Fig. 3) *Dynamic façade of Al Bahr Towers illustrating responsive shading*

7. Discussion

The analysis shows that KAPSARC is significant not only because of its architectural expression, but because of the way design and performance are integrated. Its geometry supports shading, daylight control, circulation, and spatial flexibility. Its passive strategies respond directly to the desert climate. Its smart systems strengthen operational efficiency and complement the building's environmental design.

This makes KAPSARC more than a descriptive case of iconic architecture. It demonstrates how institutional buildings can combine design quality with environmental responsibility. The project suggests that sustainability is most effective when it is treated as a design framework rather than as a collection of separate technologies.



(Fig. 4) *Daylighting and shading strategies illustrating light control and environmental performance in KAPSARC.*

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The case study also highlights a broader lesson for architecture in hot arid regions. Buildings in such climates should not depend only on mechanical cooling or technological upgrades. Greater value can be achieved when architectural form itself contributes to environmental control. In this regard, KAPSARC offers an important model for future projects in Saudi Arabia and similar contexts.

At the same time, the study recognizes that design value alone is not enough for research-based assessment. For stronger academic contribution, architectural interpretation should be supported by measurable environmental indicators whenever possible. This revised paper therefore moves beyond description by clarifying the research method, strengthening analysis, and identifying the need for quantitative evidence, as requested by the reviewers

8. Limitations and Applicability

This study has several limitations. First, it relies primarily on secondary data from official and institutional sources rather than primary monitored datasets collected by the author. Second, some reported performance values come from project descriptions and sustainability communications rather than independently reproduced simulations within this paper. Third, the case study focuses on one iconic institutional project, which means direct generalization to all building types should be approached carefully.

Nevertheless, the project has strong applicability to other research, educational, and civic buildings in hot arid regions. Its lessons are particularly relevant for:

- campus-scale institutional planning;
- projects requiring a balance between public interaction and controlled private zones;
- buildings seeking to combine passive environmental design with smart operational systems
- Saudi and Gulf-region projects aiming to align design identity with measurable sustainability performance.

What is most transferable is not the exact formal language of hexagonal cells, but the design principle of integrating geometry, climate adaptation, and intelligent operation into one coherent architectural system.

9. Sustainability, Cultural Identity, and Socioeconomic Context

KAPSARC reflects sustainability beyond environmental performance by connecting design with cultural and socioeconomic factors. Its use of courtyards and shaded spaces aligns with traditional Middle Eastern architecture, supporting both climate response and social interaction. Economically, energy-efficient strategies reduce long-term operational costs, linking sustainability with performance. As a research institution, the project also contributes to Saudi Arabia's knowledge economy, extending its impact beyond architecture.

10. Conclusion

This study has shown that KAPSARC represents a strong model of integrated smart and sustainable architectural design in a hot arid climate. Through its modular hexagonal geometry, climate-responsive orientation, sheltered courtyards, daylight control, wind-responsive features, and intelligent building systems, the project demonstrates how architecture can address environmental challenges through both passive and active strategies.

The analysis also shows that KAPSARC's value lies in measurable performance as well as conceptual quality. Reported outcomes include a 45% reduction in energy performance relative to ASHRAE baseline standards, a 35% operational energy-use reduction through ongoing management, a 30% reduction in water use, 100% non-potable irrigation water, substantial recycled and locally sourced materials, and multiple LEED Platinum recognitions. These indicators support the argument that the project is not merely sustainable in theory, but demonstrably effective in practice.

Compared with other climate-responsive Gulf precedents such as Al Bahr Towers, KAPSARC stands out for integrating environmental performance into the full logic of spatial organization and institutional programming, not only into the façade. It therefore offers a particularly valuable model for future institutional developments in Saudi Arabia and similar hot arid regions.

In conclusion, KAPSARC demonstrates that smart and sustainable design is most successful when architecture, climate response, and digital building intelligence are developed as one system. Its case suggests that the future of institutional architecture in desert climates depends less on isolated technological features and more on deep integration between form, performance, and operation.

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Sustainability, Economy & Cultural Identity in Design

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The Gap of Cultural Identity in Open Spaces: Urban Renewal Frameworks in Bahrain

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Keywords: Cultural Landscapes, Urban Regeneration, Public Space Design, Cultural Heritage Preservation, Sustainable Urban Development

Abstract. Urban regeneration in Bahrain is facing a critical tension between preserving its cultural identity, and accommodate the rapid modernization, thus comes this paper, as it investigate how the integration of cultural landscape and open spaces can strengthen the urban renewal framework, the paper uses a qualitative analysis of planning documents and case studies, using the Architects Handbook of Professional Practice for it addresses urban planning and urban design as interdisciplinary practices that shape the form, character, and social function of cities. It also discusses the public realm design, streetscapes, land use, and community revitalization, which are central to the research title and scope, and it explores policies and tools (like form-based codes) used to guide urban regeneration and enhance cultural landscapes. In addition to the Council for Regulating the Practice of Engineering Professions (CRPEP) guidelines, for they are the regulatory authority in Bahrain, as a guideline base for comparison. The paper discusses the gap presented in linking the heritage-based design principles with contemporary engineering and regulatory practices and proposes a conceptual framework that integrates cultural, spatial, and regulatory dimensions to support place-based regeneration strategies.

1. Introduction

1.1 Context and Background

The rapid urbanization that Bahrain has gone through in the past decades has reshaped its traditional cityscape, challenging the balance between modernization and cultural heritage. At one point in time, Bahrain was defined by its coastal settlement, the humble homes made from indigenous materials, the courtyard element in design, and the social dynamic of the society and its gathering areas. In contrast to its modern urban fabric that reflects the infrastructural expansion and economic diversification. Despite the national efforts toward sustainable development, many regeneration initiatives prioritize physical infrastructure over cultural identity and social cohesion.

This paper argues that the cultural landscape and public places design are critical tools for the revitalization of Bahrain's urban environment, hence the significance of this paper as it addresses the interdependence between cultural landscape, open public spaces, and the regulatory framework that shapes Bahrain's urban fabric and identity. By bridging the gap between heritage-based design principles and contemporary planning regulations. The paper brings forward the localized application of international standards of the Architect's Handbook of Professional Practice within the Bahrain regulatory environment, regulated by the Council for Regulating the Practice of Engineering Professions (CRPEP) as the regulatory authority in Bahrain. This dual framework shows how cultural identity can coexist with modern design and engineering standards, thereby advancing a context-sensitive approach in urban regeneration.

1.2 Problem statement

The current regeneration projects have revitalized selected urban areas, but many other projects have overlooked the cultural landscape aspect, value, and public real integration. This gap reveals

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the need to align heritage-based design principles and guidelines with the current modified engineering and regulatory framework.

1.3 Aim and Objective

Aim: To investigate how the integration of cultural landscape and open spaces can enhance and strengthen the urban regeneration framework.

objective:

- Examine the relationship between cultural identity, spatial planning, and regulatory practice in Bahrain.
- Analyze how The Architect's Handbook of Professional Practice and CRPEP guidelines address design governance.
- To assess selected regeneration projects (in Bahrain) and identify opportunities for culturally grounded renewal.
- Propose a conceptual framework integrating cultural, spatial, and regulatory dimensions.

1.4 Research question

How can Bahrain's urban regeneration strategies integrate cultural landscapes and open spaces within existing regulatory and professional frameworks?

1.5 Significant

This paper contributes to the field of sustainable urbanism and bridges it with cultural identity from the present realities of governing regulations. Therefore, it comes with pertinent applications for Gulf cities undergoing rapid urbanization.

2. Theoretical and Conceptual Background

2.1 Urban Regeneration and Cultural Landscape Theory

Cultural landscape is defined by UNESCO as the link between human activity and the natural built environment, for it creates a space that resides in the memory and identity. In urban contexts, such landscapes represent the evolving dialogue between tradition and modernity, and Scholars such as Zukin (1995)(1) and Mumford (1961)(2) emphasized the role of public spaces as democratic and social environments where collective urban life unfolds.

Increasing attention has been brought to cultural landscapes for urban identity, memory, and continuity, which is why more regeneration efforts are focusing on urban transformation. For example, urban landscapes are essential spatial elements of urban memory and identity construction, where memory overlooks recreational areas and important views frequently constructed through collective memory by the city's residents (3). Historical-cultural landscapes consist of a triangulation of regional culture, collective memory, and urbanization, which proves that their existence is necessary for the projection of urban spatial values (4). However, urban transformation within historical areas complicates matters of spatial continuity, where disconnection from socio-economic improvements and conservation reality applications causes fragmentation, separation, dissolution, and disidentification (5). Culture and history have also been established as a link to urban regeneration processes, where a creative city orientation influences spatial, human, economic, and civic integration, creating an interrelated developmental system through sustainable regeneration efforts, which enhance place identity (6).

Research on Bahrain's urban regeneration, cultural landscapes, and public spaces serves as a vital tool for understanding how revitalizing urban environments can help preserve community identity. For example, the Pearling Trail in Muharraq is a renowned project where cultural preservation triggers regeneration and makes sense of place, spanning 3.5 km, creating an eco-museum that transformed the city into a renowned cultural attraction (7). In Manama, the old Kanoo neighborhood of Manama is another example, where rehabilitation projects regenerate old

urban cores and re-establish a fading city identity (8). Thus, where urban sustainability and cultural transformations are concerned, Bahrain feels more intensely linked to such phenomena because much development in the country was driven by oil, leading to poor sustainability efforts before recent developments in urban planning and public policies (9). Therefore, public open spaces, including heritage sites like Bab Al-Bahrain and the Pearling Trail, are inclusive transcultural spaces that join diverse populations but are still inherently linked to local heritage values. This established the point that preservation and multicultural integration can coexist as one (10).

2.2 Public Realm and Open Space Integration

Streetscapes, parks, and public plazas shape everyday interaction and cultural identity through their design, layout, and management (11–20), Ethnographic and observational studies in cities from London to Kuala Lumpur and New York show that seating arrangements and green or natural elements spur spontaneous encounters and encourage sustained use (11–14,16,18,20). Clear, legible layouts with visual connectivity and defined boundaries help users navigate these spaces and feel included, whereas designs that lack such clarity may restrict interaction (16). Papers describe public spaces as stages for cultural expression (12,13,19,20). Markets with porous edges, plazas featuring culturally significant symbols, and parks offering art installations or monuments serve as venues where collective memory, ethnic diversity, and identity are enacted (13,19,20). Management practices, including programming, maintenance, and regulation of access, further influence whether these settings foster inclusion or inadvertently limit it (12,13,20).

2.3 Professional and Regulatory Frameworks

In Bahrain, studies describe planning governance as a centralized and state-led framework. Khalaf (2016), Mouzughi et al. (2014), and al-Nabi (2014) note that strategic documents akin to Bahrain's CRPEP guidelines, along with visions of Vision 2030 and the Bahrain National Development Plan, structure governance through public–private partnerships and top-down regulation despite persistent bureaucratic hurdles (21–23).

By contrast, in the United States of America and other global contexts there are professional codes that plays the key role in shaping the ethical and practical code of conduct like the Architect's Handbook of Professional Practice which is a book that offers detailed specifics on professional practice that covers the American Institute of Architect (AIA) Code of Ethics, that covers topic like legal aspects, the management of projects, and interdisciplinary thematic agreements, therefore, setting up the principles of standards of the architectural practice governance (24).

Johnson and Gore (2016) examine how professional codes of architectural and planning organizations have developed and found themselves converging around social issues in the 1970s, but then diverging, with planning prioritizing democratic processes and involvement of citizens, and architecture prioritizing physical projects (25).

Al Jalahma (2025) also shows how Bahrain adapts international standards in governance and applies them to the local cultural settings and implements hybrid forms that integrate the best practices across the globe and Shariah-informed values (26). Al-Soufi and Ahmed (2012) demonstrate how Bahrain has a systematic way of governing the country with its National Enterprise Architecture Framework, which gives detailed guidelines and standards in which all government services are coordinated, which in turn supports the economic vision of the kingdom by using well-organized architectural governance (27).

2.4 Conceptual Framework

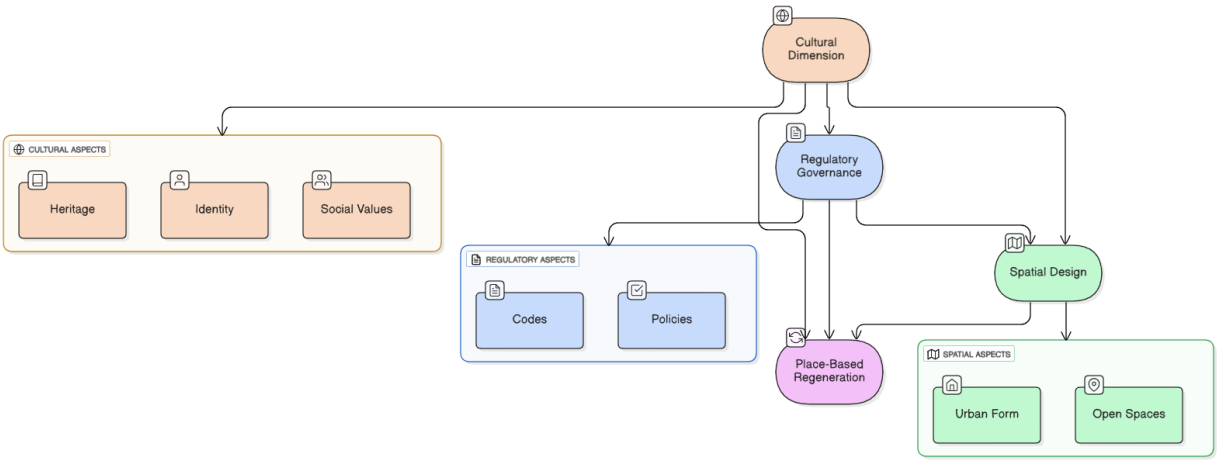


Figure 1 Conceptual Framework: Integrating Cultural, Spatial, and Regulatory Dimensions, source: author

This conceptual model positions place-based urban regeneration at the intersection of three interdependent dimensions. The first is the cultural dimension that represents the identity, traditions, and social meanings embedded in Bahrain's urban fabric. Second is the spatial design dimension that focuses on the physical aspect and morphological transformation embedded in the culture, and as an essential design element in public realm design, open space networks, and urban form. It translates cultural values into tangible design outcomes that shape how people interact with their surroundings. And finally, the Regulatory Governance Dimension that encompasses institutional frameworks, professional practice standards (e.g., *AIA Handbook of Professional Practice*), and local regulations (e.g., *CRPEP guidelines*).

3. Methodology

3.1 Research Design

A qualitative, interpretive design was employed to understand how professional standards, policy frameworks, and spatial interventions intersect.

3.2 Data Collection

- **Documents:** Bahrain's national urban policies, CRPEP guidelines, and AIA Handbook
- **Case Studies:** Two Bahraini regeneration projects representing heritage-led and contemporary approaches.

3.3 Analytical Method

Thematic document analysis and comparative case evaluation were used to identify patterns in cultural, spatial, and regulatory integration

3.4 limitation

The study focused on Bahrain's urban context and does not include empirical stakeholder interviews, which are recommended for future research and analysis.

4. Case Studies and Analysis

4.1 Contextual Overview

This subsection situates the case studies within Bahrain's broader regeneration agenda and planning instruments.

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Narrative

Over the past two decades, Bahrain's urban interventions have focused on economic diversification, waterfront-driven investment, and heritage conservation (28,29). The regeneration policies are formulated and realized through municipal master plans, prominent private project construction, and sector-specific plans that support tourism, commerce, and urban amenities (7,8). Spatial planning instruments that are applied in practice include statutory land-use plans, master plans that include waterfront and downtown districts, and project-specific design codes (often developer-led) but regulated, approved, and governed by a professional body that is CRPEP.

While the theoretical strategic documents talk about heritage protection and placemaking, the implementation stage more directly responds to financial feasibility and modern-day development potentials, placing the historic city center and fine-grained crafted areas at odds with each other more than expected (28,30).

Table 1 shows the chronology of major regeneration initiatives that reflect a shift from state-led modernization to a public–private partnership-driven urbanism that puts emphasis on waterfronts and heritage districts.

Table 1 chronology of urban development in Bahrain, source: Author

Characteristic	1970s–1990s	2000–2010	2010–Present
Focus	Foundational Urban Development	Waterfront-Led Regeneration and Economic Diversification	Cultural and Heritage-Based Urban Renewal
Key Plans	The First National Development Plans, Manama Structural Plan Establishment	Economic Vision of 2030 lunched in 2008	integrating heritage conservation within regeneration policy, National Spatial Strategy 2030
Development Model	Expansion and Modernization	Developer-Led Masterplans	Heritage Conservation
Key Projects	Initial Land Reclamation and infrastructure corridors	Amwaj Islands, Diyar Al Muharraq, Bahrain Bay	Old Muharraq, Manama Souq
Planning Approach	Zoning, Infrastructure Corridors	Form-Based Codes, Environmental Guidelines	Identity-Led Development

Table 2 showcases the key planning instruments and responsible authorities in Bahrain.

Bahrain’s regeneration model operates through a hybrid governance structure, combining state oversight with private-sector execution, for example, Public–Private Partnerships (PPPs) is used in major project like Bahrain bay and Diyar Al-Muharraq, while Developer-led Masterplans hire international consultants that little to no incorporation of local heritage or community narratives, thus the professional review and oversight is led by CRPEP to ensure technical compliance and design accountability, while the Bahrain Authority for Culture and Antiquities (BACA) reviews heritage-sensitive proposals, particularly in Muharraq and Manama’s historic sites. Because of the lack of coordination between agencies such as heritage, environmental, and planning bodies that operate under distinct mandates, a gap is created between strategic vision and on-ground implementation, creating an integration challenge to address (refer to Figure 2).

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Table 2 Planning Instruments and Actors in Bahrain's Urban Regeneration

Instrument	Purpose	Lead Agency/Actor	Relevance to Cultural Landscape
National Spatial Strategy 2030 (NSS 2030)	Sets spatial hierarchy, land-use structure, and sustainability objectives for national development.	Ministry of Municipalities & Agriculture Affairs (MMAA) / Urban Planning & Development Authority (UPDA)	Provides national policy framework linking growth centers with heritage conservation zones.
Municipal Masterplans (e.g., Manama, Muharraq)	Regulates zoning, density, and public realm at city level.	Municipal Councils under the Ministry of Municipal Affairs	Identifies heritage districts, open-space systems, and mixed-use regeneration areas.
Economic Vision 2030	Strategic framework for diversification, innovation, and urban quality of life.	Bahrain Economic Development Board (EDB)	Positions heritage and tourism as assets for economic competitiveness.
CRPEP Professional Guidelines	Regulates professional practice, design approval, and engineering standards.	Council for Regulating the Practice of Engineering Professions (CRPEP)	Ensures compliance and professional accountability in heritage and urban design projects.
Developer-Led Project Masterplans (e.g., Bahrain Bay, Diyar Al Muharraq)	Establishes land-use and form-based codes for large-scale developments.	Private developers (e.g., Bahrain Bay Dev. Co.) with government oversight	Influences spatial form and identity expression in reclaimed or new urban areas.
UNESCO Heritage Management Plan (Pearling Trail)	Integrates conservation, adaptive reuse, and tourism planning.	Bahrain Authority for Culture and Antiquities (BACA)	Central to safeguarding cultural landscape and community identity.



Figure 2 Governance Model of Regeneration in Bahrain

4.2 Case Study 1, Heritage-Based Regeneration (Muharraq)

The Muharraq regeneration project is a heritage-based intervention focused on the historic fabric, traditional streets, and intangible culture. The design strategies are focused on the conservation of the built heritage, adaptive reuse of vernacular houses, and the maintenance of the urban grain, which is defined by the narrow alleys, typologies of the courtyards, and the human-friendliness of its facade. Interventions focus on the authenticity of the materials, preservation of historic plot lines, and the introduction of selective, visually discrete contemporary services. Community engagement (cultural festivities, fairs, and workshops) created social value for conservation

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interventions for public space reactivation. This means the conserved spaces maintain character at a human scale for walkability and informal economic purposes/cultural events.

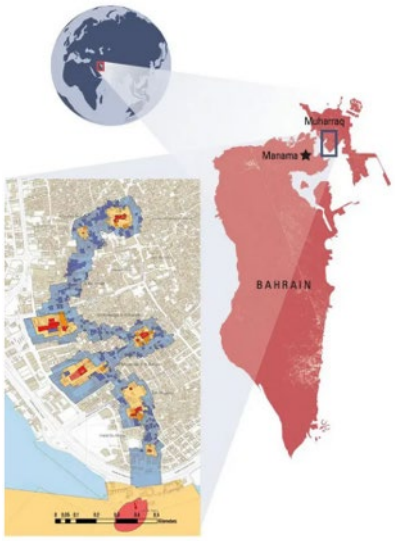


Figure 3 the pearling path project 2024, source: Bahrain Ministry of Culture and Information

In Bahrain, the historic city of Muharraq stands as the nation's most significant site of heritage-based urban regeneration. As the island's political and cultural heart for over 200 years, it embodies the urban morphologies of typical Gulf towns with small alleyways (*sikkas*), interiorized courtyards, coral stone façades, and a dense relationship between social function and the built environment. Unfortunately, in recent decades, spatial and cultural integrity has been compromised by a lack of upkeep due to development, demographic shifts, and land-use pressures.

As a response, the Pearling Path Project began in 2012 (7). This nine-year project transformed a 3.5 km area into a living eco-museum with thriving business and cultural communities. The path consists of seventeen buildings located in the city of Muharraq, three offshore oyster beds, a portion of the coastline, and the Qal'at Bu Mahir fort at the southernmost tip of Muharraq Island, where boats departed for the oyster beds. (refer to Figure 4). The structures are a collection of merchant mansions, shops, storehouses, and a mosque. It is the only surviving intact manifestation of the cultural tradition of pearling and the associated wealth which prevailed in the Gulf economy (2nd century to the 1930s), when cultured pearls began in Japan (31), elevating Muharraq into a popular local attraction hosting cultural festivals and events

The project's success stemmed from expanding beyond UNESCO preservation requirements, focusing on sustainability and continuous use, and improving cultural access (7). Muharraq stands as one of the most important traditional cities in the Arabian Gulf and represents a remaining living model of traditional Gulf urbanization (32). The regeneration demonstrates how cultural heritage tourism can effectively revitalize historic urban centers (33,34)

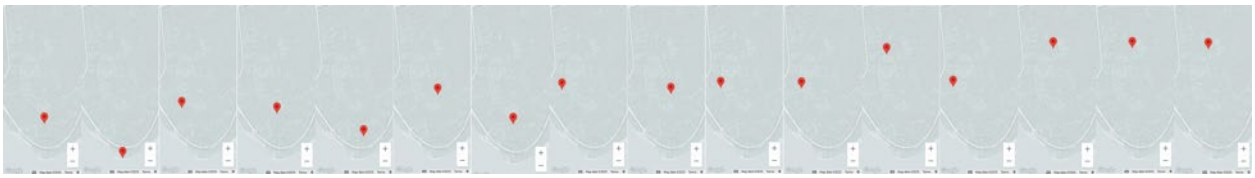


Figure 4 The Pearling Path (16 structures and the oyster's bed and shore), source: https://pearlingpath.bh

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Theoretical frameworks illustrated

The Cultural landscape theory follows the UNESCO-style, as it considers heritage as an evolving human–environment system. It incorporates Adaptive reuse and placemaking as it conserves the urban fabric while enabling new cultural uses that evolve every year.



Figure 5 Shaikh Ebrahim bin Mohammed Center. Source: Shaikh Ebrahim bin Mohammed Center for Culture and Research



Figure 6 pearl-shaped lamp post. source: Pearlingpath.bh



Figure 5 Muharraq night. source: Bahrain news agency

An example would be the Shaikh Ebrahim bin Mohammed Al-Khalifa house (refer to Figure 5), for it was rebuilt and converted into a Culture and Research Center. This project also utilized spherical white streetlamps, which were added to symbolize pearls and assist with wayfinding (refer to Figure 6). And in 2021 the Muharraq nights event took place during the nation celebration in December of that year then in 2023 it evolves into a night festive that the citizens and residents wait for every year since then (refer to Figure 7). as it stood still as a reminder of who we are, where we come from, and what our ancestors did to build this nation and how we as the future generation will continue their path. And the walk through the memory lane uses narrative-led regeneration by employing storytelling (pearling history) to create meaning and wayfinding.

These frameworks deliver a replicable model for small-scale, culturally anchored renewal. And as nothing is perfect, there are limitations to this project, as there might be a piecemeal regulatory alignment, and risk of tourism-led commodification, and occasional clashes between contemporary architectural insertions and the human-scaled heritage fabric.

4.3 Case Study 2, Contemporary Urban Renewal (Bahrain Bay)

Bahrain Bay, located in Manama, Bahrain (refer to Figure 8), is a flagship example of state-supported, private-sector-led urban renewal that reflects Bahrain's broader economic diversification agenda.

Figure 6 location of Bahrain bay in the map of Bahrain 2025. source: screenshot of google maps

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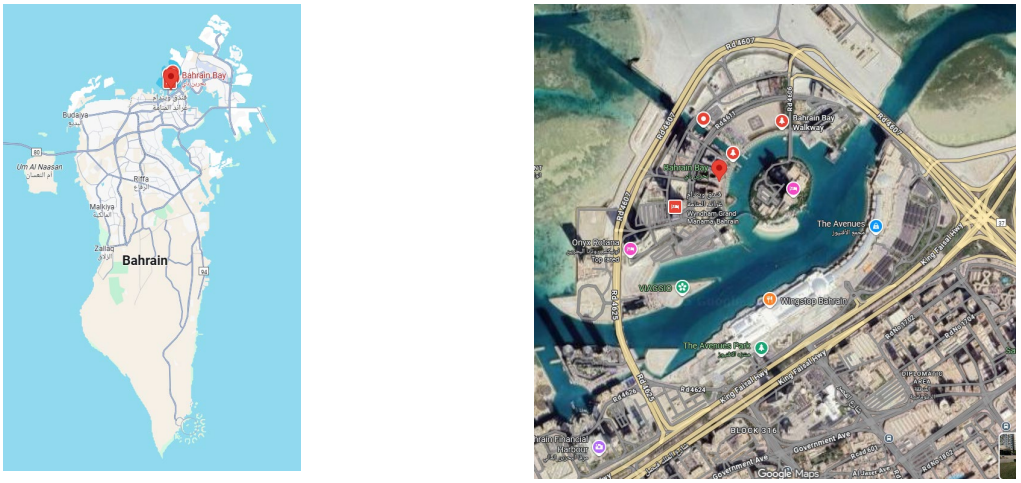


Figure 7 location of Bahrain bay in the map of Bahrain 2025. source: screenshot of google maps

The project was initiated in the early 2000s as a public–private partnership between the Government of Bahrain and Bahrain Bay Development Company. It occupies reclaimed land in the north of Manama's Diplomatic Area. Bahrain Bay integrates residential, commercial, and leisure functions anchored by global architectural icons such as the Four Seasons Hotel, the Arcapita Bank headquarters, and the United Tower (refer to Figure 9).



Figure 8 Bahrain bay master plan. source: www.som.com

The masterplan, developed by Skidmore, Owings & Merrill (SOM), employs a form-based design code to ensure visual coherence, regulated density, and high-end urban character.

Theoretical frameworks illustrated

The approach combines public–private partnerships with symbolic architecture to signal modernity and competitiveness, and it employs several key transformation principles that include:

Utilizing outdoor spaces, creating diverse building typologies, developing organic circulation routes, and integrating spatial layouts that support social interactions (refer to figure 10)



Figure 9 different views around Bahrain bay. source: www.som.com

How blending inherited (local) design elements affects dwellers' experience of place

The comparative results are relative; however, Muharraq is more placemaking for authenticity and identity of place than Bahrain Bay, for a successful integration of inherited and personally experienced urban form. Muharraq is a culturally influenced/rehabilitation-redevelopment project, while Bahrain Bay is a master planned development that tries to plop-dot its inherited traits via the contemporary (if not mostly contemporary). Additionally, Muharraq relies upon heritage-based revitalization, authentically made restoration efforts, and replication of patterns of life (how things used to be done), like spatial organization (hierarchical streets), courtyards, and materiality that relies upon a certain sense of place and identity through continuity and belonging.

Muharraq's heritage-led regeneration relates to authenticity as the spatial configuration, courtyards, and materiality represent where people came from and make them who they are to foster a sense of existence and place attachment pride, through continued acknowledgment of what once was. It's walkable and interconnected, and the memory-based place attachment allows one to appreciate where one once was and where they've come to be to create an essence of nostalgia, as things come together in a linear manner.

Conversely, Bahrain Bay employs only some locally inspired motifs, like the geometric lines and soft-edge waterfront promenades, but incorporates a commercialized, modern international masterplan. While the tributary to Bahraini culture can be perceived, it's more symbolically respected than lived, as aesthetic quality trumps social, cultural, and historically driven depth.
As such, the two exist together in proximity yet in separate realities. Without the true impact of integration and its positivity, placelessness runs the risk. Thus, sustainable regeneration in Bahrain relies on an integration of culturally landscape-driven design governance to ensure that there is a balance between modernized intentions and lived cultural appreciation.

Conclusion

This research ultimately determines that sustainable urban redevelopment of Bahrain must integrate aspects like spatial, cultural, and regulatory dimensions to bring modernization and identity together. A heritage approach based on cultural landscape theory possesses an authentic sense of place and community revitalization, while a contemporary approach represents a shallow symbolic structure of local character, thus eventually rendering placelessness. Thus, embedding inherited design principles into planning and governance frameworks, specifically CRPEP guidelines and form-based codes, can create a balanced model where economic growth coexists with lived cultural meaning and enduring urban identity.

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A Comparative Analysis of Socio-Cultural Factors Shaping Turkish Vernacular House Forms

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Keywords: Socio-Cultural Factors, Turkish Vernacular Architecture, Tradition, Values, Spatial Organization

Abstract. This research presents a comparative analysis of the socio-cultural factors shaping Turkish vernacular house forms across seven regions. The study examines the influence of religion, cultural traditions, and local customs on architectural characteristics, highlighting how these factors contribute to regional variations in housing. The regions analyzed include the Black Sea, Central Anatolia, Aegean, Eastern Anatolia, Marmara, Mediterranean, and Southeast Anatolia, allowing for a detailed investigation of the distinctive elements and forms found in each area. The research methodology combines a comprehensive review of literature with case study analysis, drawing on historical records, photographs, and published studies of Turkish vernacular architecture. Socio-cultural factors were further evaluated and ranked through a survey of experts in the field. By conducting a comparative analysis of these data, the study identifies and contrasts the socio-cultural influences on housing forms across regions. The primary objective is to elucidate how these cultural values shape regional identity within Turkish vernacular architecture.

Introduction

Culture likely shapes and organizes human interactions, and it also affects the physical environment, particularly the shape and arrangement of the space where we live [1]. Numerous studies have demonstrated how religion, culture, and values influence the design of small spaces like homes. Turkish cultural practices have had a significant impact on the country's architecture. Traditional homes as well as social and religious institutions use these materials [2,3]. The earliest publications on vernacular architecture in the late Ottoman Empire are from the early twentieth century, and they focus on wooden urban dwellings, the traditional districts that form, and the character of old Istanbul [4]. The 14th century marks the beginning of the long and rich history of the traditional Turkish home, often known as the Ottoman home. The Ottoman Empire's rapid growth expanded the population greatly at this time. As a result of the increased need for housing, Ottoman architects were forced to design homes that were both functional and visually pleasing [5]. In Turkey, myths has a significant role in shaping cultural identity of the country and its people that can provide us with insights into the importance of cultural patterns in understanding myths. Turkey, a nation brimming with a captivating culture and a storied past, holds within its myths a reflection of its rich heritage. These myths embody a tapestry woven from diverse influences, encompassing the echoes of Greek, Roman, and Persian cultures. They transcend mere tales, becoming an integral component of Turkey's cultural identity. Understanding the socio-cultural logic embedded in vernacular housing extends beyond historical documentation and holds direct

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relevance for contemporary sustainable urban development. However, sustainability in architecture encompasses not only environmental considerations but also cultural resilience and social adaptability. By examining how religious values, privacy norms, family structures, and community-oriented practices historically shaped spatial organization, this study provides insights that can inform culturally responsive housing design today. Integrating vernacular socio-cultural principles into contemporary urban frameworks can support identity preservation, enhance social sustainability, and contribute to more resilient and context-sensitive built environments. The data of this study was collected through analysis of various case studies of house forms of Turkey from seven regions in Turkey and then validated with survey with experts to rank the factors importance.

Methodology

Data were collected from secondary sources, including 58 peer-reviewed academic publications, historical records, architectural drawings, photographic documentation, and archival materials, in order to capture the historical, cultural, and architectural contexts of Turkish vernacular housing. The socio-cultural factors examined in this study were identified through a systematic synthesis of the literature on Turkish vernacular architecture and socio-spatial theory. The review process involved identifying recurring themes across regional case studies, historical accounts, and theoretical discussions concerning cultural determinants of built form. These themes were analytically coded and grouped according to conceptual similarity and frequency of occurrence. Determinants that consistently appeared across multiple regions and scholarly sources were consolidated into broader analytical categories. This iterative refinement process led to the formulation of eleven principal socio-cultural factors encompassing belief systems, social structures, environmental conditions, and everyday cultural practices that collectively shape vernacular housing morphology. Additionally, a digital survey was conducted with architecture experts, yielding 63 valid responses collected in April 2023 through convenience sampling. The data were analyzed using SPSS, employing descriptive statistics, one-sample t-tests, ANOVA, and Pearson correlation to assess questionnaire validity. The study also applied the Relative Importance Index (RII), standard deviation, and weighted mean to rank socio-cultural factors influencing Turkish house forms across seven regions. The findings informed recommendations for designers, building managers, and policymakers to enhance environmental quality and operational efficiency in such buildings. **Figure 1** illustrates the study methodological framework.

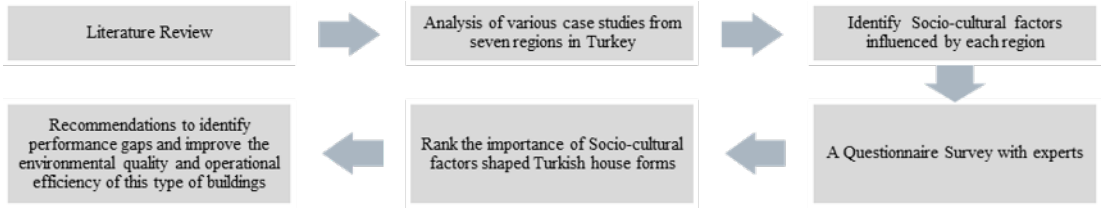


Fig1. Investigation methodological framework.

Literature Review

Turkish cultural practices have had a significant impact on the country's architecture. There are fifteen various types of houses, which can be enhanced with a more thorough classification, although the differences between these types are primarily details and specifications [6]. Following **Figure 2** illustrates the seven "Black Sea shore hinterland region, Istanbul and Marmara region, Aegean hinterland region, Mediterranean region, Central Anatolia region, Eastern Anatolia region, Southeast Anatolia region" types of vernacular house typologies according to Eldem who was the first to categorized them in 1984 [7].

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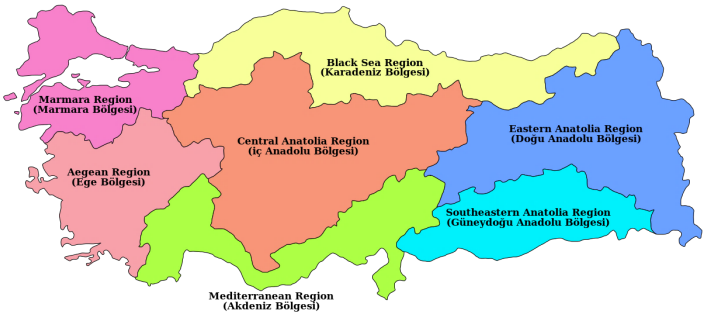


Fig 2. Turkish Regions, Source: [8].

The vernacular house of the Black Sea Region is the consequence of a very rich cultural history derived from historically diverse ethnical structures. The housing plans and architectural forms reflect area history and cultures. Every feature of the house has an explanation and has a purpose in human life. Both the plan organization and the facade aesthetic are ideal combinations of lifestyle and topography [9]. Istanbul identity is shaped based on the relationship between nature and history. Istanbul is part of the world's most remarkable geography, and it has been at the forefront of history as the capital city of the Byzantine and Ottoman Empires [4]. The Aegean Hinterland region demonstrates a distinct blend of Ottoman architectural styles, particularly in the use of timber-framed houses and ornamental embellishments. This can be linked to the region's historical ties to the Ottoman Empire, as well as the region's influence on Ottoman architecture. The unique architectural style of the Central Anatolia Region has been shaped by its rich historical background, varied cultural influences, and geographical features. For approximately ten millennia, the inhabitants of Cappadocia embraced a modest existence, relying on hunting and gathering as their primary means of sustenance [10,11]. The Turks held a strong belief in the existence of mystical beings, and it was commonly thought that these fairies made their abodes in unique hollow tufa hoodoos [12]. However, it is worth emphasizing that despite the prevalence of this belief, no scientific investigation has ever been conducted to substantiate the existence of fairies or their occupation of these chimney-like structures. In Turkish, these peculiar hollow tufa formations were referred to as " peri bacalari" underscoring their connection to the realm of mythical fairies [11]. Harran unique vernacular architecture attracts attention and the building form is not employed in other parts of Turkey, where adobe is the primary building material. The nomadic lifestyle and the environmental conditions led people to create a building form that is simple to build, like a tent, but that is shielded against heat and cold [13]. **Table 1** below summarises the socio-cultural factors shaped turhish house forms. **Table 2** presents the photographs of factors influencing the house forms.

Table 1. Socio-cultural factors influenced by each region.

Factors	**Regions**	Black Sea shore hinterland	Istanbul and Marmara	Aegean hinterland	Mediterranean region	Central Anatolia	Eastern Anatolia	Southeast Anatolia	References
Socioeconomic Status		✓	✓	✓			✓		[5,6,10–55]
Social Dynamics and Cultural Practices		✓		✓	✓	✓	✓	✓	
Socioenvironmental Context		✓	✓			✓			
Dense Neighborhood and Social Bonding		✓			✓			✓	
Religious Practices, Behaviors, and Values			✓				✓	✓	
Privacy			✓	✓	✓		✓	✓	
Historical Civilization			✓	✓		✓		✓	
Safety and Protection						✓		✓	

Mythology					✓		✓	
Functional Requirements	✓					✓	✓	
Family Structure				✓	✓	✓		

Table 2. Photographs of factors in each region.

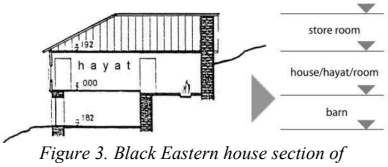


Figure 3. Black Eastern house section of distributing functions according to floor level, Source: [15].

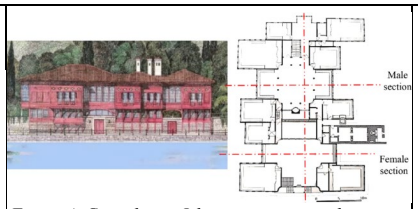


Figure 4. Considering Islamic restrictions, housing units were designed to prioritize privacy in their relationship with the surrounding environment in Istanbul and the Marmara region, clearly distinguishing between male and female spaces within the home. Source: [19].



Figure 5. The houses in this region are designed with a courtyard at the center, enclosed by towering walls that ensure privacy. House plan in the Aegen region, Source: [56].



Figure 6. kosk (private space designed as a raised platform and as part of the Sofa) Source: [57].

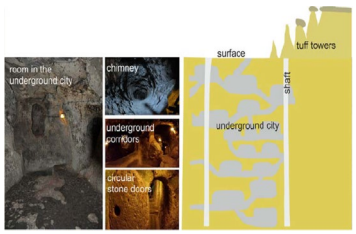


Figure 7. General scheme for underground city of Cappadocia, Source: [58].

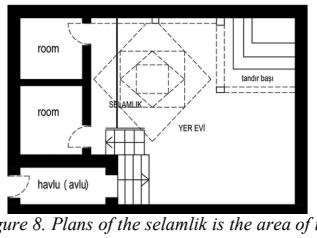


Figure 8. Plans of the selamlik is the area of the home committed for men's usage. Source: [32].

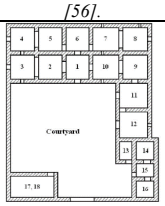


Figure 9. In Harran, it is a common practice for individuals to stay in groups, fostering a sense of community and support. Halil Özyavuz Harran House plan. Source: [46].

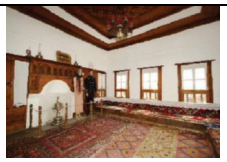


Figure 10. The baş oda, holds a special significance belongs to the patriarch of the family and is characterized by its larger size and elaborate decoration. Source:[59].

Results

Table 3 presents the demographic and professional profile of the 63 respondents. Most participants worked in private architectural practice, with additional representation from the public sector, academia, and heritage consultancy, ensuring a balance between practice, policy, and research perspectives. Professional roles were diverse, led by architectural designers and conservation specialists, alongside researchers, project managers, and technical supervisors, capturing insights across design, research, and implementation stages. Respondents reflected a broad range of professional experience, from early-career to senior experts, supporting a mix of emerging and established viewpoints. In terms of subject knowledge, the majority reported moderate to extensive familiarity with Turkish vernacular housing, indicating that the sample was well-qualified to evaluate socio-cultural factors influencing traditional house forms.

Table 3. Demographic Data Analysis.

Variable	Category	N	%
Professional Affiliation	Private Architectural Practice	30	47.6
	Public / Municipal Planning Sector	15	23.8
	Academic & Research Institutions	12	19.0
	Independent / Heritage Consultancy	6	9.5
Professional Role	Architectural Designer	18	28.6
	Conservation / Heritage Architect	14	22.2
	Urban / Housing Researcher	11	17.5
	Project or Construction Manager	10	15.9
	Site & Technical Supervisor	10	15.9
Years of Professional Experience	Early Career (0–5 years)	16	25.4
	Developing Professional (6–10 years)	14	22.2
	Mid-Career (11–15 years)	13	20.6
	Senior Professional (16–20 years)	11	17.5
	Expert Level (21+ years)	9	14.3

Knowledge of Turkish Vernacular Housing	Extensive Knowledge	28	44.4
	Moderate Knowledge	21	33.3
	Basic / Introductory Knowledge	14	22.2

Table 4 reports the Pearson correlation coefficients among the eleven socio-cultural factors and the overall composite index. The results indicate that all factors are positively and significantly correlated with one another ($p < 0.01$, two-tailed), with inter- factor correlation coefficients ranging from $r = 0.31$ to $r = 0.58$. These values suggest meaningful associations among factors while indicating that each retains a distinct conceptual contribution. Furthermore, all individual factors demonstrate strong correlations with the overall index ($r = 0.65–0.81$), confirming the internal coherence of the composite measure. Factors 3, 7, and 8 show the highest associations with the overall score, highlighting their relatively greater influence within the socio-cultural framework.

Table 4. *Pearson correlation coefficients.*

Factors	Statistic	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Factor 9	Factor 10	Factor 11	All
Factor 1	Pearson Correlation	1.00	0.42	0.39	0.36	0.33	0.35	0.38	0.40	0.34	0.31	0.37	0.65
	Sig. (2-tailed)	—	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.002	0.000	0.000
Factor 2	Pearson Correlation	0.42	1.00	0.56	0.53	0.41	0.48	0.50	0.47	0.44	0.39	0.45	0.74
	Sig. (2-tailed)	0.000	—	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Factor 3	Pearson Correlation	0.39	0.56	1.00	0.58	0.52	0.55	0.54	0.51	0.49	0.46	0.50	0.81
	Sig. (2-tailed)	0.000	0.000	—	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Factor 4	Pearson Correlation	0.36	0.53	0.58	1.00	0.55	0.51	0.49	0.48	0.46	0.43	0.47	0.78
	Sig. (2-tailed)	0.000	0.000	0.000	—	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000
Factor 5	Pearson Correlation	0.33	0.41	0.52	0.55	1.00	0.47	0.45	0.44	0.42	0.40	0.43	0.75
	Sig. (2-tailed)	0.001	0.000	0.000	0.000	—	0.000	0.000	0.000	0.000	0.001	0.000	0.000
Factor 6	Pearson Correlation	0.35	0.48	0.55	0.51	0.47	1.00	0.53	0.50	0.48	0.45	0.49	0.77
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	—	0.000	0.000	0.000	0.000	0.000	0.000
Factor 7	Pearson Correlation	0.38	0.50	0.54	0.49	0.45	0.53	1.00	0.56	0.52	0.48	0.51	0.79
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	—	0.000	0.000	0.000	0.000	0.000
Factor 8	Pearson Correlation	0.40	0.47	0.51	0.48	0.44	0.50	0.56	1.00	0.54	0.50	0.53	0.80
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	—	0.000	0.000	0.000	0.000
Factor 9	Pearson Correlation	0.34	0.44	0.49	0.46	0.42	0.48	0.52	0.54	1.00	0.51	0.55	0.78
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	—	0.000	0.000	0.000
Factor 10	Pearson Correlation	0.31	0.39	0.46	0.43	0.40	0.45	0.48	0.50	0.51	1.00	0.57	0.76
	Sig. (2-tailed)	0.002	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	—	0.000	0.000
Factor 11	Pearson Correlation	0.37	0.45	0.50	0.47	0.43	0.49	0.51	0.53	0.55	0.57	1.00	0.79
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	—	0.000
All	Pearson Correlation	0.65	0.74	0.81	0.78	0.75	0.77	0.79	0.80	0.78	0.76	0.79	1.00
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	—

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Figure 11 shows that most respondents gave positive ratings to socio-cultural factors influencing Turkish vernacular house forms, with strong agreement on the importance of religion, privacy, family structure, historical context, and everyday cultural practices. Mythology and safety/protection received more neutral responses, indicating less consensus about their impact. Very negative ratings were rare, and the overall pattern supports statistical findings that vernacular housing is primarily shaped by interconnected socio-cultural values.

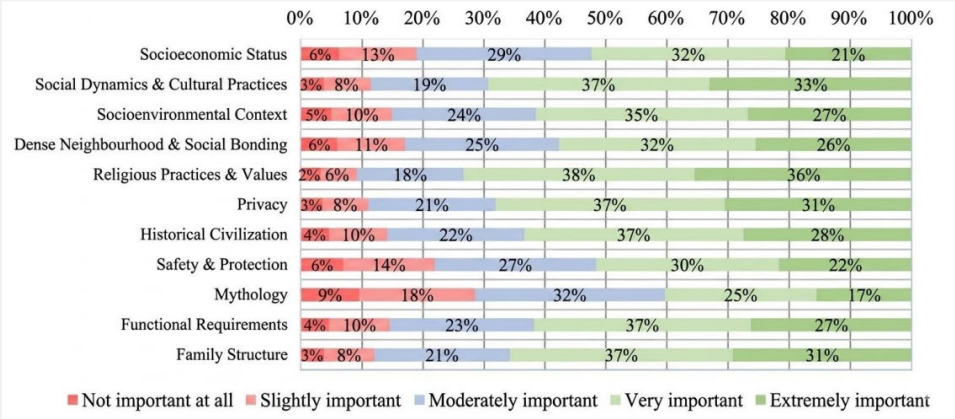


Fig 11. Percentage distribution of respondents' evaluations of socio-cultural factors influencing Turkish vernacular house forms.

Table 5 shows that all examined socio-cultural factors were perceived as having moderate to strong influence on Turkish vernacular house forms. Religious practices and values ranked as the most influential factor, followed by social dynamics and cultural practices, privacy, and family structure, highlighting the dominant role of social and cultural norms in shaping domestic spaces. Historical continuity and environmental context were also considered important. In contrast, socioeconomic status, safety and protection, and especially mythology ranked lower, suggesting a more limited or indirect impact. The generally low standard deviations indicate broad agreement among respondents. Overall, the findings confirm that Turkish vernacular housing is primarily shaped by deeply rooted socio-cultural values rather than purely economic or defensive factors.

Table 5. Statistical Analysis.

Factors	Weighted Average	Std. Deviation	RII	Overall Rank
Socioeconomic Status	3.78	0.68	0.76	7
Social Dynamics and Cultural Practices	4.12	0.61	0.82	2
Socioenvironmental Context	3.95	0.64	0.79	5
Dense Neighborhood and Social Bonding	3.89	0.66	0.78	6
Religious Practices, Behaviors, and Values	4.18	0.58	0.84	1
Privacy	4.05	0.60	0.81	3
Historical Civilization	3.98	0.62	0.80	4
Safety and Protection	3.72	0.71	0.74	8
Mythology	3.41	0.75	0.68	11
Functional Requirements	3.96	0.63	0.79	5
Family Structure	4.02	0.59	0.80	4

The statistical ranking of socio-cultural factors can be further interpreted through their spatial manifestations in Turkish vernacular housing. The highest-ranked factor, religious practices, behaviors, and values, is reflected in inward-oriented layouts, controlled visual permeability, and the spatial separation of public and private domains, often expressed through gender-differentiated spaces such as the selamlık and haremlik. The strong ranking of privacy corresponds to courtyard-

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centered typologies and hierarchical transition zones that regulate movement from public streets to semi-private and private interiors. The prominence of family structure is spatially evident in flexible multi-functional rooms and extended household arrangements that accommodate intergenerational living. Similarly, social dynamics and cultural practices are embodied in semi-open spaces, shared courtyards, and neighborhood clustering patterns that facilitate communal interaction. These spatial correlations demonstrate how abstract socio-cultural determinants identified through quantitative analysis are materially translated into architectural form, reinforcing the intrinsic relationship between cultural values and built morphology. **Table 6** shows that professional affiliation does not significantly affect how respondents rated the importance of socio-cultural factors influencing Turkish vernacular house forms. The one-way ANOVA results were not statistically significant ($F(4,58) = 0.742$, $p = 0.566$), indicating minimal differences between groups. This suggests a strong consistency of perspectives across professional backgrounds, reinforcing the reliability of the identified socio-cultural determinants regardless of respondents' institutional context.

Table 6. *Results of the One-Way ANOVA Examining the Effect of Professional Affiliation on the Perceived Importance of Socio-Cultural Factors.*

Source of Variation	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2.476	4	0.619	0.742	0.566
Within Groups	52.184	58	0.900		
Total	54.660	62			

Conclusion

The study concludes that Turkish house forms have been strongly shaped by socio-cultural factors over time, supporting Rapoport's theory that built form results from a combination of cultural values, social structures, and behavioral patterns rather than solely physical or environmental forces. Case study analysis shows that religion, family life, privacy, and community-oriented traditions have been central in shaping vernacular housing, while historical legacies from Byzantine, Ottoman, and Islamic periods further influenced materials, spatial organization, and architectural expression. Vernacular features such as inward-oriented layouts, modest functional design, geometric ornamentation, and courtyard-centered homes reflect deeply rooted cultural values. The research also stresses that neglecting traditional cultural patterns risks weakening cultural identity, even as modern housing continues to evolve with new technologies.

Statistical analysis reinforces these findings. Religious practices, behaviors, and values ranked as the most influential factor, followed by social dynamics and cultural practices, privacy, and family structure and historical civilization. In contrast, socioeconomic status and safety and protection had more moderate influence, while mythology ranked lowest, indicating a more symbolic role. In the context of accelerating urban transformation, the findings of this study suggest that cultural identity should be understood as an active design parameter rather than a nostalgic reference to the past. The socio-cultural determinants identified particularly religious values, privacy hierarchies, family structure, and community-oriented spatial practices offer adaptable principles that can inform contemporary housing strategies. Rather than replicating vernacular forms, future housing design can reinterpret underlying spatial logics such as inward orientation, courtyard typologies, graduated privacy thresholds, and flexible multi-functional spaces. Integrating these culturally embedded principles into evolving urban frameworks can enhance social sustainability, strengthen community resilience, and ensure continuity between heritage and modern development.

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Sustaining the Paradigm: Sustainability as Technocratic Soteriology and the Demand for Post-Anthropocentric Re-Foundation

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Keywords. Sustainability Critique, Technological Eschatology, Modernity and Metaphysics, Instrumental Rationality, Political Ecology, Techno-Colonialism, Artificial Intelligence (AI), Islamic Cosmology and Stewardship, Post-Anthropocentric Ethics, Decolonial Theory

Abstract. This paper contends that contemporary sustainability largely functions as a self-stabilizing adjustment within the very metaphysical architecture that produced ecological and social breakdown. Framed by Western modernity's anthropocentrism, instrumental rationality, and a teleology of linear progress, sustainability becomes a therapeutic practice of managerial mitigation—what I term *technological eschatology*—promising redemption through optimization and control. Far from re-founding first principles, mainstream approaches preserve them, treating symptoms while the crisis logic endures. The analysis proceeds in four moves: a critical genealogy of sustainability's concepts and institutions; a reconstruction of modernity's tripartite metaphysics (man, nature/place, technology); an assessment of internal sustainability strands alongside AI as a paradigm case of technological eschatology; and a constructive post-anthropocentric reframing that foregrounds Islamic cosmology's concepts of *tawḥīd*, *mīzān*, *khilāfa*, and *amāna*. From this follow actionable criteria—sufficiency over efficiency, non-negotiable limits (planetary and moral), justice (distributional and intergenerational), and virtues of restraint and care—and governance tests repositioning technology from salvific *telos* to accountable instrument. The contribution is diagnostic, normative, and practical: only by re-founding ends can tools be rightly ordered.

1. Introduction

This paper argues that contemporary sustainability largely functions as a self-stabilizing adjustment within the very metaphysical architecture that produced the socio-ecological crisis—anthropocentrism, materialism, coloniality, and a teleology of infinite progress. From the Brundtland Report's growth-friendly formulation to present ESG regimes, "sustainable development" has habitually translated planetary care into metrics, markets, and managerial protocols that rarely interrogate their own first principles.[1] Sustainability's dominant logics thus inherit—and often entrench—the disenchantment and instrumental rationality that Max Weber identified as constitutive of modernity.[2]

The central thesis is that sustainability, as theorized within Western modernity, has become a form of *technological eschatology*—anticipating redemption through optimization, prediction, and control.[3] In Heideggerian terms, the world is disclosed as *Bestand* (standing-reserve), ordered by the enframing (*Gestell*) of technics; sustainability then refines this enframing rather than displacing it.[4] Today, artificial intelligence stands as the apex of this promissory technics, amplifying prediction markets and data extraction while obscuring value judgments behind the rhetoric of optimization.[5] Far from neutral, AI participates in a political economy of

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"surveillance capitalism" with nontrivial material footprints—features that complicate its green aura.[6]

The paper's intervention is to propose a post-anthropocentric, theologically literate reframing that binds technology to non-negotiable moral limits and redefines human freedom as stewardship rather than mastery. While multiple traditions resource such re-foundation, the paper foregrounds Islamic cosmology's concepts of *tawḥīd* (unity), *mīzān* (balance), *khilāfa* (stewardship), and *amāna* (trust), which articulate obligations to creation irreducible to calculus or convenience.[7] The argument proceeds in four moves: a critical genealogy of sustainability; a reconstruction of modernity's tripartite metaphysics; internal and external critiques treating AI as a paradigm case; and a constructive post-anthropocentric alternative with criteria for policy and design. The wager is simple: only by re-founding ends can tools be rightly ordered.

2. Methodology and Research Design

The study adopts three complementary methods. First, a *critical genealogy* of the sustainability paradigm treats "sustainable development" as a historically situated formation rather than a neutral ideal, tracking how problem-definitions, metrics, and expert discourses sedimented from conservationist debates through Brundtland into ESG regimes.[8] Second, a *conceptual analysis* reconstructs modernity's metaphysical architecture across three interlocked dimensions—man (anthropocentrism, temporal imaginaries), nature/place (objectification, disenchantment), and technology (instrumental reason)—drawing on Weber's disenchantment and Heidegger's *Gestell*.[9] Third, a *comparative framework* stages external critiques and constructive alternatives from non-Western resources, with particular emphasis on Islamic cosmology and stewardship ethics alongside work in comparative philosophy of technology.

Three analytical lenses organize the inquiry. Philosophy of technology interrogates the purported neutrality of tools and systems. Political economy situates sustainability within industrial capitalism and colonial extraction, showing how ecological externalities and uneven development are structurally produced rather than accidental. Environmental humanities provide categories to parse modern spatial-temporal experience—Relph's *placelessness* and theories of social acceleration—that help explain why "green" optimization often intensifies rather than relieves crisis logics.[10] The focus is on paradigms and logics, not a comprehensive policy survey. The contribution is *explanatory-normative*: it clarifies why mainstream sustainability remains structurally complicit, and articulates criteria for a post-anthropocentric reframing that binds technology to non-negotiable ethical limits.

3. Sustainability: Concept, Evolution, and Problem-Setting

Definitions and dimensions. In its canonical formulation, "sustainable development" meets the needs of the present without compromising future generations' ability to meet their own needs—a definition expanded by subsequent scholars to include culture as a fourth pillar.[11] Competing schools turn on how substitutable nature and capital are: *weak sustainability* allows natural capital to be offset by human-made capital, whereas *strong sustainability* treats certain ecological stocks as non-substitutable. Allied debates pit green growth (decoupling) against degrowth and post-growth proposals that doubt absolute decoupling at the required speed and scale. The circular economy reframes production-consumption through restorative loops yet struggles with rebound effects. ESG translates sustainability into investor-facing metrics; meta-analyses find heterogeneous links to financial performance and mixed evidence for real-world impact.[12] The proliferation of reporting frameworks can institutionalize incremental improvements while leaving underlying growth imperatives intact.

Historical evolution. Intellectual roots reach from conservation movements to *The Limits to Growth* (1972).[13] The Brundtland Report (1987) mainstreamed the term and bridged North–

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South agendas; Rio 1992 institutionalized global targets; and the SDGs (2015) broadened scope to 17 interlinked goals. From the 2000s, sustainability became increasingly financialized through ESG ratings and carbon markets, embedding sustainability within market governance. Across these phases, metrics, markets, and management frameworks rose to dominance—features congenial to firms and states but not necessarily to ecological integrity or justice.

The crisis to which sustainability responds. The paradigm addresses overlapping planetary crises: unequivocal anthropogenic warming documented by the IPCC, dramatic biodiversity loss with up to a million species at risk (IPBES), and multiple planetary boundaries nearing or exceeding safe operating spaces.[14] These dynamics take off with fossil-fueled industrial capitalism. World-systems and coloniality scholars show how colonial extraction externalized ecological and social costs, creating asymmetric exchange and path dependencies that persist.[15] Karl Polanyi's "great transformation"—the commodification of land, labor, and money—disembedded economies from social-ecological constraints, institutionalizing growth compulsion.[16] Contemporary crisis is thus the product of a historically specific assemblage: fossil energy, industrial technique, colonial-capitalist political economy, and a modern imaginary of linear progress.

4. Modernity's Metaphysical Architecture: Man, Nature/Place, Technology

Sustainability's dominant imaginaries and instruments do not arise *ex nihilo*; they are incubated within a wider metaphysical architecture that modernity normalized across knowledge, governance, and economy. This architecture can be parsed into three co-implicated registers: a modern anthropology of the human (sovereign autonomy and linear time), a concept of nature/place (objectification, disenchantment, extractivism), and a theory of technology (instrumental rationality, standardization, managerialism). Together, these orient sustainability toward calculative optimization rather than ontological re-foundation.

4.1 Man (anthropology and time). Modernity's anthropocentrism displaces theocentrism, re-seating sovereignty in the rational, self-legislating human. Bacon's experimental program reframed knowing as mastery; Descartes proposed the subject as certain foundation and the world as extended substance available to methodical control.[17] In Charles Taylor's account, such moves coalesce in an "immanent frame" in which meaning and authority are enclosed within human horizons; transcendence becomes optional or residual. A corollary is mind–body dualism rendering the knowing subject disembodied and the world othered as object—predisposing modern science and administration to treat alterity as a problem of measurement and control. Equally decisive is modernity's temporality: the secularization of a medieval-Christian eschaton into linear progress underwrites *technological soteriology*—salvation displaced from grace to technique, from vertical transcendence to horizontal acceleration through optimization and control.

4.2 Nature/place. If the modern subject is autonomous, nature becomes the correlate object. Heidegger names the culmination: modern technology enframes beings as standing-reserve, available for ordering and extraction.[18] Weber's disenchantment registers the loss of sacred presence; Carolyn Merchant reconstructs how a living cosmos gives way to a mechanistic nature open to domination. Polanyi traced how the great transformation commodified land and labor, generating growth compulsion.[19] World-systems analysis maps center–periphery extraction premised on "cheap nature" and systemic appropriation of extra-human work.[20] Place is similarly reconfigured: time–space compression and the logic of speed produce placelessness—supermodern circulation without deep relationality.[21] In short, the modern metaphysics of nature and place has political economy built in: objectification legitimates extraction; disenchantment legitimates dispossession.

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4.3 Technology. Within this constellation, technology shifts from *techne*—a poietic, situated craft—to *technics*: standardization, optimization, and industrial scaling. Adorno and Horkheimer generalize the critique as instrumental reason: the Enlightenment's promise of emancipation devolves into domination when cognition is reduced to calculation and control.[22] Ellul adds that technics tends toward autonomy, generating self-augmenting chains of technical necessity indifferent to substantive ends.[23] Langdon Winner's question—do artifacts have politics?—elicits a qualified yes: technical forms embed and reproduce social orders. In contemporary form, these tendencies culminate in managerialism: organizational worlds in which engineering mindsets become the default ontology—problems are what can be modeled; solutions are what can be optimized. *Technological soteriology* names the modern redirection of salvific hopes into a horizon of technical transcendence—singularity, superintelligence, optimization of everything. Sustainability, when uncritical, becomes the liturgy of this faith. Without a different picture of the human, of nature/place, and of technology, sustainability is primed to optimize the crisis rather than interrupt it.

5. The Sustainability Paradigm: Internal Map and Critiques

Within contemporary practice, market-led green growth pursues decarbonization through carbon pricing, innovation, and technological substitution, with techno-optimist variants foregrounding AI for efficiency gains across energy, mobility, and buildings. At the other pole, strong sustainability insists on non-substitutable natural capitals and planetary boundaries, while degrowth and post-growth proposals argue that material throughput must contract in affluent economies to achieve biophysical stabilization with equity. Corporate ESG and impact investing translate sustainability into investor-facing metrics, aiming to align capital flows with climate and social goals.[24]

Notable achievements include mainstreaming of net-zero trajectories, substantial renewable build-out and cost declines, and partial evidence of relative decoupling of territorial emissions from GDP. ESG has diffused disclosure and board-level accountability. Yet the paradigm exhibits recurrent limits. *Rebound/Jevons effects* erode efficiency gains when improved productivity lowers costs and stimulates additional consumption.[25] *Offshoring* shifts emissions along global value chains, making producer-based decoupling appear stronger than consumption-based accounting reveals. *Greenwashing and metric capture* blunt material impact; the large divergence of ESG ratings underscores weak construct validity.[26] *Distributive injustice* persists: both low-carbon transitions (critical minerals, land for renewables) and climate harms exhibit uneven geographies of burden.

Intra-paradigm critiques are sharp. Degrowth scholars contest the "win–win" promise of green growth. Resilience is criticized as responsibilizing communities to "bounce back" while leaving structural drivers—extraction, dispossession, racialized vulnerability—intact. ESG faces charges of financialization: portfolio risk management masquerading as planetary repair. Circular economy strategies encounter thermodynamic limits that temper transformative claims. Both managerial and critical strands remain tethered to instrumentalist assumptions—optimize, measure, manage—and technocratic governance. They solve for coordination inside the very metaphysical and political-economic frame that produced the crisis, risking optimization of the problem rather than a redirection from it.

6. Technology, AI, and Technological Eschatology

6.1 From solutionism to eschatology. Across policy, design, and corporate strategy, *solutionism* casts every social-ecological problem as an optimization challenge solvable by more data, better models, and tighter control. Pushed to its horizon, solutionism matures into technological eschatology—a secular soteriology relocating hopes for salvation from moral transformation to technique.[27] Such a horizon confuses means for ends: instruments can maximize against a given

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objective function, but they cannot supply or adjudicate the *ends themselves*. That task belongs to substantive moral and political judgment about what should be valued and limited. When sustainability is absorbed into the solutionist frame, its *telos* risks becoming "more efficient management" rather than reorientation of the human–earth relationship.

6.2 AI as apex of modern technics. Contemporary AI is the operational apex of this technics. At scale, AI amplifies prediction, data colonialism, surveillance capitalism, behavioral governance, and platform concentration.[28] Its material base depends on energy- and resource-intensive cloud infrastructures whose planetary costs are increasingly legible: training and serving large models impose substantial carbon burdens, while critical minerals for hardware link AI to extractive frontiers with well-documented social and ecological costs.[29] Rebound dynamics—"smart" optimization lowering marginal costs and stimulating additional demand—threaten to outpace efficiency gains. AI systems reproduce and scale algorithmic bias; predictive scoring disproportionately burdens racialized and precarious populations.[30] Governance by optimization depoliticizes value choices: key assumptions—which objectives, which trade-offs, whose data—are buried in pipelines and loss functions, presenting political decisions as technical necessities. Current "AI ethics" initiatives often amount to ethics washing without addressing power, extraction, and enforceable limits.

6.3 Why tech cannot be the telos. Tools are means; they presuppose and magnify the ends we select. Without a normative ontology—commitments to stewardship, dignity, planetary limits, and intergenerational justice—capable machines amplify the crisis logic: more extraction, more control, more acceleration. Prediction does not tell us *what is worth predicting*; optimization does not tell us *what is worth optimizing*; scale does not tell us *what must be limited*. As MacIntyre argues, practices are sustained by internal goods and virtues that no technique can generate; detached from those, institutions tend toward external goods of power and profit.[31] A decolonial sustainability must therefore reorder technology from salvific horizon to accountable instrument, governed by prior ends it cannot supply and bounded by harms it must not cross.

7. External Critique: Non-Western Frames and an Islamic Alternative

7.1 Seeing sustainability from outside. Viewed through non-Western lenses, mainstream sustainability reveals blind spots flowing from its tacit universalism. It naturalizes a single metaphysics—the modern, secular, individualist picture of the human—erasing cosmologies in which personhood is relational (Ubuntu), embedded (Indigenous), or cultivated through self-cultivation (Confucian). Confucian eco-humanism understands humans as nodes in a triad of Heaven–Earth–Human; sustainability appears as *becoming worthy* rather than optimizing indicators. African Ubuntu philosophy approaches flourishing as *being-with*—repair, reciprocity, and restraint as constitutive goods rather than external constraints. Indigenous climate justice re-centers relational responsibilities to land and kin; sustainability becomes treaty-keeping and guardianship, not managerial control. Latin American pluriversal design refuses the one-world ontology of growth, inviting distinct cosmo-techniques that re-embed making within place and meaning.[32] These alternatives share a commitment to thick normativity—first principles about what counts as the human, the good, the sacred, the limits—that set the horizon for institutions and tools.

7.2 Islamic cosmology and ethics of stewardship. An Islamic alternative articulates a live normative ontology capable of ordering institutions and tools. At its metaphysical core stands *tawḥīd* (Divine unity): all beings derive from and depend upon the One; reality is not a field for autonomous mastery but a theophanic order. This unity entails *mīzān* (balance/measure)—a divinely set equilibrium that humans must honor: "He has raised the sky and set the balance—so

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do not transgress in the balance."[33] Humans are appointed *khalīfa* (stewards) on earth, charged with *amāna* (trust) to keep creation's order and judge justly; wanton excess (*isrāf*) is explicitly proscribed.[34]

In this frame, freedom is redefined as responsible agency under moral law, not the license of domination. Vertical transcendence—humility before a higher sovereignty—counterposes modern linear progress: technique cannot redeem the soul. Technology is subordinated to ethical ends (*maqāṣid al-sharīʿa*): preservation and enhancement of religion, life, intellect, progeny, and wealth in just balance.[35] Sufficiency (*kifāya*, *qanaʿa*) takes precedence over efficiency. Classical doctrines recognized protected zones (*ḥimā*, *ḥaram*) for water, grazing, and habitat; waste and harm are prohibited under *la ḍarar* (no harm) and *ḥisba* (market oversight for public good). Contemporary scholars extend these to modern governance: stewardship obliges intergenerational equity; trust proscribes externalizing harms; limits demand caps and sufficiency policies rather than perpetual throughput.[36]

This alternative does not reject tools; it reorders them. AI may serve monitoring or allocation if and only if it is embedded within ethical authority, transparent accountability, and prior limits—it cannot supply the ends it must obey. Islam's cosmology provides first principles (unity, balance, stewardship, trust, limits) that answer precisely where mainstream sustainability is thinnest: not a romantic past nor a technocratic future, but a normative present—a way to make and govern that binds power to purpose.

8. Constructive Reframing: A Post-Anthropocentric Sustainability

8.1 Normative commitments. A post-anthropocentric sustainability begins by de-centering human entitlement and acknowledging intrinsic value in non-human creation—a basic ontological claim: ecosystems, species, and places possess worth irreducible to human utility. Aldo Leopold's land ethic remains exemplary: humans are "plain member and citizen" of a biotic community, and moral considerability extends to soils, waters, plants, and animals.[37] Hans Jonas's *imperative of responsibility* follows: the enlarged causal reach of modern technology imposes duties toward distant others, future generations, and the biotic world—some thresholds (extinction risks, irreversible harms, planetary boundaries) are not negotiable under cost–benefit calculus.[38] Sustainability must accordingly replace managerial optimization with *stewardship* and *care*: a fiduciary duty to protect, restore, and transmit a more-than-human inheritance, oriented to the flourishing of interdependent beings rather than the maximization of aggregate outputs.

8.2 Criteria and governance. Translating these commitments into practice requires criteria that reflect ends, not just means. *Sufficiency over efficiency*: Thomas Princen argues that meeting needs "within enough" is the only logic aligned with ecological reality, since efficiency without sufficiency triggers rebounds and scale effects.[39] *Limits*: coupling planetary boundaries with moral limits—no species sacrifice, no sacrifice zones—operationalized in Raworth's "safe and just space."[40] *Justice*: distributional, recognitional, and intergenerational—from environmental justice's analysis of uneven burdens to duties to future generations.[41] *Virtues as operational criteria*: mercy, justice, truthfulness, and temperance understood as public capacities guiding institutional design and professional practice, not private sentiments.[42] *Place and dwellability*: design against placelessness by restoring attachment, legibility, and care for the *genius loci*.[43]

These ends demand institutional translation: a precautionary principle shifting the burden of proof when plausible serious harm looms; liability for externalities through polluter-pays instruments; commons governance for shared resources drawing on Ostrom's design principles;[44] and stewardship charters embedding duties and consent.

8.3 Technology repositioned. Technology must move from *telos* to instrument. Before deployment, technics should pass four tests: a *Purpose test* (*why do it?*—linking to higher goods

such as biodiversity protection or sufficiency); a *Limit test* (*how far?*—respecting biophysical and moral thresholds); an *Equity test* (*who benefits/costs?*—with ex ante protections for vulnerable communities); and a *Care test* (*who/what is protected?*—ensuring living systems and places are not treated as expendable). Applied to AI, this repositioning entails: transparency and contestability for value-laden choices;[45] energy and compute caps aligned with climate goals;[46] data sovereignty and anti-extraction protocols;[47] alignment with sufficiency (prioritizing demand reduction, habitat monitoring) rather than consumption stimulation; and prohibitions on optimization that monetizes harm—surveillance capitalism, manipulative behavioral targeting, and extractive platform lock-in. As Jonas cautions, when the scope of possible harm expands beyond precedent, prudence must rule over prowess.[48] Reframed this way, sustainability ceases to be the therapeutic wing of modern technocracy and becomes a normative project: ordering economies, designs, and tools toward *enoughness*, justice, and the durable habitation of places.

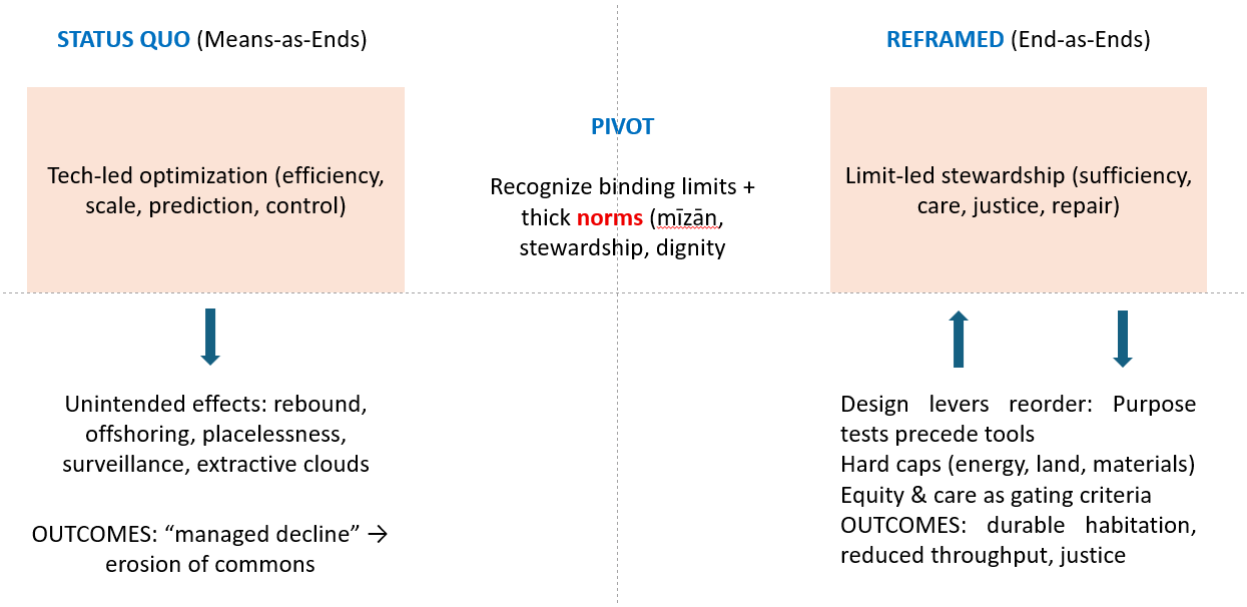


Figure 1 — *From Tech-Led Optimization to Limit-Led Stewardship Conceptual flow, schematic*

9. Policy, Design, and Practice Implications

The normative reframing advanced above is not an abstract philosophical exercise; it carries direct institutional consequences. If sufficiency, stewardship, and non-negotiable limits are to function as constitutive ends rather than rhetorical gestures, they must be embedded in the material grammar of cities, economies, and computational systems. The following implications translate the post-anthropocentric framework into concrete guidance across four domains: urban design and architecture, economic policy, governance, and AI governance.

Urban/architectural. In hot-arid and mixed climates, inward-oriented typologies—courtyard housing, shaded passageways, compact blocks—reduce heat gain, enhance privacy, and create low-energy microclimates; their logics are well documented in Islamic and vernacular urbanism.[49] Incorporating climate-fit materials with high thermal mass and low embodied energy further cuts lifecycle impacts. At the urban scale, prioritizing walkability over speed—mixed uses, calmed traffic, human-scale frontages—links to mode shift, safety, and health. Local circularity (urban mining, building component reuse, materials passports, neighborhood repair spaces) keeps value in place and reduces throughput. Place-repair requires design for legibility, enclosure, and care, re-stitching streets, squares, courtyards, and ecotones that invite dwelling.

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Economic. Where throughput already exceeds ecological ceilings, post-growth and degrowth pathways targeting sufficiency within planetary boundaries are warranted, focusing on provisioning systems—housing, mobility, food—that meet needs without aggregate expansion. Repricing externalities via carbon and material excises internalizes climate and biodiversity costs. Public funds should seed repair/reuse commons and shared fabrication infrastructures; a "performance economy" selling service rather than stuff aligns firms with durability and maintainability.

Governance. Embed moral limits in law: hard caps for biophysical ceilings, no-go protections for critical habitats, and non-compensable bans on sacrifice zones. Establish participatory stewardship councils for local resources drawing on polycentric governance with clear rules, monitoring, and graduated sanctions.[50] Planning and conservation should recognize non-market value—sacred sites, cultural landscapes, and biodiversity as ends in themselves—within statutory appraisal and compensation regimes.

AI governance. Align computational infrastructures with climate and justice aims through energy/emission budgets for training and inference, lifecycle reporting, and siting on low-carbon grids.[51] Create public-interest compute (shared research clouds with open auditing) to reduce duplication and private lock-in. Adopt enforceable "do-no-harm" standards for high-impact models—environmental and distributive impact assessments, meaningful human oversight with contestability and redress.[52] Require Purpose, Limit, Equity, and Care tests for AI in the built environment. These measures re-order practice: design for enoughness, govern for commons and care, and treat technology as accountable instrument—not *telos*.

10. Conclusion

This paper has argued that much of contemporary sustainability functions as technological eschatology: a managerial soteriology promising redemption through optimization, prediction, and control, thereby treating symptoms while leaving intact the metaphysical architecture—anthropocentrism, disenchantment, and technocratic reason—that generated the crisis. In Ellul's terms, the technological system becomes self-augmenting, conferring necessity on whatever is technically possible; "greener" tools rarely unsettle the ends they serve.[53] Nor do managerial adjustments meet the ethical threshold implied by Jonas's imperative of responsibility, which demands categorical limits when the scale and irreversibility of harm exceed precedent.[54] Meanwhile, planetary boundaries are not advisory but binding; exceeding them cannot be offset by efficiency, markets, or metrics.[55]

If sustainability is to deliver genuine socio-ecological flourishing, it must be re-grounded in first principles that de-center human entitlement, affirm intrinsic value in the more-than-human world, and bind technology to non-negotiable limits. Leopold's land ethic offers one anchor; virtue traditions construe practical reason as ordered to goods internal to practices rather than to aggregate outputs.[56] Raworth's "safe and just space" gives a pragmatic frame for coupling social foundations to ecological ceilings—but only if sufficiency and restraint replace throughput expansion as the default *telos*.[57] In line with pluriversal and religious cosmologies, sustainability must recover thick normativity—stewardship, trust, balance—that disciplines technique rather than defers to it.[58]

The work ahead is twofold: *rebuild the axioms*—articulate a post-anthropocentric, limit-bound ontology of the human and the earth, and a virtue-inflected ethics of care and justice; then *build tools to fit those ends*—redesign institutions, metrics, and technics (AI included) so that purpose, limit, equity, and care are constitutive constraints, not ex post audits. Without this inversion of primacy—from means to ends—"sustainability" will remain an eloquent name for managed decline.

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Beyond the Façade: Architecture in the Arab World / Projects and Positions

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Abstract. Many cities in the Middle East and North Africa (MENA) region are experiencing rapid growth that presents significant challenges in terms of resource consumption, in spite of the fact that there are historical examples that can serve as models for understanding how to produce climate-responsive and culturally-sensitive architecture. Drawing upon under-researched archival material from the Aga Khan Award for Architecture, the project *Beyond the Facade* focuses on revealing design knowledge from six architectural projects from the late twentieth century across the UAE, Saudi Arabia, Syria, and Iraq. The project demonstrates how local knowledge can have transnational relevance to the development of environmentally and culturally sustainable strategies. Rather than treating archives as static historical records, this study transforms them into active sources for providing knowledge discovered through analysis. Employing generative analytical methods, the study utilizes three-dimensional drawings, stop-motion animation, and 3D-printed relief models to investigate and communicate how the façades in the projects are more than a separation between interior and exterior.

Introduction

Beyond the Facade is an ongoing critical examination of how facades can be constructed to embody cultural meaning, address environmental performance, and respond to aspects of human experience. To date six buildings in the Arab world awarded the Aga Khan Award for Architecture have been analyzed; the buildings selected are not only regionally significant but offer a counter-narrative to dominant global architectural approaches that deny the importance of context. Instead of treating these buildings as isolated case studies or stylistic icons, the project positions them as material evidence of a approaches to architecture shaped by climate, craft, and context. More importantly, this research uses archives not merely to retrieve historical data but to produce new modes of architectural engagement. Analytical methods and representational techniques (three-dimensional drawings, stop-motion animation, and 3D-printed relief models) reconstructs the structural and environmental logic of the facade. This approach, which focuses on ideas of "spatial thickness" rather than the surface detailing emphasized in tectonic analyses, offers a relevant method for understanding facade performance as a fusion of environmental, symbolic, and social dimensions.

In an era where climate-responsive, culturally-grounded design is increasingly urgent, these buildings are not relics but prototypes. They embody a design ethos that integrates tradition with innovation, offering frameworks for informing future practice across global contexts. This study therefore asks: **how can architectural archives be re-examined through visual analytical methods in order to uncover climate-responsive and culturally embedded design strategies**

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within modern architecture of the Arab world? By reconstructing the spatial logic of selected projects through drawings, models, and animations, the research seeks to reveal how facade systems operate not merely as aesthetic surfaces but as environmental and social infrastructures.

Case Studies

Abu Nawas Development Project (Baghdad, Iraq (1980–1981) (Skaarup & Jespersen))

The Abu Nawas Development Project (Fig. 1) is an emblematic example of climate-conscious urbanism that offers globally relevant insights into sustainable residential design. Conceived as part of a larger 1970s renewal initiative, the project transformed a 3-kilometer stretch of the Tigris riverfront into a medium-density, community-oriented neighborhood. With 278 terraced units ranging from one-bedroom flats to four-bedroom townhouses, the design prioritizes privacy through features like front courtyards, back gardens, roof terraces, and shaded pedestrian lanes—reinterpreting the social and environmental logics of vernacular Baghdadi courtyard houses within a formalized planning framework [1].



Fig 1: Photographs of the Abu Nawas Development Project. Courtesy of Aga Khan Award for Architecture, 1987.

Relying on exploded three-dimensional drawings and an analysis of architectural attributes, the analytical method exposes the building envelopes as performative systems rather than decorative shells (Fig. 2). Recessed apertures, brick cladding, and the integration of systems to mitigate the impact of solar radiation are not superficial features, but function as both aesthetic features and environmental mediators. The brick façade is analyzed for its thermal properties, material use, and symbolic continuity, while the spatial layering of thresholds - garden, court, shaded entry - is reconstructed to show how environmental modulation is embedded in spatial and material sequences.

This reframing moves beyond cataloging archival data; it activates the project as a design prototype (Fig. 2). Abu Nawas demonstrates how urban density, social interaction, and climatic adaptability can coexist through a logic of wall assembly and shading - offering an alternative to energy-intensive suburban typologies or imported glass-clad housing blocks. The study positions it as a replicable model for urbanism in hot climates and as a critical artifact in understanding how regional modernism can inform contemporary sustainable design practices [1].

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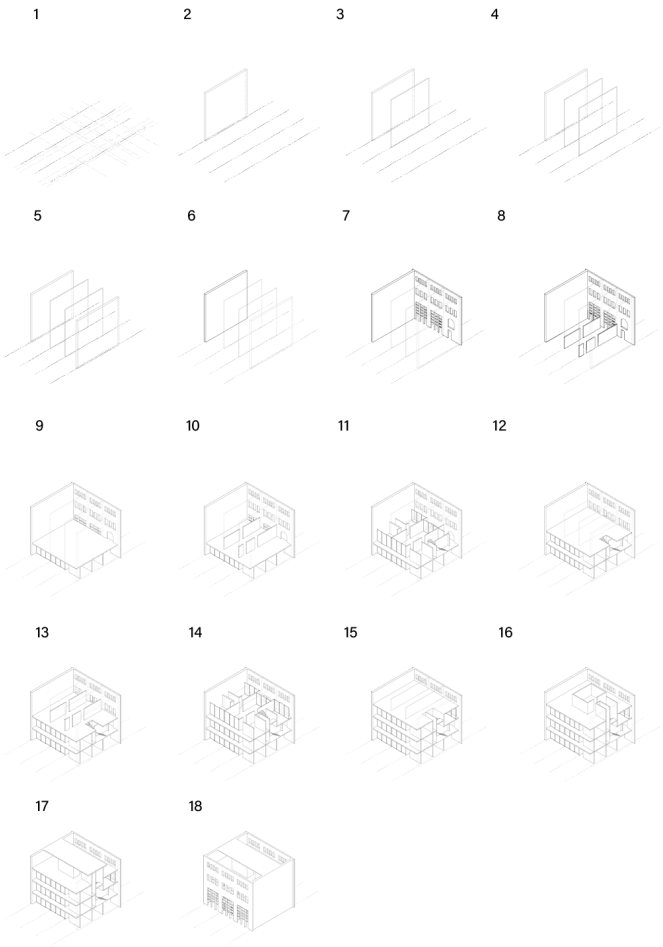


Fig 2: Abu Nawas Development Project - stop-motion animation sequence. © Omar Darwish

National Commercial Bank (Jeddah, Kingdom of Saudi Arabia (1983) (SOM))

The National Commercial Bank (NCB) Headquarters is reinterpreted not simply as an architectural icon, but as a model of environmentally performative high-rise design that proposes a response to context (Fig. 3). Moving away from the normative glass tower, the NCB deploys a stereotomic massing strategy—triangular in plan and cloaked in travertine—that prioritizes internal courtyards and shaded loggias over exterior glazing [7].

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Fig 3: Photographs of National Commercial Bank. Courtesy of Architect (submitted to the Aga Khan Award for Architecture), 1989.

Three-dimensional drawings and stop-motion animations illustrate how the courtyards, paired with the central vertical atrium, act as passive environmental systems—drawing hot air upward and diffusing daylight across office floors (Fig. 4). Rather than a flat surface, the façade forms a volumetric boundary regulating thermal comfort and providing a degree of privacy. The NCB proposes an alternative to energy-intensive vertical typologies by embedding climatic responsiveness into the building's volume. This reframing allows the project to be seen not as a historical example, but as a forward-looking prototype for vertical architecture in arid urban contexts.

By shifting the narrative from visual monument to spatial system, the study argues that vertical urbanism can be achieved not through technological excess, but through the adaptive reuse of traditional strategies—such as courtyards, recessed walls, and inward orientation—rendered through contemporary forms [7].

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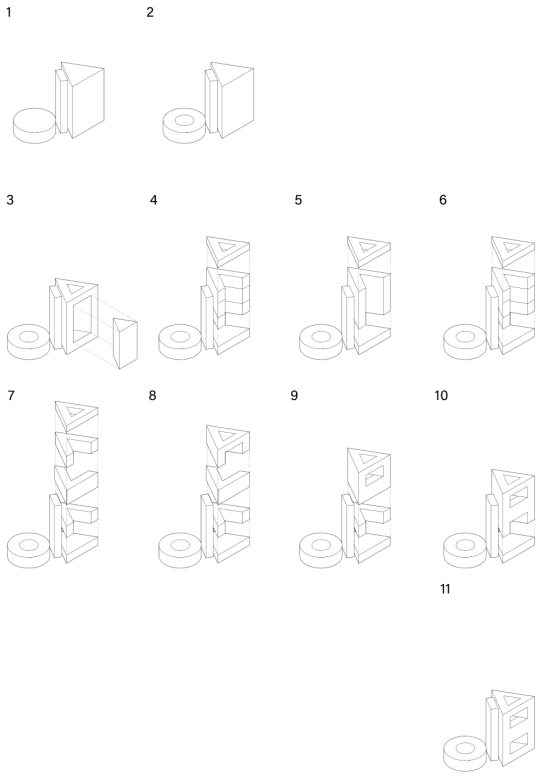


Fig 4: National Commercial Bank - stop-motion animation sequence. © Omar Darwish

Ministry of Foreign Affairs (Riyadh, Kingdom of Saudi Arabia (1984) (Henning Larsen))
The Ministry of Foreign Affairs exemplifies how architecture attempts to balance cultural symbolism with environmental performance. While its historic references to Najdi architecture and Islamic monumental forms are well-documented, this study recasts the building through a new lens to reveal a spatial language based on depth, mass, and filtered light (Fig. 5). Sectional analyses show how thick wall assemblies, vaulted corridors, and domed courtyards function not only as cultural markers but also as passive climate-control devices [6].

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Fig 5: Photographs of the Ministry of Foreign Affairs. Courtesy of Architect (submitted to the Aga Khan Award for Architecture), 1989.

The façade is not treated as an aesthetic layer but as a spatial and environmental medium (Fig. 6). Wooden screens (mashrabiyas), recessed windows, and deep wall sections are studied for their role in minimizing heat gain, guiding air movement, and framing social experience. These elements are not retrofitted nostalgia but are integrated into a modern civic building to support diplomatic activity.

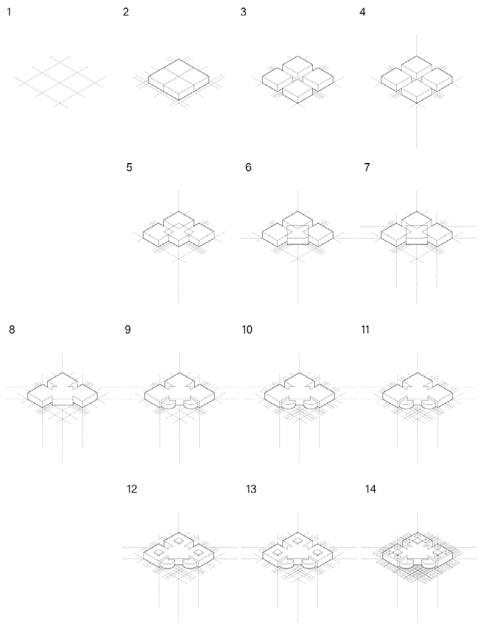


Fig 6: The Ministry of Foreign Affairs—stop-motion animation sequence. © Omar Darwish

The Ministry presents a compelling case for how governmental architecture can assert national identity without relying on mimicry or superficial symbolism. It models a performative monumentality—projecting cultural continuity while minimizing environmental impact. For architects and policymakers alike, it offers a replicable template for designing civic infrastructure rooted in place, climate, and public memory [6].

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French Cultural Centre (Damascus, Syria (1986) (José Oubrerie and Kirkor Kalayciyan))
The French Cultural Centre is recontextualized as a spatial mediator between a dense historic fabric and the need for a contemporary structure that accommodates specific institutional needs (Fig. 7). Rather than focusing solely on its stylistic dialogue with local architecture, this study engages its inward-oriented massing and vertical courtyard as environmental and symbolic strategies. The central atrium is revealed—through sectional diagrams and animations—as a thermal and experiential core, regulating light, ventilation, and circulation [2, 4].



Fig 7: Photographs of French Cultural Center. Courtesy of Architect (submitted to the Aga Khan Award for Architecture), 1992.

The façade is read as a gradient of exposure and enclosure: solid stone on the south interfaces with the dense city block, while the more open northern elevation engages a civic plaza (Fig. 8). Grilles, screens, and atrium voids become tools for environmental control rather than merely stylistic gestures. This layered understanding positions the building not as an aesthetic compromise between French and Syrian traditions but as an architectural resolution of cultural and climatic tensions.

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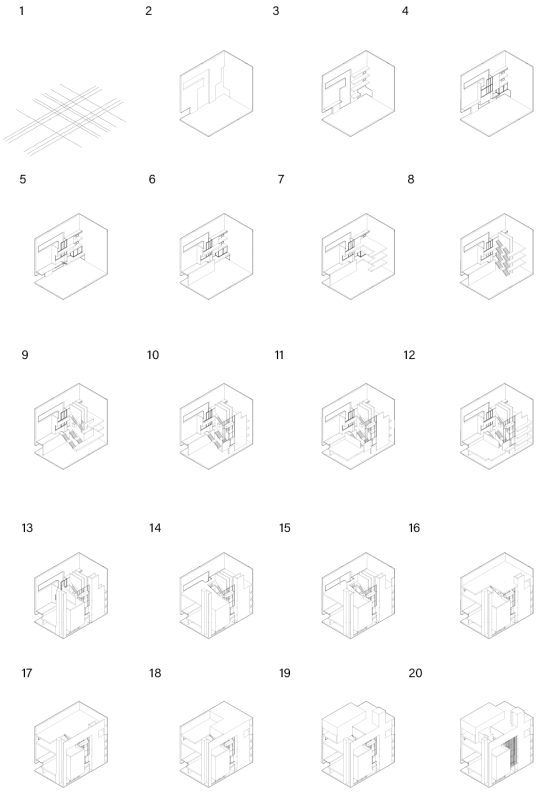


Fig 8:The French Cultural Centre—stop-motion animation sequence. Courtesy of the author.

The French Cultural Centre illustrates how institutions—especially those with dual or foreign affiliations—can build contextually without erasure or imposition. The project explores the potential of façade articulation to create depth as a means of climate mediation over visual flatness, a lesson increasingly urgent in contemporary sustainability discourse [2].

Abu Dhabi Cultural Foundation (Abu Dhabi, United Arab Emirates (1981) (The Architects Collaborative))

The Abu Dhabi Cultural Foundation can be considered an infrastructural typology of cultural urbanism (Fig. 9). Rather than merely a symbolic project of nation-building, the building's courtyard-centered layout and shading strategies are unpacked as a compositional and environmental system. Through physical modeling and drawing reconstructions, its arcades, mashrabiya patterns, and shaded walkways are analyzed for their spatial logic and climatic responsiveness [3].

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Fig 9: Photographs of Abu Dhabi Cultural Foundation. Courtesy of Architect (submitted to the Aga Khan Award for Architecture), 1985.

The analysis shows how the façade is more than surface: it is a network of filters—structural, visual, and thermal—that operate collectively to create spatial porosity and climatic equilibrium (Fig. 10). This re-reading contributes to positioning modern heritage not as fixed icons, but as operational systems with transferable knowledge.

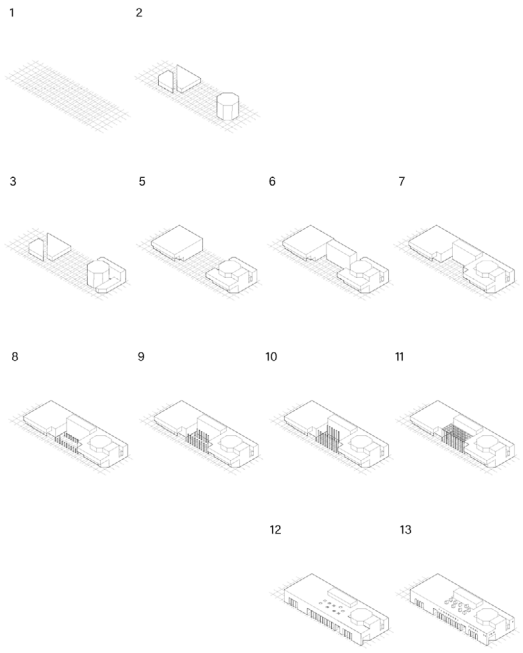


Fig 10: The Abu Dhabi Cultural Foundation—stop-motion animation sequence. © Omar Darwish

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The Cultural Foundation thus becomes a didactic case in how postcolonial states can produce architecture that is both rooted in vernacular grammar and anticipatory of future needs—offering an instructive model for cultural institutions worldwide seeking to bridge past and present through built form [3].

Corbachi Building (Baghdad, Iraq (1952–53) (Rifat Chadirji))

The Corbachi Building is not simply as a hybrid of residential and commercial functions but as a strategic approach to issues such as urban density, multi-use typology, and thermal mediation (Fig. 11). Brick lattice screens, recessed corridors, and masonry envelopes operate as environmental buffers and spatial organizers [8].



Fig 11: Kamil and Rifat Chadirji Photographic Archive, Aga Khan Documentation Center at MIT, ca. 1953

Analyses reveal how the building internalizes traditional market *souk* typologies by employing double-loaded corridors. Residential duplexes above the market are a vertical reinterpretation of Baghdad's courtyard homes. Brick screens are not just a formal reference, but function as a calibrating device for privacy, ventilation, and light filtration.

This analytical reframing demonstrates that Chadirji's work goes beyond modernist adaptation (Fig. 12). It represents a regional logic of urban living that remains under-acknowledged in global discourse. In a world facing increasing urban density and environmental stress, the Corbachi Building offers an alternative to glass towers and gated compounds—a model for compact, climate-attuned, socially vibrant architecture that bridges tradition and innovation [8].

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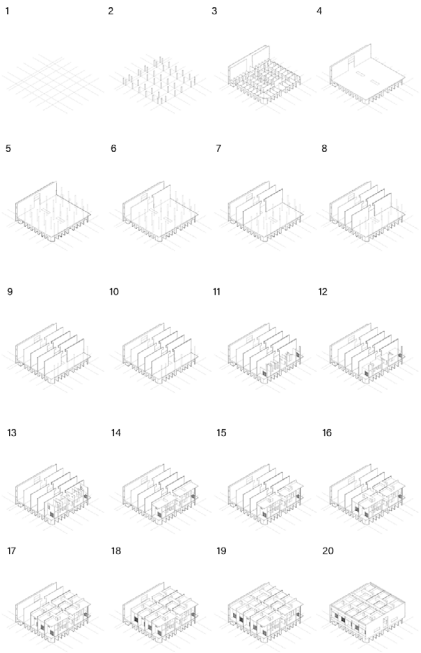


Fig 12: Corbachi Building—stop-motion animation sequence. © Omar Darwish

Research Methods and Visual Analysis Techniques

A distinctive aspect of the study is the use of innovative research and visual representation techniques to analyze and communicate facade behavior and design intent. This multi-method approach integrates exploded axonometric drawings, sectional axonometric studies, relief models, and stop-motion animations—each providing a unique perspective on construction, spatial experience, and environmental performance. By synthesizing insights from these tools, the study developed a rich, multi-sensory analysis of each building, exceeding what conventional photographs or textual descriptions could convey.

Exploded axonometric drawings were employed to deconstruct the complex assemblies of each facade. These three-dimensional representations reveal concealed spatial relationships and construction layers. These cutaway diagrams offered insights into the spatial hierarchy behind facade systems. A sectional axonometric of the French Cultural Centre's (Fig. 13) atrium exposed how sunlight enters through skylights and filters through multiple levels, affecting interior ambiance. In the National Commercial Bank, the vertical cut clarified the inward-facing skyscraper typology and its climate control logic, showing airflow rising through the central atrium (Fig. 14).

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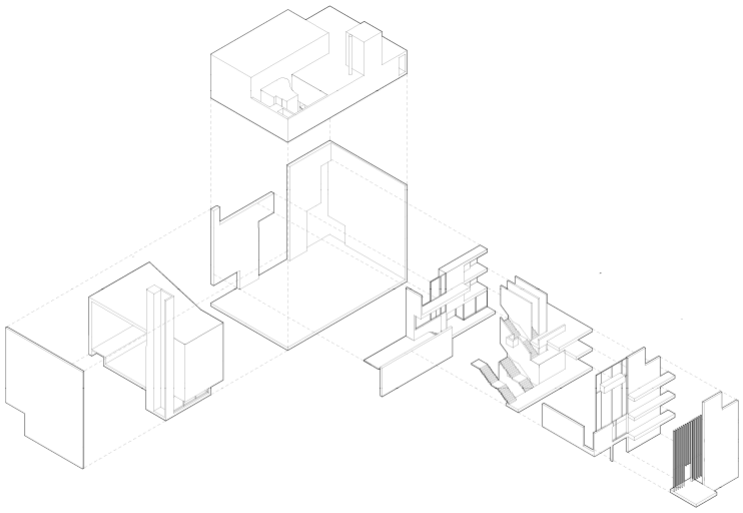


Fig 13: French Cultural Centre—exploded sectional axonometric. Courtesy of Omar Darwish.

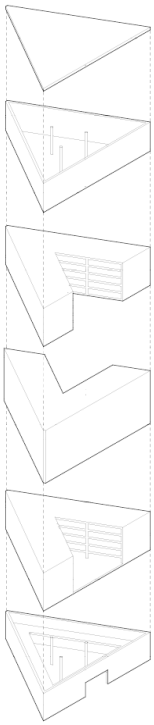


Fig 14: National Commercial Bank—exploded sectional axonometric. Courtesy of Omar Darwish.

Relief modeling added a tactile, empirical layer to the study. These physical models recreated facade fragments or sectional details, allowing close study of geometry and light/shadow. A model of the Abu Dhabi Cultural Foundation's courtyard elevation (Fig. 15) demonstrated how its arcade cast shadows and protected its interior glass facade, while a Corbachi Building model (Fig. 16) highlighted the visual rhythm between blank walls and perforated screens. Modeling reveals spatial and construction insights, reinforcing visual observations with experiential understanding.

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The models also revealed subtleties like alignment precision in repetitive motifs or the scale of user interactions, such as depth of recessed windows and permeability of brick screens.

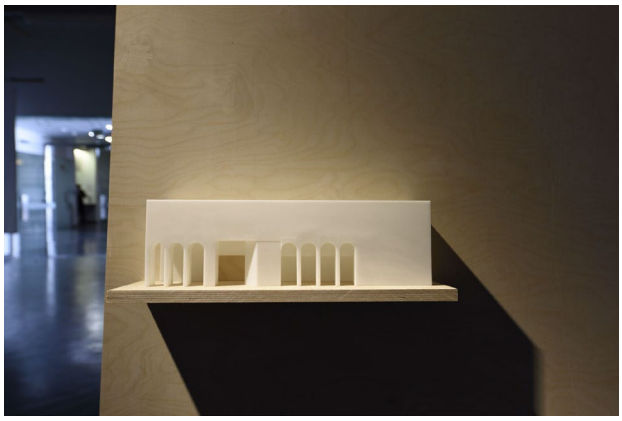


Fig 15: Abu Dhabi Cultural Foundation - Relief Model. Courtesy of Omar Darwish and Kevin Mitchell.



Fig 16: Chorbachi Building - Relief Model. Courtesy of Omar Darwish and Kevin Mitchell.

Stop-motion animations simulate construction sequences and illustrate the spatial and formal logic of projects. One animation sequentially assembled the Corbachi Building model (Fig 16), revealing its modular structure and layered planning. These dynamic visualizations enriched the static documentation, offering digestible and engaging storytelling that distilled complex ideas for broader audiences.

Together, these visual techniques revealed dimensions of architectural performance that were not immediately legible in the archival documents. Exploded axonometric drawings exposed hidden structural and spatial relationships within facade assemblies. Sectional reconstructions clarified environmental strategies such as ventilation, shading, and internal courtyards. Relief models enabled the study of depth, shadow, and material articulation at a tactile scale. Stop-motion animations illustrated construction logic and spatial sequencing, transforming static archival information into dynamic representations of environmental performance. By combining these methods, the research demonstrates how visual reconstruction can function as an analytical tool for extracting environmental and spatial knowledge from archival material.

Adapting Modernist Principles in the Arab World

The period during which these buildings were conceived (1950s–1980s) corresponds to a flourishing of alternative approaches across the Arab and Islamic world. This was a movement – or more accurately, a confluence of parallel efforts across different countries – where architects

sought to create modern architecture that was responsive to local climate, materials, and cultural values. It was partly a reaction against the placeless International Style of modernism and partly an assertion of newfound national identities in the post-colonial era.

This study's impact extends beyond its six case studies. It proposes a pedagogical model that reorients architectural education toward analytical making, multimodal research, and culturally grounded readings.

Beyond the Facade shows the potential of the studying built work in order to understand and transmit design principles and strategies that employ components such as thick facades, courtyards, screening devices, and typological hybridity. These are strategies with global resonance as we rethink how to build in the face of climate change and cultural homogenization.

Another facet of adapting modernist principles is the role of local architects who championed novel design approaches in their home countries and throughout the region. Rifat Chadirji, the designer of the Corbachi Building, is a prime example. He was part of a wave of Arab architects who sought to synthesize modernist ideas with vernacular forms in the mid-twentieth century. Chadirji's work and writings argued for an architecture that could be "international" in its techniques and functional layouts, yet intimately Mesopotamian in its spirit – something he often achieved by using local materials like brick, and by drawing on the abstract forms of Iraqi heritage (from Mesopotamian arches to Baghdad's 19th-century masonry). The Corbachi Building's inspiration from Le Corbusier's Unité d'Habitation is a testament to engaging with modernist concepts (mixed-use high-density living) while its execution in Baghdad's urban grain with an interior bazaar shows adaptation to local urban life [8].

The education and exchange of ideas in the region during these decades also fueled this movement. Many Arab architects were Western-educated (Chadirji in London, Oubrerie is French, Henning Larsen is Danish) but they often returned or practiced in the Arab World, bringing both modernist training and a rediscovered appreciation for their own heritage. The projects also benefited from cross-pollination via events like the Aga Khan Award seminars, regional conferences, and an emerging body of literature on Islamic architecture's relevance to modern times. Publications like *Architecture for Islamic Societies Today* (which the Aga Khan Trust for Culture put out) and others provided platforms to discuss conservation vs. development, identity vs. progress.

Specific regional narratives can be tied to each building as well. For instance, the Abu Nawas Development in Baghdad must be viewed against the backdrop of the oil boom era in Iraq (1970s) when there was a push for modernization, often with the help of international firms (hence the Danish collaboration) but a desire to keep an Iraqi character. The use of solar energy and modern building techniques in Abu Nawas juxtaposed with preserving Baghdad's heritage buildings on site perfectly encapsulates the country's brief optimism in blending technology with tradition before wars interrupted.

In summary, these six buildings exemplify how the tenents of the modern movement in architecture were adopted and adapted in various Arab contexts. They are products of architects who believed that modern architecture must grow from local soil. Their successes, highlighted by the Aga Khan Award, in turn influenced subsequent generations – showing that building in the Middle East could move beyond sterile importation of glass boxes toward a more meaningful architecture. The critical acclaim (and in some cases, enduring popularity) of these projects validated the idea that respecting tradition does not constrain creativity, but rather enriches it.

Broader Implications and Educational Value

Beyond the Facade offers a model for how to engage deeply with buildings through a variety of media. In architectural pedagogy, there is often a gap between design studio culture (which emphasizes creating new designs with visual communication) and history/theory courses (which emphasize writing and analysis). This project bridges that gap by using design communication

tools – drawings, models, animations – in the service of historical and theoretical analysis. For students and young architects, it exemplifies a proactive way of learning from precedents: rather than passively reading about these buildings, one actively reconstructs and re-presents them. This approach fosters a multi-dimensional understanding. For instance, the stop-motion animation of the Damascus Cultural Centre's sunlit courtyard or the exploded axonometric of the Jeddah Bank makes complex concepts (like passive cooling or spatial sequence) understood more intuitively than by reading a paragraph of text. Importantly, the content of the study fills a niche in architectural education as it addresses projects in locations that are outside of the "centers" of the Modern Movement. While iconic Western modernist buildings are exhaustively taught, the equally ingenious works outside of the "centers" context are often excluded.

In terms of contributions to architectural archives and preservation, the study acts as a supplementary archival record for the buildings it covers. For buildings like the Corbachi Building or Abu Nawas Housing – which are lesser-known internationally and located in regions that have faced conflict – having detailed descriptions, analytical drawings, and documented interpretation is itself a contribution. In cases where original drawings might have been lost or are not publicly accessible, the drawings and models become a part of the recorded history of the building. They might aid future researchers by providing visual material to serve as a basis for further interpretation. One could imagine, for example, a future conservation effort in Baghdad using the drawings of Corbachi's facade from this study as a reference if original plans can't be found. Reconstructions are not a substitute for original as-built drawings, but the material can be instructive. Even for well-known buildings like the National Commercial Bank, the study provides synthesized knowledge – combining design narrative, technical innovation, and cultural significance in one place – which can be useful for professionals and scholars.

The study also advocates for a position that views preservation as not only about historical buildings; rather, preservation should be extended to preserving knowledge and ways of thinking that have value in terms of contributing to solving contemporary challenges. For instance, the effectiveness of inward-oriented design in hot climates (demonstrated by NCB and the Ministry of Foreign Affairs) is a principle worth "preserving" and reusing in future projects, rather than discarding in favor of glass towers. The study's reflections effectively serve as lessons learned that can influence contemporary sustainable design debates. Similarly, the cultural sensitivity displayed in these projects is something to carry forward – as globalization continues, the examples set by these buildings on how to build with identity are increasingly relevant. In a way, the study contributes to preserving not just the memory of these buildings, but the ethos they represent: an ethos of thoughtful, contextually grounded design.

Moreover, the approach of combining sensory and analytical techniques promotes a multi-method analytical approach to architecture that has implications for preservation practice. Typically, heritage documentation involves measured drawings, photographs, and perhaps 3D scans. "Beyond the Facade" study suggests adding experiential analyses – like animations showing how a space is assembled – to the documentation toolkit. This is especially useful for preserving intangible qualities of heritage, like ambiance or usage patterns, which standard documents might miss. In educational settings, this approach trains students not just to see architecture as static forms but as dynamic environments interacting with people and nature over time.

Conclusion

Through the reconstruction of six projects using drawings, models, and animations, the *Beyond the Facade* reveals how facades and spatial systems encode environmental intelligence and symbolic intent, and how users interact with built form in ways shaped by climate and tradition.
Generative analytical methods, three-dimensional drawings, stop-motion animation, and 3D-printed relief models are used to investigate and communicate how the façades in the projects are more than a separation between interior and exterior. The project demonstrates how local

knowledge can have transnational relevance to the development of environmentally and culturally sustainable strategies. *Beyond the Facade* contributes to broader global debates on sustainable architecture, modern heritage, and visual research methodologies. The project also demonstrates that architectural archives can be a dynamic resource that connects past practices with current and future efforts to ensure environmental and cultural sustainability.

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Beyond Performance: Identity in Architecture

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Keywords: Identity, Sustainability, Culture, Economy, Architectur

Abstract. Sustainable architecture is commonly evaluated through environmental and economic performance metrics such as energy efficiency, material use, and lifecycle cost. While essential, these parameters alone do not explain why certain buildings remain socially relevant and adaptable over time, while others become obsolete, despite meeting technical standards. This study examines cultural identity as a functional design parameter in sustainable architecture and demonstrates how culturally grounded design strategies influence environmental performance, social sustainability, and economic durability. Through a qualitative methodology that combines a literature review and comparative case study analysis, the research investigates three culturally significant projects: Aranya Low-Cost Housing in India, Souq Waqif in Doha, Qatar, and Poundbury in England. The findings reveal consistent patterns across diverse contexts, showing that culturally embedded spatial organization, vernacular design strategies, and community-oriented planning enhance long-term usability, environmental responsiveness, and economic durability. Based on these insights, the study proposes an architectural framework that enables the systematic integration of cultural sustainability within contemporary design practice.

Introduction

Sustainable architecture reduces environmental impacts while promoting socio-economic and cultural benefits. Most frameworks emphasize measurable parameters such as energy use, material efficiency, and lifecycle cost. While essential, these factors do not fully explain why some buildings remain functional and adaptable over time whereas others become outdated despite meeting technical sustainability standards.

Architecture is closely tied to culture. Cultural identity integrates local traditions and values into architecture, ensuring that the built environment resonates with community identity. Cultural norms shape everyday activities such as living, working, and social interaction, thereby influencing the way buildings are inhabited, modified, and sustained over time.

Despite this, cultural identity is often addressed superficially rather than as a functional design parameter. Sustainable guidelines rarely provide clear methods for evaluating cultural aspects alongside environmental and economic performance. As urbanization continues, many cities risk losing cultural identity; integrating cultural context ensures sustainability extends beyond carbon reduction to preserving the essence of place.

Many studies already show that vernacular architecture can be environmentally responsive because it uses local materials and climate-based design strategies. However, cultural identity is often treated only as a background condition or heritage value, rather than as something that can actively guide architectural decisions. In most sustainability research, buildings are evaluated through measurable technical factors such as energy performance, materials, and environmental efficiency [1]. This research approaches the issue differently by positioning cultural identity as a practical design parameter. Instead of discussing identity only in theoretical terms, the research translates cultural characteristics into five architectural indicators: spatial adaptability, climatic responsiveness, social integration, material and construction logic, and longevity. These indicators allow architects to consider cultural patterns and community practices during the design process,

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making sustainability more responsive to local context rather than relying only on universal environmental metrics [2].

Cultural identity is examined as a functional parameter in sustainable architecture through a literature review and comparative analysis of selected mixed-use environments. The analysis identifies how culturally rooted design strategies support environmental performance, economic sustainability, and long-term usability while informing a framework for integrating cultural identity into architectural decision-making.

Literature Review

Identity: People, Place, Culture, Design: According to the Oxford Dictionary, identity refers to who or what a person is, the essence of an individual. While identity may describe individuals, it can also represent groups, societies, or nations. Culture is shaped by human activity and is closely connected to place, region, and the surrounding natural environment. Place represents the interaction of geology, biology, climatology, and topography, which together create distinctions in the world we inhabit. Through everyday interaction with the built environment, the identity of a place becomes part of human experience [3].

Christian Norberg-Schulz describes architecture as a medium that links cultural identity and place. According to Norberg-Schulz, “the unexamined assumption of architecture is that it has an identifiable essence; understanding this essence is necessary for both the discourse and practice of architecture” [4].

In architectural discourse, identity is not a fixed condition, but an evolving process shaped by human interaction with place and environment. Repeated spatial experiences allow culture to unfold through architecture, while place itself is shaped by memory, human presence, and the physical environment. Architecture therefore operates as a mediator between environment and identity [3].

Vernacular Architecture and Sustainable Design: Vernacular architecture is widely recognized as an environmentally responsive form of construction shaped by climate, material availability, and local knowledge systems [5,6]. It typically relies on locally available and renewable materials such as wood, bamboo, stone, and thatch. Passive design strategies; such as natural ventilation, daylighting, and thermal regulation, are central features of vernacular buildings. In addition to environmental responsiveness, vernacular architecture preserves local traditions and construction practices, supporting cultural heritage and community participation.

Research on vernacular architectural traditions demonstrates how environmental responsiveness is embedded within region-specific passive strategies. Features such as courtyards, building orientation, envelope design, and transitional spaces act as climate moderators across diverse geographical contexts. Within this perspective, sustainability in vernacular architecture becomes closely linked with cultural identity, as climatic adaptation is often embedded within culturally derived architectural practices [3].

The integration of cultural identity in sustainable architecture can also support economic efficiency. Vernacular construction typically relies on local materials and locally available skills, which strengthens regional economies. By combining traditional knowledge with contemporary innovation, architects can pursue sustainability while maintaining the cultural character of place [7].

Economic Stability and Cultural Identity: Economic stability in architecture is closely related to adaptability, durability, and cultural continuity. Traditional industrial economies largely followed a linear model of “take, make, and dispose,” a system that depletes resources and generates significant waste [8]. In response to these challenges, contemporary sustainability discourse has increasingly shifted toward balancing economic growth with environmental responsibility. This transition has contributed to the emergence of concepts such as the circular

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economy, bioeconomy, and green economy, which seek to align economic development with environmental and social sustainability.

The circular economy describes a system in which products, materials, and resources are continuously recycled, resulting in no or minimal waste. It is based on three principles: design to eliminate waste; keep materials and products in the cycle of use; and restore natural systems [9].

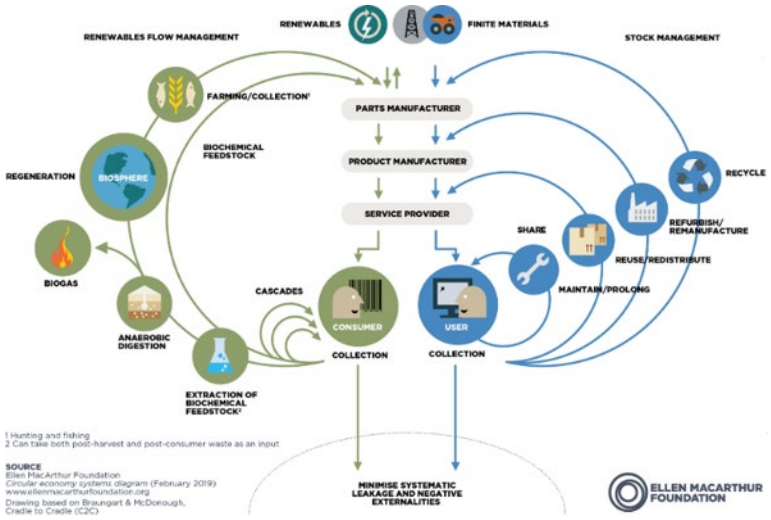


Fig. 1 The Circular Economy – by Ellen MacArthur
Source: Ellen MacArthur Foundation (2012)

Recent circular design approaches emphasize recycling, dismantling, and reuse, promoting a more symbiotic relationship between construction and the environment [10]. These strategies prioritize longevity, adaptability, and sustainable materials while enabling buildings and components to be repaired, reused, or recycled at the end of their life cycles [11,12]. Many vernacular architectural traditions already reflect these principles, emerging from local cultures, climates, and material constraints, with construction knowledge passed down through generations.

Methodology

The research adopts a qualitative approach combining literature analysis and comparative case studies. The methodology is structured to examine relationships between cultural identity, environmental sustainability, social sustainability, and economic durability within architectural design. The literature review establishes theoretical foundations drawn from research and professional discourse on vernacular architecture, cultural identity, and participatory design.

Three case studies were selected to represent diverse cultural and geographical contexts, while maintaining relevance to sustainable architectural practice: Aranya Low-Cost Housing in Indore, India, Souq Waqif in Doha, Qatar, and Poundbury in Dorset, England. Selection criteria included (1) demonstrated integration of cultural identity, (2) environmental responsiveness, (3) social sustainability through community engagement, and (4) evidence of long-term adaptability. Analysis was done using consistent parameters: spatial organization, vernacular architecture, environmental strategies, social integration, and economic adaptability. Comparative evaluation was done to identify recurring patterns across contexts.

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Table 1- Sectors included in selected circular economy initiatives at the local and regional levels Source: OECD (2024), OECD Survey on the Circular Economy in Cities and Regions, OECD, Paris; desk research.

City / Region	Initiative	Waste	Construction & Demolition	Land Use & Spatial Planning	Food & Beverage	Manufacturing Industry	Water & Sanitation	Energy	Biomass
Amsterdam (Netherlands)	Amsterdam Circular 2020–25	✓	✓	✓	✓	✓	✓		✓
Barcelona Metropolitan Area (Spain)	Circular Economy Promotion Programme AMB Circular (2019)	✓	✓	✓	✓		✓	✓	✓
Flanders (Belgium)	Circular Flanders (2016)	✓	✓	✓	✓	✓	✓		
Greater Porto Area (Portugal)	LIPOR's commitment to circular economy principles (2018)	✓	✓	✓	✓			✓	
Nantes (France)	Circular Economy Roadmap	✓	✓	✓	✓			✓	✓
North	CIRWAS	✓	✓	✓	✓	✓	✓	✓	✓
Paris (France)	Circular Economy Plan of Paris 2017–20	✓	✓	✓				✓	✓
Rotterdam (Netherlands)	Rotterdam Circularity Programme 2019–23	✓	✓	✓	✓	✓	✓		✓
Scotland (United Kingdom)	Circular Glasgow	✓	✓		✓	✓	✓	✓	
Tilburg (Netherlands)	Tilburg Circular Agenda 2019	✓	✓	✓	✓	✓	✓	✓	

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Case Studies

Aranya Low-Cost Housing, Indore, India: "They are not houses but homes where a happy community lives. That is what finally matters," B.V. Doshi.

The Aranya housing project covers a total of 220 acres, with the first phase developed over 100 acres. The housing complex shows sustainable design through its incremental housing model and community-oriented hierarchy. The project integrates streets, courtyards, and semi-private spaces derived from traditional Indian settlement patterns, which help social interaction while maintaining privacy.



Fig. 2 Aerial view of the complex
Source – Vastushilpa Foundation

The flexible housing units allow residents to expand dwellings according to evolving family and economic needs; this adaptability supports economic sustainability by reducing construction costs and enabling a phased investment. The project demonstrates how culturally responsive architecture will enhance sustainability through compact layouts and passive ventilation strategies [13].

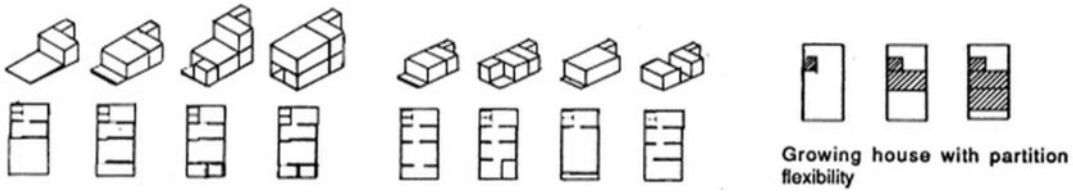


Fig. 3 Modules of the houses
Source – Vastushilpa Foundation

Souq Waqif, Doha, Qatar: Souq Waqif, a traditional marketplace, represents an effort to preserve cultural identity in a rapidly modernizing urban context. This district underwent adaptive rehabilitation to maintain its cultural essence while improving sustainability. The redevelopment signifies traditional architectural elements such as narrow shaded alleys, courtyard spaces, and local construction materials rooted in the Qatari climate and cultural context.



Fig. 4 View of the market at night
Source: Khan et al. (2021)

The cultural significance of this marketplace lies in its role as a living place for community interaction, commerce, and cultural practices. The narrow streets and shaded passages reduce solar exposure, while traditional spatial organization helps natural ventilation strategies that reflect vernacular architecture. This alignment of traditional design and contemporary sustainability shows how cultural identity can be a part of durable, resilient urban environments. Economically, the marketplace functions as a vibrant commercial hub for local artisans, traders, and tourists. Its economic success shows how traditional design can sustain livelihoods and contribute to the overall urban economy [14].

Poundbury, Dorset, England: Poundbury is a planned urban expansion, designed under the principles of Prince Charles and implemented with the involvement of the Duchy of Cornwall. The project integrates traditional urban design principles, local vernacular architecture, and sustainable planning practices to create a mixed-use community. The development prioritizes human-scale streets, diversified housing, mixed-use buildings, architectural forms, and materials. It relies on

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local building traditions and reinforces the region's cultural identity and heritage. Sustainability is sought through compact urban form, pedestrian-oriented design, and integration of local services within walking distance.

These strategies reduce vehicular dependence and improve environmental performance without relying on high-tech solutions. The emphasis on local materials and crafts supports the economy by engaging local trades and reducing supply-chain environmental costs. This culturally significant urban morphology contributes to social sustainability by enhancing community interaction and human comfort, which in turn reinforces long term viability [15].



***Fig**. 5 Poundbury, Aerial View*
Source: Poundbury [Photograph]. https://www.aster.co.uk/about-us/housebuilding/developer-led/poundbury-dorset

Analysis and Key Findings

This comparative analysis of Aranya Low-Cost Housing, Souq Waqif, and Poundbury reveals a consistent pattern across global vernacular architecture. Despite there being a difference in their geographic and socio-economic contexts, all three projects show that cultural identity functions as a component of sustainability, not just a symbol of meaning.

To better understand the relationship between cultural identity and sustainability across the three projects, the case studies are compared using five analytical indicators derived from the literature review: spatial adaptability, climatic responsiveness, social integration, material and construction logic, and longevity.

Table 2 - Comparative Analysis of Case Studies

Indicator	Aranya Housing (India)	Souq Waqif (Qatar)	Poundbury (England)
Spatial Adaptability	High – Incremental housing allows residents to expand dwellings over time	Moderate – Historic urban fabric with adaptable commercial uses	Moderate – Planned masterplan with limited incremental change
Climatic Responsiveness	High – Courtyard planning and passive ventilation	High – Narrow shaded streets reduce solar exposure	Moderate – Compact walkable form but less climate-specific design
Social Integration	High – Hierarchy of streets and courtyards encourages community interaction	High – Marketplace functions as active social and cultural space	High – Walkable mixed-use planning supports community life
Material & Construction	Local low-cost materials and simple construction techniques	Traditional materials reflecting regional building practices	Regional vernacular materials and traditional building forms
Longevity & Reuse Potential	High – Incremental growth allows long-term adaptability	High – Cultural continuity supports long-term urban relevance	High – Durable urban form designed for long-term settlement

The comparison highlights how each project applies vernacular spatial strategies in different ways. Aranya demonstrates strong spatial adaptability through its incremental housing model, allowing residents to expand homes as family and economic conditions change. Souq Waqif maintains traditional market typologies and pedestrian-oriented spaces that sustain everyday social

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interaction while improving environmental comfort. Poundbury highlights walkable streets and human-scale urban form, supporting community engagement and reinforcing local identity. These patterns reflect findings in vernacular architecture research that link culturally grounded design to long-term usability.

Economic sustainability is also evident across the three cases. Incremental housing at Aranya reduces initial construction costs and enables phased investment over time. Souq Waqif sustains local commerce and cultural tourism, while Poundbury supports local economies through mixed-use planning and the use of regional materials. These strategies also align with circular economy principles by encouraging incremental development, material continuity, and long-term adaptability. Together, the cases show that environmental performance, cultural identity, and economic durability operate as interconnected aspects of sustainable architecture rather than as separate objectives.

Architectural Framework for Integration

The literature review and comparative case analysis inform an architectural framework for integrating cultural sustainability into contemporary design practice.

The framework places cultural identity alongside environmental and economic factors as a core design parameter.

The framework consists of five interconnected indicators:

1. Spatial Adaptability: Ability of architectural spaces to accommodate evolving cultural practices and user needs through incremental growth, flexible layouts, and modular design.
2. Climatic Responsiveness: Integrating passive strategies such as shaded circulation, courtyards, orientation, and material mass to achieve thermal comfort with minimal energy dependence.
3. Social Integration: Support for community interaction, participation, and ownership through inclusive public spaces, pedestrian-oriented planning, and familiar design.
4. Material and Construction: The use of locally available materials and construction methods acknowledges cultural traditions while supporting environmental performance and economic viability. This approach also strengthens circular economic practices by encouraging local material cycles, repairability, and adaptive reuse as integral aspects of culturally sustainable design.
5. Longevity and Reuse Potential: Longevity refers to the capacity of buildings and urban environments to remain relevant over time through adaptability, cultural continuity, and flexibility.

The framework functions as a practical guide across different stages of architectural design. During site analysis, architects can examine local settlement patterns, cultural practices, and traditional spatial hierarchies to identify opportunities for spatial adaptability and social integration. In the schematic design stage, climatic responsiveness can inform building orientation, shading strategies, and the use of courtyards or transitional spaces that reflect regional environmental knowledge. During design development, the framework can guide decisions related to modular expansion, material selection, and construction systems that support long-term adaptability and local maintenance practices. By using the indicators as a design checklist across project stages, architects can ensure that cultural identity is integrated into spatial, environmental, and material decisions rather than treated only as aesthetic reference.

For example, when designing housing in a hot-dry climate, architects can apply these indicators during the design process. Spatial adaptability can be addressed by planning units that allow

incremental expansion as household needs change. Climatic responsiveness may guide the orientation of buildings and the inclusion of shaded courtyards or narrow circulation paths that reduce heat exposure. Social integration can be considered by arranging shared courtyards, streets, or marketplaces that encourage everyday interaction among residents. Material and construction decisions may prioritize locally available materials and building techniques that are familiar to local builders and easier to maintain. Finally, longevity and reuse can be supported by designing flexible structures that allow future modifications rather than requiring complete replacement. Through these steps, cultural identity becomes part of everyday design decisions rather than remaining only a symbolic reference.

Conclusion

The analysis shows that sustainability in architecture cannot be separated from economic and cultural factors. Evidence from the literature and the comparative case studies demonstrates that culturally responsive design can strengthen environmental performance, social sustainability, and economic resilience. The findings also indicate that cultural identity extends beyond visual or symbolic representation. Cultural patterns influence how buildings are used, how well they adapt over time, and how long they remain relevant within a community.

The proposed framework translates cultural identity and circular economy principles into practical design indicators that can guide architectural decision-making. By encouraging adaptability, material continuity, and long-term usability, the framework supports design approaches that move beyond linear construction practices toward more resilient and regenerative built environments.

These findings expand the understanding of sustainability to include place, memory, and community as essential components of architectural performance. Further research may evaluate the measurable outcomes of buildings designed using this framework and explore its application across diverse cultural and geographic contexts.

Ultimately, architecture that ignores cultural identity risks becoming environmentally efficient yet socially irrelevant, sustainable in metrics, but fragile in meaning.

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Saudi Narratives in Campus Design: Student Perspectives on Cultural Identity and Sustainability

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Keywords: Saudi Narratives, University Campus Design, Cultural Identity, Sustainability, Students' Perspectives, Online Survey

Abstract. The research paper examines the intertwining of cultural identity and sustainability in university campus design through the lens of Saudi students. As Saudi Arabia embarks on its Vision 2030 initiative, there is a growing emphasis on creating educational environments that reflect national heritage while promoting sustainable practices. The study utilizes a pilot survey with closed-ended and open-ended questions, to gather insights from students regarding their perceptions of how cultural narratives are integrated into PMU campus design. The findings reveal that students value the incorporation of traditional Saudi architectural elements and local materials, viewing them as essential to fostering a sense of belonging and cultural pride. Additionally, students express a desire for campus designs that prioritize sustainability through green spaces and energy-efficient structures. The results suggest that aligning university design with cultural identity does not only enhance student engagement but also supports the broader goals of sustainability and national development. This paper contributes to the discourse on educational architecture by highlighting the importance of student voices in shaping campus environments that reflect Saudi values and aspirations.

Introduction

The importance of reflecting national cultural identity in the educational environment cannot be overstated. For Saudi students, campuses are more than just places of learning; they must reflect their cultural values, historical context, and social norms. As modern educational institutions strive to create inclusive and welcoming environments, understanding how students interpret and interact with the architecture and design of their campuses is increasingly important. With the adoption of Vision 2030 in Saudi Arabia, there is increasing attention to creating sustainable environments that promote environmental responsibility and resource efficiency [1].

This study explored Saudi university female students' views on sustainability practices on their campuses, examining how these practices align with their cultural values and expectations. Thus, beyond cultural identity, sustainability becomes a key factor in campus design. This study aimed to illuminate the complex interplay between cultural identity and sustainability at Saudi universities by integrating student voices into the debate on university campus design.

Therefore, this work contributes to the growing body of knowledge on campus design by highlighting the importance of student voices in shaping the future of educational environments in Saudi Arabia. Understanding student perspectives and perspectives will enable the creation of campuses that not only meet contemporary educational needs but also reflect the most significant aspects of the cultural identity and sustainability aspirations of universities and student communities.

Literature Review

In the contemporary higher education landscape, university campus design plays a key role in shaping the student experience. Well-designed university campuses not only foster effective

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learning environments but also improve student well-being, engagement in learning and decision-making, and foster a vibrant university community [2].

As higher education institutions evolve to meet the needs of modern students, the importance of incorporating cultural identity and sustainability principles into campus design is becoming increasingly evident. In Saudi Arabia, where rapid modernization coexists with rich cultural traditions [3], the primary challenge is to create educational spaces that honor local traditions while promoting sustainable practices.

Cultural identity is a key aspect of the educational experience, especially in a culturally rich context like Saudi Arabia. Campuses serve as microcosms of society, reflecting the values, traditions, and history of their university communities. In this regard, integrating cultural identity into campus design does not only enhance the aesthetic appeal of universities but also fosters a sense of national and cultural belonging among students [4].

In the context of globalization, as Saudi Arabia navigates its unique cultural landscape, understanding how cultural narratives can influence campus design is essential for creating spaces that reflect and resonate with students. Conversely, sustainability is becoming a critical aspect of university campus design, addressing the pressing need for environmentally responsible practices in the face of climate change and resource depletion. In the Saudi context, where environmental issues are particularly acute, incorporating sustainable design principles into campus architecture and landscape design is crucial [5]. This not only aligns with global sustainable development goals but also supports the Kingdom's Vision 2030 initiative, which emphasizes environmental protection and sustainable development [1].

The literature review covered several key topics: the role of campus design in enhancing the educational environment, the importance of cultural identity in shaping the student experience, principles and practices of sustainability in the educational context, and student perspectives on the campus environment.

Campus Design and Educational Environment

University campus design plays a critical role in shaping the educational environment, significantly impacting student learning, well-being, and engagement [6]. A well-designed campus can enhance academic achievement by providing spaces that foster collaboration, creativity, and successful interactions between students and faculty. Research has shown that the physical environment of educational institutions can influence students' motivation, engagement, and overall satisfaction with their educational experience [7].

For example, several studies highlighted that well-lit, spacious, and aesthetically pleasing learning spaces improve student concentration and reduce stress [8, 9]. Moreover, the design and accessibility of university facilities can significantly impact students' ability to navigate their learning. A study by Akbar et al. (2023) found that environments reflecting inclusivity and diversity foster students' sense of belonging, which in turn enhances their engagement and academic success [10]. Therefore, when designing university environments, in an effort to ensure all students have the opportunity to succeed in their studies, which are aimed at shaping their professional identities and developing their national identity, architects should prioritize inclusivity and accessibility [11].

Researchers have also examined the relationship between specific design elements and learning outcomes. For example, a study by Khan (2024) investigated the impact of collaborative learning spaces on student engagement and found that flexible learning environments that allow for both individual and group work significantly improve student interaction and learning outcomes [12]. Similarly, the inclusion of green spaces and natural elements in campus design is associated with improved mental well-being and academic performance [13]. These findings highlight the importance of considering how physical spaces can facilitate or hinder the educational process.

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The Interplay of Cultural Identity and Sustainability

The research showed that students who feel their cultural identity is acknowledged and respected in the educational environment are more likely to actively participate in the learning process and form positive relationships with other students and faculty [14, 15]. Conversely, when cultural identity is marginalized or ignored, students may experience feelings of alienation and disengagement. For example, the study conducted by Miller et al. (2026) found that culturally relevant pedagogy that integrates students' cultural backgrounds into the curriculum contributes to a more inclusive and effective learning environment [16].

Cultural identity is inextricably linked to individuals' sense of belonging to a particular cultural group, encompassing shared values, beliefs, traditions, and practices that shape individuals' worldviews. In educational contexts, cultural identity plays a significant role in shaping students' experiences, interactions, and overall engagement in the learning environment. Recognizing the importance of cultural identity can enhance students' sense of belonging and self-esteem, which is crucial for their personal development in general and academic success in particular.

The integration of sustainability elements into the campus design process is based on a holistic approach that incorporates environmental, social, and economic considerations. It aims to create an educational environment characterized not only by functionality and aesthetic appeal, but also by sustainability and the responsibility of decision-makers. The environmental aspect aims to minimize the ecological footprint through the use of renewable resources, energy-efficient technologies, and eco-friendly, local materials. Key strategies include water conservation, waste reduction, recycling, and more. The creation of green spaces contributes to the health of the university campus ecosystem and the preservation of biodiversity in the country as a whole [17].

The social aspect of sustainability emphasizes the importance of creating an inclusive, equal-opportunity environment that fosters student engagement in the learning process, promotes social interaction and student well-being, while supporting the university diverse cultural identities [18].

From an economic perspective, sustainable campus design aims to balance financial viability with environmental and social considerations. The financial viability of a university campus includes investments in energy-efficient infrastructure to reduce operating costs, as well as developing partnerships with local communities and businesses to support the sustainable economic development of all partners [19]. By integrating all three aspects into their development process, university campuses create a resilient system capable of supporting long-term sustainability goals while simultaneously improving student learning outcomes.

The interplay between cultural identity and sustainability in university campus design presents both challenges and opportunities that can significantly impact the educational environment [20]. In striving to create sustainable campuses, universities must consider how such initiatives align with the cultural traditions and identities of their student populations. This relationship is particularly relevant in Saudi Arabia, where rich cultural traditions and a growing focus on sustainability converge in the higher education context.

Student Perspectives on Campus Environment

The literature review revealed that despite the growing emphasis on sustainability in higher education, the integration of cultural identity into sustainable design practices remains understudied, particularly in the Saudi Arabian context, and the views of university students are generally ignored.

However, engaging students in the co-design and co-creation of university campuses could create spaces that foster a sense of belonging and cultural pride while simultaneously addressing sustainability challenges. By incorporating student voices, educational institutions could create an environment that fosters both cultural pride and environmental responsibility, ultimately improving the overall student experience and contributing to the achievement of broader sustainability goals in higher education [21].

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Identified Research Gaps

Despite the growing body of research on campus design, sustainability, and cultural identity, there are significant gaps in the research discourse, as many of the existing studies focus on broader topics of sustainability or cultural identity in isolation from the academic context [22, 23]. Furthermore, the interplay between these two dimensions in the context of Saudi universities has not been adequately addressed so far. Specifically, there is scarcity for empirical studies examining students' perceptions of how their cultural identity can be effectively integrated into sustainable campus. These gaps limit our understanding of the unique cultural narratives that could enrich the university environment and enhance the educational experience.

Furthermore, while a growing number of studies highlight the importance of sustainable practices in higher education [24], few studies have specifically examined how these practices relate to the cultural values and national identity of Saudi stakeholders [25]. This gap highlights the urgent need for research examining how cultural identity shapes students' perceptions of sustainability and their engagement in campus design processes.

Furthermore, most existing research tends to focus on institutional perspectives, neglecting the importance of incorporating student voices in shaping environments that reflect both cultural identity and sustainability.

Addressing these identified gaps is essential for developing a comprehensive understanding of how cultural identity and sustainability can be integrated into campus design, particularly in the Saudi Arabian context. Accordingly, further research is needed to explore the specific cultural narratives that Saudi students of both genders would like to see reflected in the university environment and how these narratives may influence the sustainability practices of Saudi universities.

Methodology

Research Paradigm and Research Design

This study utilized a constructivist research paradigm, which emphasizes the subjective nature of human experience and the importance of understanding individual perspectives. According to constructivism, knowledge is constructed through social interactions and personal experiences [26], making it indispensable for exploring the complexities of cultural identity and sustainability from the perspective of Saudi female university students.

The study utilized a mixed-methods approach, employing an online survey on Google Forms, which recruited Saudi female university students. This approach facilitated the exploration of diverse perspectives on cultural identity and sustainability in campus design [27].

The online survey was developed based on a comprehensive review of existing research related to cultural identity, sustainability, and campus design. The survey combined closed-ended and open-ended questions to collect both quantitative and qualitative data. The survey's key sections covered four areas, including collecting demographic information, exploring cultural identity, assessing students' awareness of campus sustainability, and identifying students' campus design preferences related to their cultural identity.

Sampling Strategy and Data Collection

As this study was a pilot study, the purposive sample was small (22 participants) and consisted of female students studying at Saudi Arabia's oldest private university. A purposive sampling strategy was used to recruit participants. The survey link was distributed through the university's Blackboard platform and social media platforms.

Data collection was conducted using Google Forms, an online tool that ensured the anonymity and confidentiality of all respondents. Access remained open for 20 days. After completing the data collection phase, the quantitative data was analyzed using Google Forms software to identify trends and patterns related to students' perceptions of cultural identity and sustainability in campus

design. Qualitative responses were analyzed thematically to identify key themes and narratives that provided a deeper understanding of participants' experiences and preferences.

Ethical considerations were a priority throughout the research process. All participants were informed of the study's objectives, the voluntary nature of their participation, and their right to withdraw at any time. The study design adhered to ethical standards, including ensuring the anonymity and confidentiality of participants.

Analysis of online survey responses provided valuable insights into Saudi female students' views on cultural identity and sustainability in campus design. The results are grouped into three key themes: cultural identity, sustainability awareness, and campus design preferences.

Findings and Interpretation

The respondents' answers to both the closed-ended and particularly the open-ended questions revealed that a significant majority of the respondents value cultural representation, indicating a strong desire for campus designs that honor their heritage.

Most students feel the need for their cultural identity to be better represented, highlighting a gap that the university could address in future design initiatives. A substantial number of students feel that campus designs lean towards modernity, indicating a potential area for universities to better integrate traditional elements.

Therefore, only 40.9 percent of the respondents confirmed having a sense of belonging to the university based on its cultural representation (see Fig. 1 below).

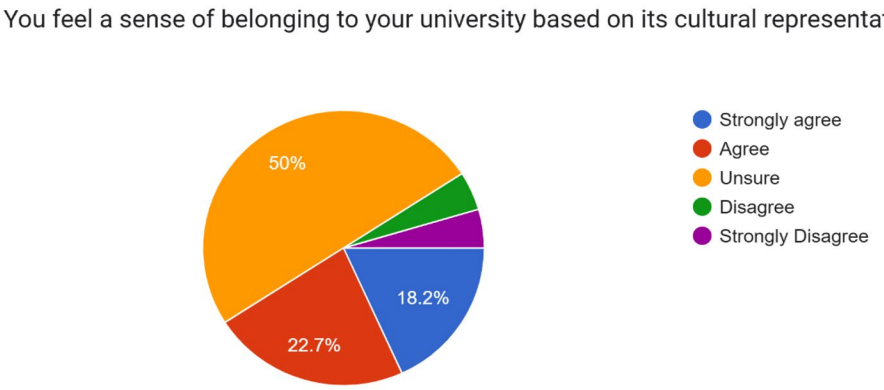


Fig. 1. The respondents' sense of belonging to based on the university cultural representation

Thus, a number of students focused on the need for more Islamic design elements to be introduced to both the exterior and interior design of the university: "Islamic architectural influence," "Islamic design elements, and spaces that reflect local culture and values," "Traditional Saudi patterns incorporated into architectural style of buildings, etc.," "Campus design should prioritize Saudi cultural identity by including traditional architecture," "Maybe not prioritised, but it would be easiest to incorporate shurafat along the exterior," "Cultural storytelling through 'art' and landscape." The suggestion to "Integrate diversity from several Saudi regions" seems to be of particular importance.

An overwhelming majority of the respondents (81.8 percent) agreed that Saudi cultural identity should be reflected in the university campus design (see Fig. 2 below).

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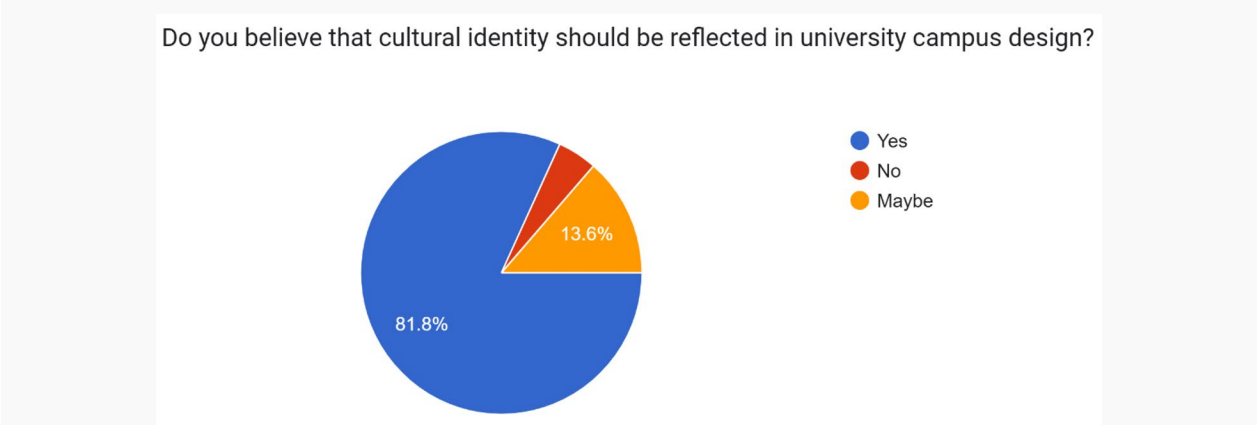


Fig. 2. The need for cultural identity reflected in the university campus design.

The respondents' nearly unanimous agreement on the benefits of traditional design elements underscores the importance of cultural heritage in shaping campus aesthetics. Therefore, the students' strong expectation for the university to actively promote their cultural identity suggests that students seek institutional support for their cultural narratives.

A number of students highlighted the importance of introducing more gathering spaces: "More gathering spaces on campus since it's small and contains a large number of students showing our heritage," "Cool and conditioned community and hospitality spaces," "Gathering areas."

The preference for green spaces and sustainable materials aligns with students' cultural values and desire for environments that promote well-being and environmental responsibility: "Traditional architectural patterns, Arabic calligraphy, local materials, and spaces that reflect Saudi heritage and culture," "Using traditional Islamic patterns, local materials, and spaces for community gathering," "Traditional architecture, Islamic patterns, and local materials," "Campus design should prioritize Islamic architectural elements, climate-responsive spaces, community areas, and accessible prayer facilities to reflect Saudi cultural identity," "Shaded courtyards," "Desert bloom." Several students emphasized the need for prayer facilities for female students "More prayer facilities," "Close and accessible prayer spaces," "Spaces for prayer". Therefore, regular engagement with natural spaces indicates that students value these environments for relaxation and socialization.

The respondents' replies to the question "How does the physical environment of your campus affect your overall university experience?" revealed the students' consensus on the positive impact of sustainable designs on their well-being suggests that students view their environments as influential on their mental and emotional health: "It's where I spend most of my day, so the environment determines how that part of my day goes," "Having a nicer physical environment can make us, students, much more motivated to come and study every day," "I don't personally prioritize the way campus looks; however, I wish there are comfortable locations designed for us to study at." "A comfortable, well planned campus makes daily life easier and more enjoyable and might even improve attendance," "It gives confidence," "It effects the mood," "It affects comfort, focus, and student interaction," "A comfortable and well-designed campus makes studying easier, improves focus, and creates a more positive learning experience," "A clean and comfortable campus helps me focus, study better, and enjoy university more," "Clean spaces and quiet study rooms help me focus and enjoy campus life." Some students sounded more specific: "If the environment is accessible, has enough seating indoor and out, has greenery, and varied food options, it makes me hate the university less."

Answering the question, "How do you think university design can better support sustainability initiatives?" the respondents highlighted the importance of green spaces, solar panels, and recycling systems. Quite a number of students underlined the need for the use of

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solar energy (which is particularly important and logical for Saudi Arabia having 3,300 sunny hours a year in average [28]), which can be accumulated with solar panels: “By adding solar panels,” “Universities can use more energy-efficient buildings, solar panels, and recycling programs,” “Using solar panels, water conservation, energy conservation (i.e. lights that automatically turn off when there isn’t anyone in the room through sensors),” “Using energy-efficient buildings, renewable energy like solar panels, water-saving systems, green spaces, and shaded walkways to reduce environmental impact,” “More solar use, native plants, and better recycling would make the campus greener,” “Universities can use solar energy, recycling systems, and more green spaces,” “Green spaces, solar energy, and recycling facilities,”

The survey participants’ perception that sustainability initiatives are only occasionally implemented suggests that universities need to enhance their efforts in promoting sustainable practices. It is noteworthy, that Prince Mohammad Bin Fahd University, the oldest private university in KSA, is already proceeding with installation of solar panels in its campus [29].

Several students provided appreciative replies: “I think they’re already half way through by having a walkable pathways, green spaces, and what looks like a recycling system. But could go the extra mile by using renewable energy and water conservation.” Some students provided specific suggestions: “University design can support sustainability in a cultural way by creating spaces that encourage sustainable habits and awareness among students. For example, campuses can include areas for community gardens, sustainability events, and educational displays about environmental responsibility. When sustainability is visible in everyday campus life, it helps build a culture where students value and practice sustainable behaviors,” “By including sustainable options in cafes, the cafeteria, and the events that take place (less plastic options, more sustainable alternatives),” “By using local materials,” “By using green spaces, energy-efficient buildings, recycling systems, and encouraging environmentally friendly practices,” “By recycling systems.” The respondents’ willingness to engage in sustainability initiatives suggests that students are proactive about contributing to positive change in their environments.

Answering the question “Can you share an example of a campus feature that you feel strongly represents Saudi cultural identity?,” the respondents highlighted “The mosque,” “A prayer room in every building,” “Separate campuses for males than females,” “Separation between male and females,” “Traditional Saudi architectural elements, like arches and mashrabiya patterns, reflect our cultural identity,” “An example is a dedicated mosque for female students, designed with Islamic decorations and geometric patterns, and powered by solar energy for lighting, combining Saudi cultural identity with sustainability,” “The modern buildings with Saudi geometric patterns reflect local culture well,” “I like how they put the carpet area near the entrance.” However, several students did not manage to identify any campus features representing Saudi cultural identity: “Have no idea,” “I can’t think of anything,” “I haven’t noticed anything,” “Don’t have any in mind.”

Answering the question “What changes would you like to see in your university’s design to enhance cultural representation and sustainability?,” the respondents offered the following: “Adding more cultural art displays, shaded seating, and sustainable landscaping would improve both culture and sustainability,” “More e-bikes,” “To see solar system producing electricity and purifying water, allowing design students to implement their ideas,” “Maybe the university can have more cultural elements in its design overall, and more of a green infrastructure.”

Another important issue was a lack of university campus cultural or sustainable initiatives, in which the students could participate. Although a majority of the respondents (63.6 percent) have participated in one or more initiatives or projects related to cultural identity and sustainability on the university campus, a big amount of the respondents haven’t participated in any initiatives of the kind (see Fig.3 below).

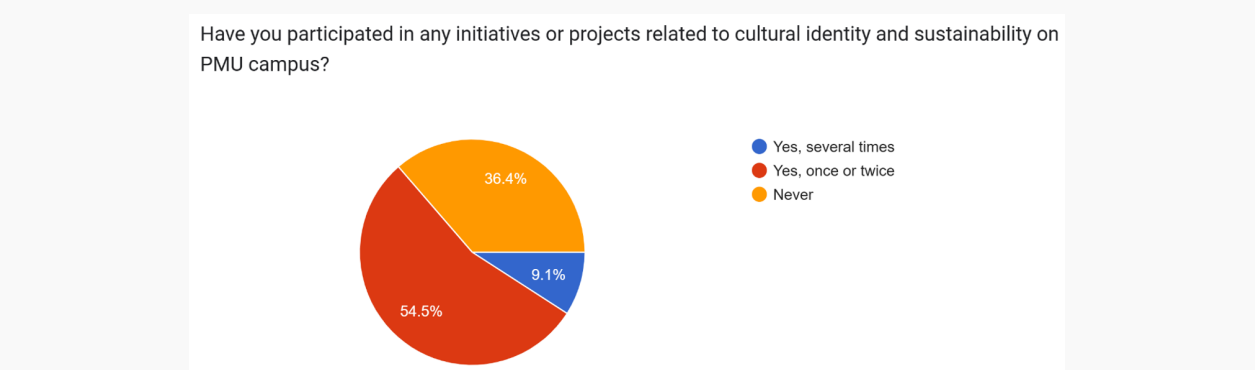


Fig. 3. The respondents' participation in campus initiatives related to cultural identity and sustainability.

These data highlighted the importance of developing culture and sustainability initiatives integrated in the university campus.

The students' responses revealed their interest in both the university's current campus design, their national identity and Saudi cultural heritage and up-to-date trends of sustainable development. Answering the question about the importance of students' voice in campus design decisions, 95.5 percent of the respondents acknowledged its importance (see Fig. 4 below).

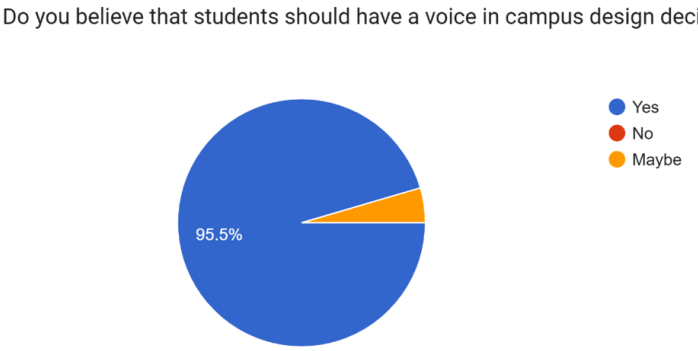


Fig. 4. The importance of students' opinion in the university campus design solutions.

Therefore, it revealed the students' concern about their university in general, the campus design in particular, as well as their Saudi heritage and sustainability.

Conclusion and Discussion

The study yielded several key findings related to the integration of significant elements of Saudi culture, student awareness of sustainability, the integration of national cultural and sustainability elements into the university's campus design, and participation in initiatives that promote campus sustainability.

Conclusion

A significant majority of the female students participating in the survey, expressed a desire for campus design that truly reflects their cultural identity. This reflects a broader global trend for educational institutions to serve as spaces that honor and celebrate local traditions and values.

While student awareness of sustainability varies, the study confirmed a significant interest among university students in participating in sustainability initiatives on campus. This interest points to an opportunity for the university to enhance its educational programs and sustainability initiatives in line with the key national values held by most students.

The students expressed a clear preference for campus designs that combine both traditional architectural elements and modern sustainability practices. This highlights the potential for creating spaces that are not only functional but also culturally significant, reflecting the students'

identities. The students' willingness to participate in initiatives that foster cultural identity and sustainable development demonstrates a proactive student community striving to make a meaningful contribution to positive environmental change.

Discussion

The results of the study presented in this research paper contribute significantly to the growing debate about the importance of integrating both cultural identity and sustainability into university campus design. The findings highlighted the importance of a systems approach, design strategies, student engagement, and sustainability education.

Integrating cultural identity and sustainability components into university campus design should be holistic and based on a systems approach. By recognizing the relationship between cultural identity and sustainability, universities can create environments that foster student academic success, student and faculty well-being, and community engagement. Universities should consider developing design strategies that incorporate local cultural elements, such as traditional architectural styles and local building materials to foster students' sense of belonging.

This study highlighted the importance of designing educational spaces that not only meet functional needs but also reflect cultural identity and a commitment to sustainability. There is a clear need for universities to strengthen their efforts to educate students on the principles of sustainable development, while remaining mindful of the importance of preserving the national cultural heritage for current and future generations of Saudi citizens.

As universities continue to evolve in today's rapidly changing world, incorporating student voices and perspectives will be crucial to creating inclusive, attractive, and sustainable campuses [30]. Involving students in decision-making processes related to campus design and sustainability initiatives is essential. Future research could expand on these findings by examining the opinions of different student groups and analyzing the long-term impact of culturally and environmentally responsible campus design on student perceptions, learning experiences, and outcomes [ibid.].

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Drawing the Smart City: Shifts in Urban Representation from Figure–Ground to Digital Visualization

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Keywords: Smart Cities, Urban Representation, Architectural Drawing, Diagrammatic Urbanism, Digital Visualization

Abstract. Urban paradigms have historically generated specific modes of representation, shaping not only how cities are drawn but also how they are conceived and understood. This paper presents a preliminary reflection on selected transformations in urban representation, tracing a trajectory from spatial continuity to diagrammatic and relational visualizations based on networks, infrastructures, and layered systems. Beginning with Giambattista Nolli's figure–ground map of Rome, later discussed in figure–ground theories by authors such as Colin Rowe, the city emerges as a continuous spatial field where public and private realms are negotiated through drawing. The discussion then moves to modernist zoning diagrams, in which functional abstraction and color-coded mapping redefine urban space as an organizational system rather than a spatial continuum. The paper subsequently examines projects such as OMA's Melun-Sénart proposal, where layered diagrams and infrastructural logics introduce a more relational understanding of the urban environment, echoing broader debates on mapping and diagrammatic practice. Rather than proposing a definitive narrative, the paper frames these historical examples as exploratory steps toward understanding emerging digital visualizations, including dynamic mapping, digital twins, dashboards, and data-driven interfaces, that increasingly mediate contemporary urban knowledge. These evolving representational practices suggest a gradual shift from static spatial drawings toward more networked, relational visualizations based on infrastructures and data-driven systems.

1. Introduction. Drawing the City in the Age of Smart Urbanism

Contemporary debates on smart cities often emphasize technological infrastructures, data collection, and digital governance. Yet, beyond technical systems, smart urbanism also transforms the ways in which the city is represented, visualized, and conceptually framed. Architectural drawing has historically played a central role in shaping urban knowledge, mediating between spatial imagination and modes of organization. As James Corner notes, mapping is not a neutral reflection of reality but an operative practice that constructs relationships and meanings through representation (Corner, 1999). Within this perspective, the emergence of smart city discourse can be understood not only as a technological shift but also as a transformation in the visual culture through which urban space is conceived.

In contemporary smart urbanism, mapping increasingly shifts from a finished representational artifact to an operational interface: a medium through which urban data are queried, filtered, and acted upon in near real time. This interface condition repositions the map from a descriptive graphic to a socio-technical instrument embedded in standards, platforms, and data governance frameworks. In this context, the key question becomes not only *how cities are drawn*, but *how drawings participate in steering, accountability, and public value claims*.

The paper frames urban representation specifically through the lens of architectural drawing, understood not merely as a tool of depiction, but as an operative medium that constructs, organizes,

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and mediates urban knowledge across different historical paradigms. This approach operates across both architectural and urban scales, positioning drawing as a mediating device between spatial form and broader urban systems.

The paper adopts a historical-comparative and theoretical approach, analyzing selected moments in the evolution of urban representation, from figure–ground drawing to digital visualization, in order to identify shifts in the role and logic of architectural drawing. The selected examples (Nolli, modernist zoning, OMA, and digital interfaces) are not intended as exhaustive, but as representative moments that reveal key shifts in representational logic.

Earlier moments in architectural history reveal how changes in representation correspond to broader shifts in urban thinking. Giambattista Nolli's eighteenth-century plan of Rome, later interpreted within figure–ground theories by Colin Rowe and Fred Koetter, framed the city as a continuous spatial field structured by the interplay of solids and voids (Rowe & Koetter, 1978). In contrast, modernist planning introduced functional zoning diagrams that redefined urban space through abstraction and color-coded organization, as articulated in the discourse of CIAM and the Athens Charter (Le Corbusier, 1943; Mumford, 2000). By the late twentieth century, diagrammatic practices explored by architects such as Rem Koolhaas and theorists like Stan Allen shifted attention toward infrastructures, networks, and layered systems, suggesting a more relational understanding of urban form (Koolhaas, 1995; Allen, 1999).

Today, within the context of smart cities, emerging digital visualizations ranging from dynamic mapping to data-driven interfaces further extend this trajectory, redefining the role of drawing as an active mediator between spatial form and informational processes. As Antoine Picon argues, contemporary urban intelligence increasingly operates through spatialized digital systems that reshape how cities are observed and interpreted (Picon, 2015). Rather than proposing a definitive theory of smart urbanism, this paper offers a preliminary architectural reflection on selected shifts in urban representation, tracing how different modes of drawing ranging from figure–ground plans to layered diagrams anticipate the visual logics that underpin current smart city imaginaries. This paper asks how urban representation has shifted from figure–ground drawings to data-driven digital visualizations, and how architectural drawing continues to operate within this transformation. Across these shifts, representation moves from revealing spatial continuity to enabling systemic governance.

2. The City as Spatial Continuum. Nolli and Figure–Ground

Among the historical examples that reveal how urban representation constructs spatial knowledge, Giambattista Nolli's Nuova Pianta di Roma (1748) remains a foundational reference. More than a cartographic document, Nolli's plan established a graphic language through which the city could be understood as a continuous spatial field. By representing accessible interiors such as churches, courtyards, and public institutions, with the same graphic treatment as exterior urban space, the drawing dissolves rigid distinctions between inside and outside, foregrounding instead the continuity of urban experience. What emerges is a spatial interpretation of the city, where representation operates as a tool for revealing relationships rather than merely describing form.

Later architectural theory would reinterpret this approach through the lens of figure–ground analysis. Colin Rowe and Fred Koetter, in Collage City, highlighted how the alternation between solid and void structures the legibility of urban form, framing the city as a dynamic equilibrium between built mass and open space (Rowe & Koetter, 1978). In this reading, Nolli's drawing becomes a proto-analytical instrument, capable of revealing urban structure through graphic contrast. The black-and-white logic of the plan does not simply distinguish buildings from space; it articulates a continuous urban field in which public life unfolds across thresholds, interiors, and streets. Representation, therefore, operates here as spatial continuity rather than functional abstraction. The Nolli map mirrors how the city is experienced as a sequence of spatial thresholds rather than isolated objects (Diamond, 2022). It preserves ambiguity between inside and outside,

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private and public. So, in a sense, Nolli's approach to visualizing the city preserves experiential continuity.



Figure 1. Giambattista Nolli, Nuova Pianta di Roma (1748). Figure–ground representation articulating urban continuity through the graphic equivalence of interior and exterior public space.

The emphasis on relational space resonates with subsequent analytical frameworks such as space syntax. Although developed centuries later, the work of Bill Hillier and Julienne Hanson proposes that spatial configurations shape patterns of movement and social interaction, reinforcing the notion that urban form operates as a continuous field rather than as isolated objects (Hillier & Hanson, 1984). While Nolli's plan was not conceived as an analytical diagram in a contemporary sense, its graphic logic implicitly acknowledges the importance of spatial connectivity and accessibility, qualities that later theoretical models would attempt to quantify.

In contrast to later modernist diagrams, which often abstract the city into functional zones, Nolli's representation maintains a direct relationship with spatial experience. The city is not divided according to programmatic categories but understood through the interplay of built mass and accessible space. This approach reinforces the architectural dimension of urban drawing, where representation operates as a spatial instrument capable of mediating between physical form and lived experience. The plan's enduring influence lies precisely in this capacity to visualize urban continuity without reducing complexity to a single functional or infrastructural logic.

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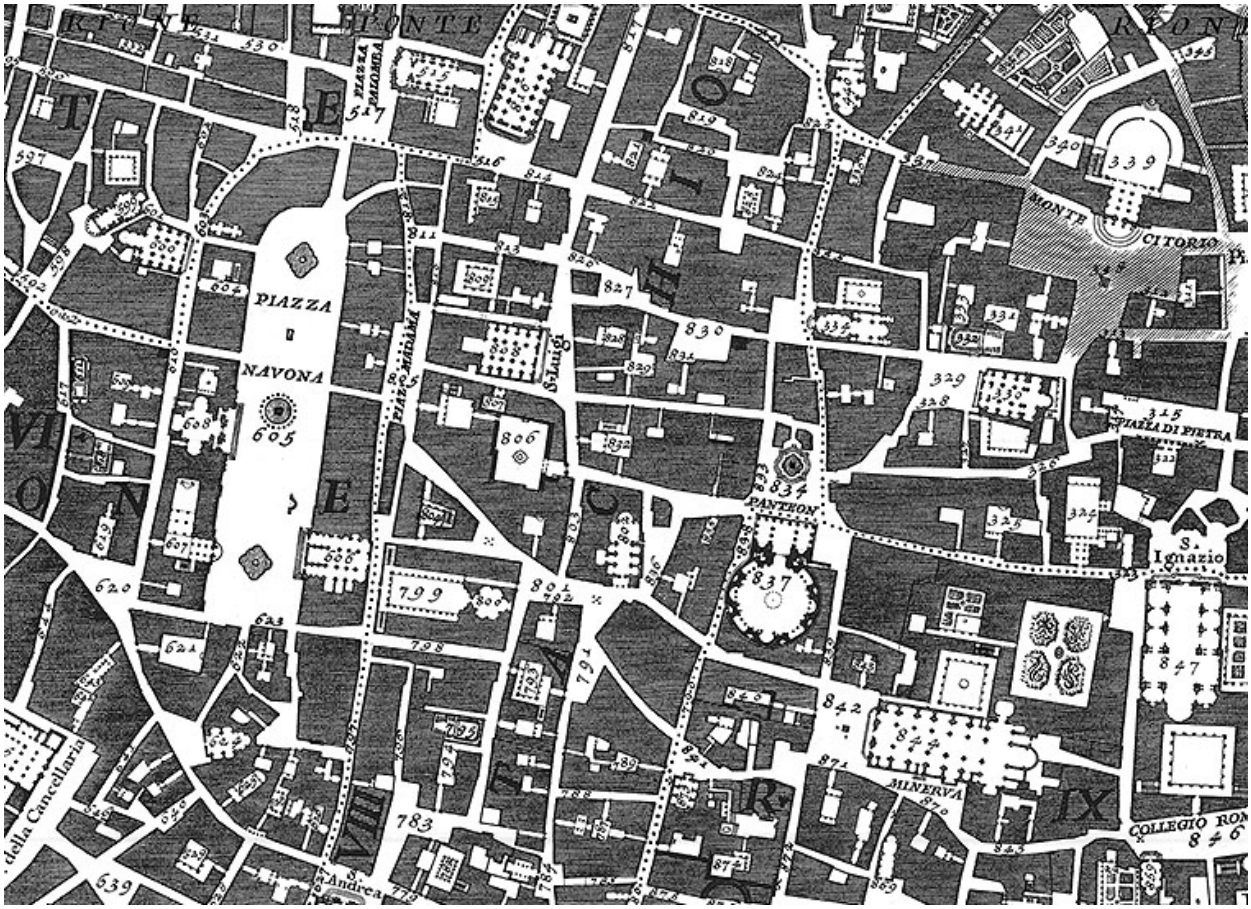


Figure 2. Nolli's Nuova Pianta di Roma (1748), illustrating the collapse between interior and exterior public space through graphic continuity.

Within the broader trajectory outlined in this paper, Nolli's drawing can be understood as an early expression of representation as spatial continuity. Rather than isolating elements, the figure–ground logic constructs a coherent urban field where solids and voids operate as complementary components of a larger system. This mode of representation establishes a foundation against which later transformations, from functional zoning to diagrammatic networks, can be read as shifts in how urban space is conceptualized and visualized. In the context of contemporary discussions on smart cities, revisiting Nolli does not imply nostalgia for historical forms but offers a reminder that urban representation has long been tied to the ways spatial relationships are made visible through drawing.

3. The City as Functional Diagram. Modernist Zoning

If Nolli's figure–ground logic framed the city as a continuous spatial field, modernist planning introduced a radically different representational language. Rather than emphasizing the continuity between built form and public space, early twentieth-century urbanism increasingly relied on diagrammatic abstraction to organize the city according to functional principles. The emergence of zoning diagrams, particularly within the discourse of CIAM and the Athens Charter, marked a decisive shift in how urban space was visualized and conceptualized.

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Figure 3. Functional zoning diagram from CIAM discourse, illustrating the separation of dwelling, work, circulation, and leisure as discrete urban territories.

Representation moved away from spatial continuity toward a system of categorization in which urban life was separated into distinct domains such as dwelling, work, circulation, and leisure (Le Corbusier, 1943; Mumford, 2000).

Graphically, this transformation is evident in the transition from the black-and-white figure–ground drawings associated with earlier urban analysis to color-coded maps that foreground functional differentiation. In these diagrams, color replaces spatial depth as the primary organizational device, translating complex urban environments into legible schemes of programmatic order. The city is no longer depicted as a continuous field of accessible spaces but as a structured composition of zones, each assigned a specific role within a broader urban system. Representation, in this context, becomes an instrument of planning rather than an exploration of spatial relationships. Through modernist zoning, the city becomes legible as a system of functions rather than as overlapping spatial conditions. Spatial ambiguity and transitional thresholds are replaced by programmatic clarity, translating urban complexity into clearly differentiated functional territories. Modernism therefore in its approach to visualizing the city loses spatial ambiguity.

This shift reflects broader ambitions within modernist architecture to rationalize the city through abstraction. Figures such as Ludwig Hilberseimer explored planning strategies that reduced urban form to clear, repeatable patterns, reinforcing the idea that representation could operate as a tool for standardization and control. The diagrammatic clarity of zoning plans enabled planners to visualize the city at a metropolitan scale, yet this clarity often came at the expense of the spatial ambiguity and experiential richness evident in earlier drawings such as Nolli's plan. The urban field was reinterpreted not as a continuum but as a composition of discrete functional territories.

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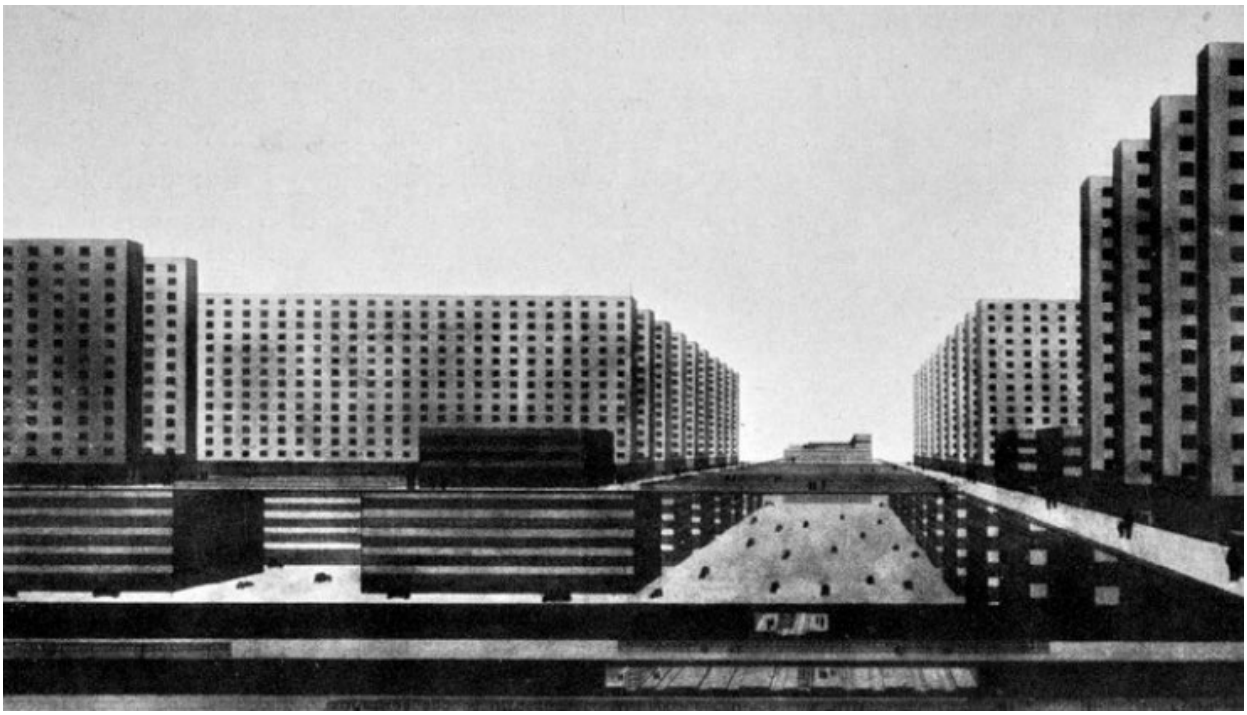


Figure 4. Ludwig Hilberseimer, "The New City" (1944), exemplifying urban abstraction through repetitive and standardized zoning structures

Despite their reductive tendencies, modernist zoning diagrams introduced an important conceptual innovation: the city as an organizational system. By abstracting urban complexity into visual codes, these representations laid the groundwork for later diagrammatic practices that would expand beyond functional separation toward infrastructural and relational logics. As Stan Allen suggests, the diagram in architecture operates less as a representation of form than as a generator of organizational relationships (Allen, 1999). Seen from this perspective, modernist zoning can be understood not simply as a historical rupture but as a transitional moment in which representation shifts from spatial description toward systemic thinking. In the diagrammatic urbanism of OMA, and others, the city becomes a layered field of interactions. However, in privileging systems and organization over material articulation, drawing becomes abstracted from texture, scale, and material presence. The diagram organizes complexity but often suppresses the sensory and tectonic dimension of urban form. The city is understood as logic before it is understood as matter (Lefebvre,1991). So, in a sense, the representation of the city here loses the specific tactile representations that identify the city.

In relation to contemporary smart city discourse, this moment is particularly significant. The reliance on abstraction, coding, and visual categorization anticipates later forms of urban visualization in which information is layered, filtered, and translated into graphic interfaces. While modernist diagrams were primarily concerned with functional efficiency, their graphic logic established a precedent for understanding the city through visual systems rather than purely spatial drawings. The move from figure–ground continuity to functional diagram thus represents a crucial step in the evolving relationship between architecture, representation, and urban knowledge.

4. The City as Layered System. Diagrams, Infrastructure, and Networked Urbanism

If modernist zoning translated the city into a functional diagram, late twentieth-century architectural practice began to question the limits of rigid categorization, exploring instead more open and relational modes of representation. Within this context, the work of Rem Koolhaas and the Office for Metropolitan Architecture, particularly the proposal for Melun-Sénart, offers a

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significant shift in how urban space is visualized. Rather than organizing the city through fixed zones, the project deploys layered diagrams that foreground infrastructure, networks, and the coexistence of multiple urban logics within a flexible framework (Koolhaas, 1995).



Figure 5. OMA, Ville Nouvelle Melun-Sénart competition proposal (1987). Layered infrastructural diagram redefining urban space as a relational system.

In contrast to the color-coded clarity of modernist planning, these diagrams operate through superimposition and ambiguity. Infrastructure is no longer merely a background system supporting urban form but becomes the primary structuring device of the project. Lines, bands, and fields replace the discrete blocks of zoning plans, suggesting a city defined less by static territories than by dynamic relationships. Representation here moves away from categorization toward a more relational language, where drawing becomes a means of organizing flows, intensities, and spatial hierarchies across multiple scales.

The diagrammatic turn of this period reflects broader theoretical discussions on mapping and architectural representation. As Stan Allen argues, diagrams function as instruments capable of articulating organizational strategies rather than fixed forms, enabling architects to engage with complexity without reducing it to singular geometries (Allen, 1999). Similarly, James Corner's notion of mapping as an active and projective practice highlights how representation can generate new spatial possibilities rather than merely documenting existing conditions (Corner, 1999). Within this framework, Melun-Sénart can be understood not simply as an urban proposal but as an experiment in representational methodology, where the city is conceived as a layered system open to transformation.

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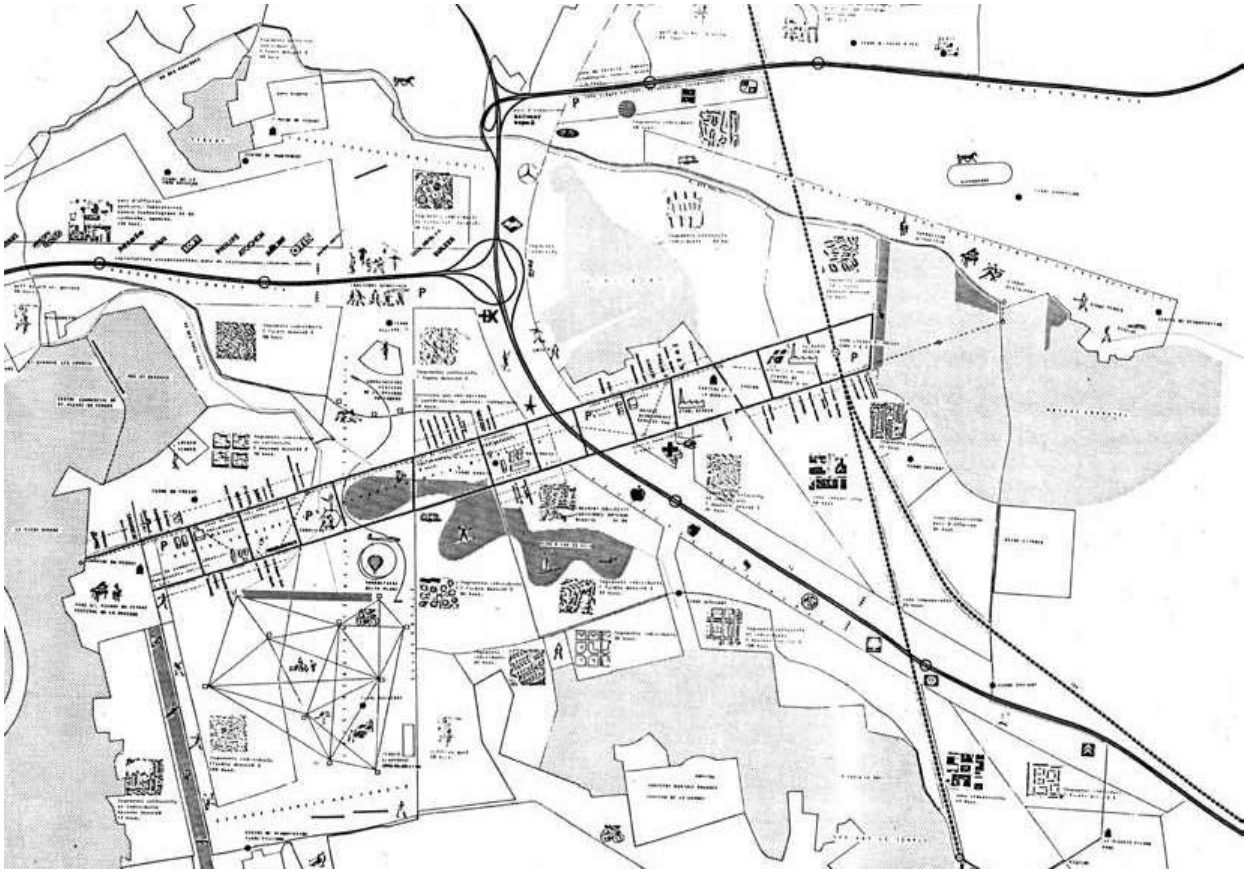


Figure 6. OMA, diagrammatic study for Melun-Sénart, illustrating superimposed networks and infrastructural stratification.

This approach marks a departure from both Nolli's spatial continuity and modernist functional zoning. While figure–ground drawings emphasized the relationship between solids and voids, and zoning diagrams organized the city through programmatic separation, the layered diagrams of late twentieth-century urbanism introduce a more fluid understanding of urban structure. Networks, infrastructures, and spatial fields overlap, suggesting a city that cannot be fully captured through a single representational logic. The urban drawing becomes less about defining boundaries and more about revealing interactions between heterogeneous elements.

Seen in relation to contemporary discussions on smart cities, this diagrammatic shift anticipates a broader transformation in how urban complexity is visualized. By foregrounding networks and relational systems, projects such as Melun-Sénart move representation closer to a condition in which the city is understood through interconnected layers rather than isolated forms. Although still grounded in architectural drawing, these diagrams begin to operate as proto-interfaces, hinting at modes of visualization that extend beyond static plans toward dynamic and adaptive frameworks. Representation, in this sense, evolves from functional ordering toward systemic thinking, a transition that prepares the ground for the emerging digital visualizations explored in the following section.

The evolution of urban representation discussed so far can be synthesized through a comparative framework that highlights shifts in representational logic, drawing techniques, and the conceptualization of the city across different historical phases.

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Table 1. Comparative framework of shifts in urban representation

Phase	Representational Logic	Mode of Drawing	Urban Concept	Role of Architectural Drawing
Figure–Ground (Nolli)	Spatial continuity	Plan (solid/void)	City as continuous field	Reveals spatial relationships and public accessibility
Modernist Zoning	Functional abstraction	Diagram (color-coded)	City as organized system	Classifies and separates functions
Diagrammatic Urbanism (OMA)	Relational systems	Layered diagrams	City as networked field	Organizes flows, infrastructures, and interactions
Smart City Visualization	Data-driven processes	Digital interfaces	City as dynamic informational system	Mediates real-time data and supports decision-making

This comparison clarifies how urban representation progressively shifts from spatial continuity to functional abstraction, then toward relational systems, and finally to data-driven visualization. Across these phases, architectural drawing does not disappear but is continuously redefined, moving from a tool of spatial description to a medium that organizes, interprets, and ultimately interfaces urban complexity.

5. Emerging Digital Visualizations. Toward Dynamic Mapping in Smart Cities

The diagrammatic explorations of late twentieth-century urbanism prepared the ground for a further transformation in how cities are represented within contemporary smart city discourse. While earlier architectural drawings relied on plans, diagrams, and layered systems to visualize urban complexity, current digital environments increasingly translate the city into dynamic interfaces composed of data layers, real-time mapping, and interactive visualizations. Rather than replacing architectural drawing altogether, these emerging representational modes extend its logic, shifting attention from static spatial description toward processes, flows, and continuously updated information.

Within the framework of smart cities, visualization plays a crucial role in mediating between urban space and technological infrastructure. As Antoine Picon suggests, digital systems introduce a new form of "spatialized intelligence," in which urban knowledge is constructed through the integration of sensors, networks, and computational platforms (Picon, 2015). Dashboards, digital twins, and heat maps exemplify this transformation, presenting the city not as a fixed composition of buildings and streets but as a dynamic field of intensities and relationships. Representation becomes increasingly performative, enabling planners and designers to monitor, simulate, and anticipate urban processes rather than simply document physical form.

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Figure 7. Urban digital twin interface integrating real-time data streams and 3D spatial modeling.

This shift resonates with broader discussions on the digital turn in architecture. Mario Carpo argues that contemporary design culture moves from the mechanical reproduction of standardized forms toward a computational environment characterized by variability and continuous adaptation (Carpo, 2017). In the context of urban visualization, this transformation redefines the role of drawing: plans evolve into interfaces capable of aggregating heterogeneous data streams, while maps operate as platforms for navigating complex informational environments. The city, in this sense, is no longer represented solely through geometry but through layered visualizations that combine spatial, social, and environmental parameters.

Urban digital twins are increasingly understood not simply as detailed 3D city models but as socio-technical systems combining technologies, institutions, and governance frameworks. As Batty and Kitchin note, data-driven urbanism introduces new epistemological questions about how cities are known and governed (Batty, 2013; Kitchin, 2014). While digital simulations promise analytical insight, they also risk reducing spatial experience to quantifiable metrics.

At the same time, systematic reviews suggest that many of these ambitions are still only partly achieved, largely because of persistent hurdles such as limited institutional capacity, uneven participation, and the difficulty of integrating fragmented data sources. Kitchin's idea of "digital twins and deep maps" helps sharpen this point: 3D models can function both as analytical tools and as narrative media that capture place-based perspectives. That dual role challenges the common assumption that more data and more layers automatically lead to better understanding of the city.

Dashboards are now a standard smart-city representation, translating urban complexity into actionable indicators and alerts. Once institutionalized, they do more than inform: they shape what is seen and measured, define "performance," and make issues governable by turning them into metrics. Seen this way, contemporary mapping still has the diagram's talent for simplifying and organizing complexity, but it now depends on databases, interface design, and constant updating. Representation shifts from making a drawing to running an ongoing service.

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Seen in continuity with the historical trajectory outlined in this paper, contemporary smart city visualizations can be interpreted as an evolution of representational strategies rather than a complete rupture. Just as modernist zoning diagrams abstracted urban complexity into functional codes, and late twentieth-century diagrams explored networks and layered systems, digital interfaces translate urban space into dynamic fields of data. The emphasis shifts from defining form to visualizing relationships, from static composition to adaptive frameworks. Representation, therefore, becomes a hybrid practice operating at the intersection of architecture, technology, and urban governance. In this approach, the representation of the city is increasingly encountered as information before it is encountered as space risking the loss of embodied experience (de Lange & Ruijer, 2025).

Rather than proposing a definitive theory of smart urbanism, this section suggests that the visual culture of smart cities extends long-standing architectural concerns with mapping, diagramming, and spatial organization. The emergence of dynamic mapping environments points toward a new phase in the evolution of urban representation, where drawing increasingly mediates between physical space and informational processes. This condition does not eliminate the architectural dimension of representation but repositions it within a broader ecosystem of digital visualization, raising questions about how designers might engage with these tools while preserving the spatial intelligence embedded in architectural practice.

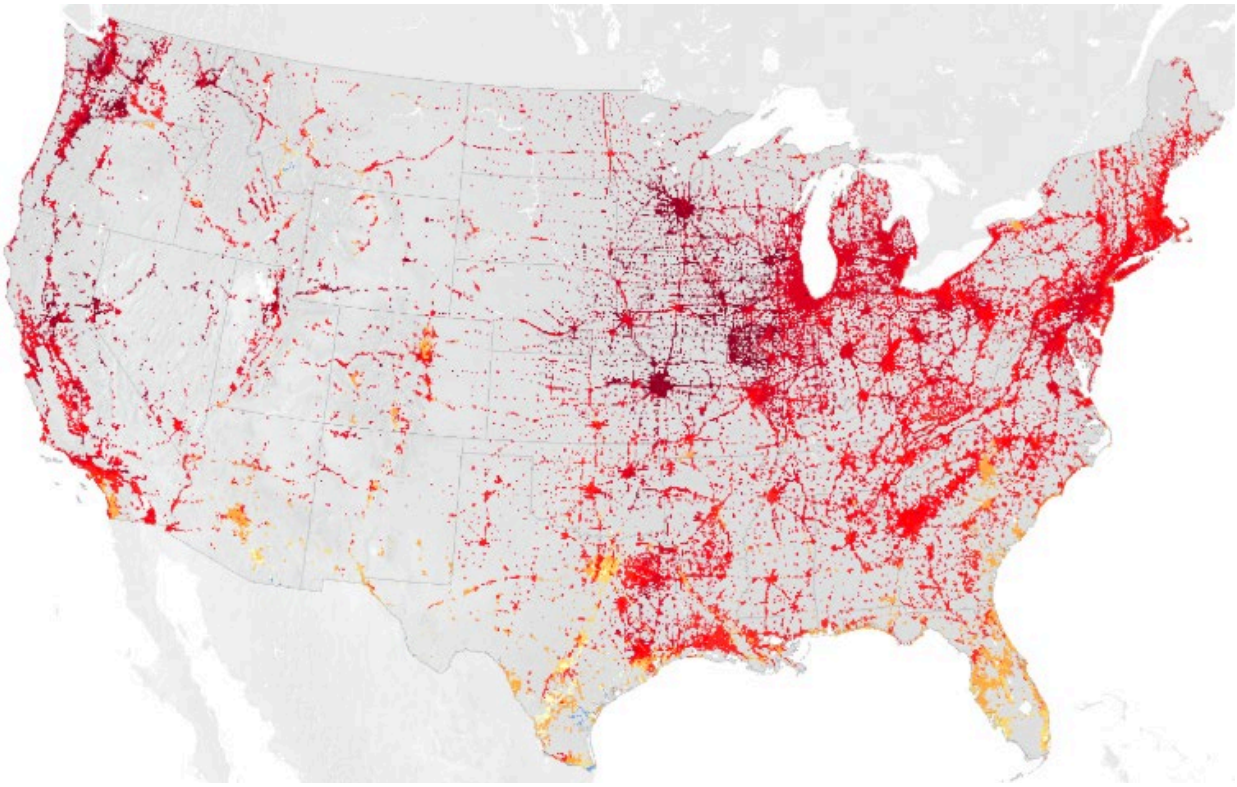


Figure 8. Data-driven urban visualization showing dynamic mapping of mobility flows and environmental intensities.

6. Conclusion. Urban Representation and the Visual Culture of Smart Cities

Tracing the evolution of urban representation from Nolli's figure–ground plan to contemporary digital visualizations reveals how drawing has continuously mediated changing conceptions of the city. Rather than a linear progression, these shifts reflect transformations in how spatial relationships are understood and communicated, from spatial continuity to functional abstraction, to relational systems, and ultimately to data-driven visualization.

Within the context of smart city discourse, emerging digital visualizations extend this trajectory by introducing dynamic interfaces that integrate spatial form with informational processes. Dashboards, digital twins, and real-time mapping environments suggest that urban representation is increasingly oriented toward monitoring, simulation, and adaptive management. Yet, rather than replacing architectural drawing, these tools can be understood as part of a longer continuum of representational practices, where abstraction and visualization operate as instruments for engaging with urban complexity.

Revisiting historical modes of representation highlights the enduring role of architectural thinking within contemporary digital environments. The spatial continuity of Nolli, the organizational logic of modernist diagrams, and the relational layering of late twentieth-century urbanism all resonate, in different ways, with current smart city visualizations. Rather than opposing digital interfaces to traditional forms of drawing, the evolution of urban representation suggests an expanded field in which spatial, diagrammatic, and informational logics coexist.

At the same time, this transformation raises critical questions. As urban representation becomes increasingly data-driven, there is a risk that what can be measured and visualized is privileged over what is experienced but less quantifiable. The city risks being understood as information before it is encountered as space.

Within this evolving landscape, architectural drawing does not disappear but is redefined, shifting from the representation of space toward a hybrid practice that integrates spatial, diagrammatic, and data-driven modes of thinking. This repositioning opens new possibilities for architectural research, suggesting that the future of drawing lies not in resisting digital systems, but in critically engaging with them while preserving the spatial intelligence that remains central to architectural practice.

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Culture and Contemporary Architecture: A Comparative Analysis of Context-Responsive and Culturally Detached Design

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Keywords: Critical Regionalism, Placelessness, Comparative Case Analysis, Cultural Identity Theory

Abstract. Architecture serves as a primary medium for expressing cultural identity, yet globalized modernism often produces "placeless" environments. Scholarly discourse often attributes this homogenization to technical necessity, whereas recent theory suggests it stems from a "fantasized gap" between professional "learned culture" and local "popular culture" [12]. This study evaluates the tension between global innovation and local cultural expression through the lens of social mediation. Using a qualitative comparative case study, the research assesses three iconic projects against a standardized analytical rubric. The Burj Khalifa (Dubai), the MAXXI Museum (Rome), and the National Museum of Qatar (Doha) were selected to represent varying degrees of contextual integration within contemporary practice. The research utilizes Critical Regionalism and Citizen Mediation [12] to analyze climate responsiveness, narrative symbolism, and validation through use. Findings indicate that while the Burj Khalifa and MAXXI Museum prioritize formal spectacle over local social norms, the National Museum of Qatar successfully bridges the gap between expert design and popular heritage. This paper proposes a comparative rubric that treats culture as a collective social project, offering a tool for architects to regain vitality in modern design.

Introduction

Historically, architecture functioned as a direct response to a community's way of life, with spatial organization and structural forms shaped by local climate and social values. From the courtyard houses of the Middle East to vernacular dwellings worldwide, architecture served as a physical manifestation of cultural identity, reinforcing collective memory. In the contemporary era, however, the adoption of universal design languages has produced built environments that appear detached from their geographical and social contexts.

This detachment is rooted in the early 20th-century movement toward Purism and the "International Style," championed by figures like Le Corbusier, whose focus on standardized, machine-like forms was a direct response to the specific technical and social shifts of industrialization. While these methods addressed a particular historical necessity, their continued application as a universal standard ignores the specificities of place and has contributed to the homogenization of the modern world. Scholars like Philippe Madec argue that this persistent detachment is often justified by a "fantasized gap" between "learned culture"—the academic world of architects—and "popular culture," or the way people live. This divide is often used to protect professional "laziness or fear," leading to designs that prioritize solo artistic expression over the "common human world"[10].

To investigate this phenomenon, this study addresses the following research questions: What specific indicators demonstrate successful cultural integration in contemporary iconic projects? How do modern architectural cases differ in their responsiveness to context when evaluated under the same theoretical lens? How does *citizen mediation* and *validation through use* impact the social vitality of a modern structure?

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Through a review of existing literature and a comparative analysis of the Burj Khalifa, the MAXXI Museum, and the National Museum of Qatar, this research explores the consequences of culturally detached design. The primary contribution of this paper is the development of a comparative framework designed to evaluate the cultural performance of modern structures. By assessing cases against standardized variables—including climate responsiveness, and spatial-cultural practices—this study provides a transparent analytical procedure to bridge the gap between theoretical regionalism and practical implementation.

Theoretical Framework

This research is grounded in the understanding that architecture is not a neutral or purely functional discipline, but a cultural and social act that reflects the values, beliefs, and historical conditions of the society in which it is produced. To evaluate this relationship, the study first utilizes *Cultural Identity Theory*, which explains that buildings act as a physical record of a society's shared memories and traditions. It suggests that by embedding cultural values into spatial organization and material choices, architecture becomes an active participant in shaping a community's social life [13].

The second lens is *Critical Regionalism*, which argues that modern buildings must fundamentally respect local climate, topography, and traditions to avoid architectural homogenization. This theory seeks to balance unavoidable modern construction technology with a specific "spirit of place," or *genius loci*, ensuring that new developments remain deeply rooted in their specific geographic surroundings [7].

Finally, the framework applies the "*Fantasized Gap*" to address the distance between how architects think and how people actually live. This concept suggests that architecture is a "collective social project" where a design is only truly successful when it is "validated through use" and embraced by the community it serves [12].

To ensure an objective analysis based on these theories, this study establishes specific criteria to categorize contemporary architectural projects. *Culturally Detached* architecture is defined as design that prioritizes universal design languages, global aesthetics, and economic efficiency over local identity. Key indicators for this category include the use of standardized international style forms and materials that ignore regional climate needs, such as universal glass facades in arid regions. Furthermore, detached designs are characterized by the displacement of traditional social spaces in favor of foreign floor plans that do not accommodate local ways of life.

In contrast, *Context-Responsive* architecture is defined as design that treats cultural and environmental context as a foundational principle. The criteria for this category include the integration of climate-responsive strategies, such as passive shading, and a strong spatial-cultural alignment where layouts facilitate local social rituals. Additionally, context-responsive projects utilize narrative symbolism, where architectural forms are inspired by regional landscapes or history rather than global spectacle, ensuring the building remains a meaningful extension of its location.

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Table 1, The Case Analysis Matrix, derived from the previously mentioned theories, provides the framework for evaluating the selected case studies:

Evaluation Criteria	Description of Analytical Lens
Climate Responsiveness	The use of regional strategies or modern technology to address local environmental conditions.
Spatial-Cultural Alignment	The alignment of floor plans and circulation with traditional social rituals and privacy norms.
Urban Contextual Fit	The integration of the building with the surrounding historical fabric, street interface, and urban continuity.
Validation Through Use	Evidence of "social vitality" where the design is understood, functional, and embraced by its users.

The Relationship Between Culture and Architecture

Architecture has historically functioned as a physical expression of cultural identity, reflecting the values, traditions, and social structures of the societies that produce it. Before the rise of industrialized construction, buildings were shaped by local materials, craftsmanship, and the specific daily rituals of the inhabitants [14].

A primary evidence-based example of this relationship is the Majlis in Middle Eastern residential architecture. Within regional housing scholarship, the Majlis is defined as a dedicated space for hosting guests, strategically secluded from the private family quarters to maintain the cultural necessity of privacy. Scholarly analysis demonstrates that these spatial configurations are not merely aesthetic preferences but are socio-spatial requirements that align with tribal social structures and religious privacy norms [2][14].

However, contemporary studies indicate a significant shift as modern homes in the region increasingly adopt Western-centric floor plans. This adoption often neglects the Majlis in favor of a globalized open floor plan, creating a functional misalignment between the built environment and the user's cultural needs. This displacement represents a movement toward "placelessness," where the design prioritizes "learned culture" over the actual social practices of the inhabitants. [15]

The Rise of Globalized Modern Architecture

The twentieth and twenty-first centuries witnessed an unprecedented mobility of ideas, capital, and professionals, contributing to the global spread of modern architectural styles characterized by standardized forms and expansive glass façades. While these advancements introduced innovative construction techniques, they also promoted a culture of uniformity where buildings in vastly different contexts began to resemble one another.

A significant manifestation of this globalization is the typological displacement of traditional domestic spaces. This is most evident when comparing the traditional Middle Eastern Majlis to the standardized open-plan concept currently favored by international design initiatives. Historically, the Majlis is defined by its strategic seclusion from the family living quarters to maintain the cultural necessity of privacy. This layout allows for a "physical record of shared memory" where guests are hosted without penetrating the private domestic core. This configuration accommodates the lived social rituals of the community [2].

In contrast, the standardized open-plan concept prioritizes transparency, spatial flow, and efficiency. By removing interior walls to create interchangeable spaces, the open plan absent-mindedly erases the cultural norms of gender-specific hosting and domestic privacy. This represents a "learned culture" approach where global modernity is prioritized over the practical social behaviors and privacy needs of the inhabitants.

Consequences of Ignoring Cultural Context

When architectural design prioritizes global aesthetics over contextual sensitivity, it produces measurable environmental and functional failures. By utilizing socio-spatial and environmental

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research, these consequences can be identified as a direct result of the fantasized gap between design theory and lived reality. Rather than relying on general observations, environmental research provides concrete data on the failure of universal modernism in arid climates [12].

Thermal Performance and Solar Gain. Fully glazed envelopes result in internal heat gains that exceed regional comfort thresholds by up to 15°C without massive mechanical intervention [4].

Sustainability Gap. The uncritical application of universal technology strips architecture of its environmental specificity, turning buildings into high-energy "machines" rather than integrated shelters [7].

Without validation through use, spaces are frequently modified by inhabitants or remain underused because the modern architecture failed to provide for their daily social rituals. A design is only truly successful when it is treated as a collective social project; otherwise, the building exists as an isolated object rather than a meaningful extension of its location [12].

Case Studies of Culturally Detached Architecture

To evaluate the extent to which modern architectural practices negotiate the balance between global innovation and local meaning, this study applies a consistent five-variable rubric to two internationally recognized "culturally detached" examples. These cases represent the dominance of "learned culture"—the academic and professional focus on global status—at the expense of regional "popular culture".

Case 1: The Burj Khalifa, Dubai. The skyscraper stands as the tallest structure in the world and a global symbol of economic ambition. While it represents a pinnacle of structural engineering, it exemplifies the "placelessness" associated with international skyscraper typologies.

Climate Responsiveness. Technical documentation highlights a high-performance glass façade designed to mitigate extreme solar gain. However, environmental research indicates that fully glazed envelopes in the Gulf lead to internal heat gains that exceed regional comfort thresholds, resulting in a total reliance on high-energy mechanical cooling rather than passive regional shading strategies [4].

*Spatial-Cultural Alignment.*The tower adopts standardized international office and luxury residential floor plans. It lacks the socio-spatial seclusion traditionally required for Middle Eastern privacy norms and provides no evidence of reinterpreting vernacular layouts.

Urban Contextual Fit. As an isolated icon of modernization, the tower follows international typologies rather than responding to the historical urban fabric of the region. Its scale creates a visual spectacle that functions independently of the surrounding cultural landscape.

Validation Through Use. Critiques describe the tower as a "vertical exclusive island," where high entry costs and extreme security protocols create a physical and social barrier for the general public. This isolation is a physical manifestation of the gap between an elite "learned culture" of global architectural spectacle and the "popular culture" of the local community’s daily social rituals [20].

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Fig. 1. Burj Khalifa in Dubai disconnects from contextual culture (Source: ArchEyes [5])

Case 2: MAXXI Museum, Rome. Designed by Zaha Hadid, the MAXXI is celebrated for its futuristic and fluid architectural form. However, it serves as a primary example of how prioritizing formal experimentation can lead to a "fantasized gap" between design intent and programmatic reality.

Climate Responsiveness. The building utilizes massive concrete forms and fluid glass transitions that reflect an experimental modern aesthetic rather than engaging with Rome's specific climatic conditions or regional material palette.

Spatial-Cultural Alignment. The design prioritizes dynamic concrete curves and dramatic interior spaces. Research suggests that when design prioritizes aesthetics over the human experience, spaces often become alienating or fail to support the social interactions characteristic of the local culture [8].

Urban Contextual Fit. The museum stands in sharp contrast to Rome's historical urban fabric. It acts as an isolated architectural object, lacking "permeability" with the street interface and failing to engage with the surrounding heritage or urban continuity.

Validation Through Use. Documented operational issues at the MAXXI Museum illustrate a significant failure in social mediation. Reports noted that internal circulation and entrances were fundamentally misaligned with the building's purpose, with doors being too small to accommodate the large-scale contemporary artworks the museum was intended to house. This functional

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oversight serves as a primary example of where the designer's focus on a solo artistic expression creates a disconnect from the practical requirements of the project. By prioritizing formal experimentation over programmatic reality, the structure fails to achieve the "social vitality" required for a successful collective social project, ultimately resulting in a space that is aesthetically celebrated but functionally detached from its intended use [16].



Fig. 2. Maxxi Museum in Rome ignores surrounding urban context (Source: The Architectural Review [16]). Case Study of Context-Responsive Modern Architecture

National Museum of qatar (NMoQ). In contrast to culturally detached examples, the NMoQ demonstrates how a "collective social project" can bridge the "fantasized gap" between professional expertise and popular heritage. By treating culture as a central design generator, the project functions as a meaningful expression of society rather than an isolated architectural object.

Climate Responsiveness. The museum reinterprets traditional shading techniques through its interlocking disk structure. These disks create deep overhangs that provide natural thermal buffers and shaded pathways, effectively mimicking the cooling effects of the vernacular Sikka (alleyway). Environmental data from the Global Sustainability Assessment System (GSAS) confirms this efficacy, as the NMoQ achieved a Platinum rating for operations, largely due to its "self-shading" logic which significantly reduces the mechanical cooling loads typically required in the Gulf [9].

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Spatial-Cultural Alignment. The spatial sequence narrates the nation's development from Bedouin life to modern statehood. When architecture aligns with collective cultural memory, it avoids the "placelessness" of globalized modernism [2].

Urban Contextual Fit. The museum represented successful integration of the historic palace of Sheikh Abdullah bin Jassim Al Thani. By preserving this "site of memory", the design is validated by the public as a physical record of shared identity rather than a foreign imposition [18].

Validation Through Use. The museum's interlocking disk structure provides essential shaded public plazas that facilitate modern social rituals and community gathering. By reincorporating traditional courtyard concepts and preserving the historic palace as a "site of memory," the design maintains historical urban continuity and is validated by the public as a meaningful extension of their shared identity. Ultimately, the NMoQ regains the architectural "vitality" that is often lost in culturally detached projects, proving that a contemporary structure can be both a global icon and a functional, inhabited shelter [18].



Fig. 3. National Museum of Qatar in Doha respects cultural traditions (Source: The Destination Management Company of Qatar Airways [14]).

Conclusion

The analysis highlights a persistent tension between globalization-driven "learned culture" and culturally responsive design. While the Burj Khalifa and MAXXI Museum demonstrate how iconic structures can become detached from their context in pursuit of global spectacle, the NMoQ proves that modernity and identity can coexist.

Summary of Contributions

This research contributes a comparative rubric—measuring climate, space, urban fit, and social validation—to bridge the gap between theoretical regionalism and practical implementation. The paper demonstrates that architecture is most successful when it is treated as a physical record of shared memory and a response to specific environmental truths.

Future Work

Future research should utilize Post-Occupancy Evaluations (POE) to further measure the social vitality of these spaces over time. Additionally, exploring how local policy can encourage "citizen mediation" will be essential in moving toward an architectural paradigm that harmonizes modern advancement with cultural consciousness.

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Smart Survey Methods for Coastal Heritage Conservation in Saudi Arabia: The Case of Al Qatif

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Abstract. In a context marked by rapid urbanization, economic restructuring, and increasing tourism pressure, the coastal historic fabrics of the Gulf are exposed to processes of alteration, material loss, and progressive disappearance. Among these, the coral- and sand-based settlements, such as Al Qatif in Saudi Arabia, represent highly fragile heritage systems that are undergoing severe reduction and irreversible transformation. Within this framework, there is an urgent need to apply advanced digital technologies - such as Geographic Information Systems, 3D survey techniques, and heritage modelling platforms - integrated with an analogical and participatory approach, including student involvement and field-based activities, in order to document and interpret coastal heritage that is at risk of disappearance. These tools must be understood not as neutral solutions, but as critical devices capable of revealing the material, environmental, and stratigraphic complexity of these urban systems. The contribution also addresses the risk of "heritage washing," understood as the reduction of heritage to simplified aesthetic imagery lacking historical and material depth, when digitalization is not guided by a scientific and context-sensitive approach. Al Qatif is thus proposed as an emblematic case for applying a smart approach to fragile coastal heritage, where sand, coral, and urban memory form an inseparable system to be recorded, understood, and preserved through advanced digital and integrated methodologies.

1. Introduction

Smart Survey Methods for Coastal Heritage Conservation in Saudi Arabia: The Case of Al Qatif describes the transformation of coastal historic settlements in the Arabian Gulf under the pressures of rapid urbanization, economic change, and large-scale development. The research highlights the progressive loss and fragmentation of vernacular coastal fabrics, especially coral- and sand-based settlements. These vulnerabilities are related both to the fragile material characteristics of traditional buildings and to the intense economic pressures that, especially during the final decades of the twentieth century, reshaped the coastal areas around Dammam and Khobar.

Al Qatif is used as a key case study due to its long historical continuity and current vulnerability as a coastal oasis settlement in Saudi Arabia. The research situates these dynamics within broader regional planning processes that have reshaped traditional urban systems into more complex and polycentric structures. It also underlines the tension between development and heritage conservation, often exacerbated by limited regulatory frameworks. In conclusion, the study emphasizes the importance of integrating digital survey technologies with participatory and field-based approaches to improve the documentation, interpretation, and preservation of fragile coastal heritage.

2. From Vernacular Coastal Settlements to Polycentric Megaregions

The Arabian Gulf coastal territories are currently undergoing profound transformations driven by rapid urbanization, economic diversification, and large-scale tourism development strategies.

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Since the 1970s oil boom, nations surrounding the Arabian Gulf have witnessed rapid coastal urbanization, which accelerated in the early 2000s with the emergence of large-scale coastal 'mega-projects' designed to accommodate growing populations, attract international investments, and promote tourism [1, 2]. Indeed, over the past half-century, population centers in the Arabian Gulf have evolved from small fishing and trading villages into globally interconnected megacities [3].

Processes that have often resulted in the fragmentation of historic urban fabrics within traditional settlements and in the gradual erosion of vernacular urban landscapes, originally built with materials such as coral stone, mud, and sand-based composites [4].

As highlighted by Al-Hathloul and Edadan (1993), during the 1990s Saudi Arabia was undergoing a phase of spatial consolidation and economic diversification, characterised by planning strategies aimed at the efficient use of resources and the strengthening of regional centres through infrastructure-driven investment criteria [5]. This approach contributed to the gradual emergence of a polycentric settlement system, clearly observable along the eastern coast, where Al Qatif, Dammam, and Al Khobar have developed as major urban and functional hubs, closely linked to economic growth processes and to the expansion of energy-related and port infrastructures [5].

Within this framework, regional planning in the Eastern Province has operated as a key instrument for structuring and consolidating this spatial configuration [6]. As noted by UN-Habitat (2019, p. 39), the *Strategic Regional Plan for the Eastern Region* (2005) seeks, among its objectives, to address coastal development imbalances through a more distributed urban hierarchy, a principle operationalised in the *Dammam Metropolitan Plan*, which includes Qatif within a wider urban system while recognising its agricultural base, fishing activities, and heritage assets, yet largely reinforcing sectoral land-use zoning and low-density expansion patterns. Moreover, as noted by UN-Habitat (2019, p. 39), the Local Plan further consolidates this logic through extensive residential expansion zones and large infrastructural buffers, particularly for oil and gas pipelines, with limited integration of mixed-use development. The resulting spatial structure reinforces car dependency and contributes to the fragmentation of the urban fabric, despite the stated objectives of balanced and sustainable regional development.

2.1. Al Qatif: Between Heritage Persistence and Loss

Qatif is one of the oldest coastal settlements in Saudi Arabia, with origins dating back to around 3,500 BC, and retains only a limited portion (612 hectares) of its original walled urban fabric characterised by an organic and historic morphology [6]. As noted by UN-Habitat (2019, p. 66), the city's transformation can be understood through four main spatial and socio-economic components: Tarout Island, the coastal settlements (Qatif, Anak, Saihat), the central oasis, and the oasis frontier. While Tarout Island preserves significant archaeological and historical assets, including Tarout Castle, these are increasingly threatened by urban expansion and land reclamation, alongside the progressive loss of vernacular structures [6].



Fig. 01 - Al Qatif – photographic documentation of historic buildings. Authors' Edition, 2025

The historic core of Al Qatif developed as a dense and compact oasis settlement system, characterised by a fine-grained urban morphology adapted to climatic constraints and irrigation-based agriculture. Traditional neighbourhoods were organised around palm groves, irrigation systems, and a network of narrow pathways, reflecting a strong integration between the built form and the ecology of the oasis.

Early descriptions of the city highlight its hybrid identity as both an inland oasis and a coastal trading node, shaped by its proximity to pearling routes and maritime exchanges across the Gulf [7].

According to UN-Habitat (2019, p. 80), within an evidence-based and multi-scalar analysis, four main critical issues affecting the sustainable urban development of Qatif were identified, including the increasing vulnerability of historic and vernacular urban heritage. In the absence of a clear regulatory framework capable of distinguishing historic fabrics from informal and unplanned areas, many traditional neighbourhoods are subject to demolition and replacement to make way for new urban developments. This process not only entails a significant loss of heritage and urban identity, but also leads to a rupture in the relationships between historic fabrics and the surrounding urban context, resulting in a disconnection from existing building typologies and settlement patterns [6, 8]. As concluded in the UN-Habitat (2019) report, the persistence of inhabited historic areas highlights the urgency of targeted conservation and upgrading strategies aimed at improving living conditions, services, and the preservation of the remaining vernacular heritage. Especially, Tarout Island (part of the Al Qatif area) is currently integrated into Saudi Arabia's Vision 2030 strategy, which aims to enhance cultural tourism and heritage conservation [9].

2.1.2. Al Qatif: as a pilot study

The vernacular architecture of Tarout Island, as well as that of the remaining historic core of Al Qatif, is characterised by traditional coral stone houses and maritime heritage structures, reflecting the area's long-standing historical dependence on the sea [9].

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Fig. 02 - Al Qatif – photographic documentation of historic buildings. Authors' Edition, 2025

Al Qatif can serve as a pilot study because parts of its historic urban fabric still remain despite demolitions and abandonment; documenting, mapping, and measuring these fragile structures could establish a pioneering framework for consolidating fragile heritage restoration processes in Saudi Arabia. An example of an, already, ongoing restoration process in Qatif is the rehabilitation of Abu Loza's Historic Bath, which represents one of the first documented efforts to address the deterioration of vernacular heritage within the historic urban fabric; as described in *Rehabilitating Abu Loza's Historic Bath: A Case Study of Heritage Conservation and Reuse Opportunities in Qatif, Saudi Arabia* (2025). The restoration strategy is based on a scientific and condition-based assessment of the building, identifying critical damages across all facades and interior spaces, and prioritising urgent structural consolidation and material repair [10]. In addition, the authors wrote that in technical restoration measures, the project emphasises the importance of qualified expertise and heritage-sensitive methodologies to ensure authenticity and long-term stability. Moreover, it highlights the potential for adaptive reuse of the bathhouse as a cultural and tourism asset, aligning conservation actions with broader urban regeneration objectives in Qatif [10].

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Fig. 03 - Al Qatif – photographic documentation of historic buildings. Authors' Edition, 2025

3. GCC Urban Territories: A Mosaic of Heritage Preservation and Conservation

The literature highlights that the protection of tangible heritage in Saudi Arabia has developed through a legal framework initially established in 1972 and later strengthened in 2014, primarily focused on the safeguarding of archaeological sites, historic buildings, and cultural artefacts. Institutional responsibility lies mainly with the Ministry of Culture and the Heritage Commission, which carry out documentation, inventorying, restoration, and heritage valorisation activities, increasingly aligned with broader urban development and Vision 2030 strategies [11]. Moreover, specific case studies emphasize the urgency of targeted intervention for heritage conservation. In particular, the study on the Farasan Islands underscores the need for immediate rehabilitation and management actions for heritage sites, stressing the importance of community participation and stakeholder identification in conservation processes [12].

3.1 The Risk of Cultural Heritage Washing in the Conservation Projects Across the GCC Region

The progressive disappearance of historic urban centers could be linked to the recent phenomenon named "Architectural Heritage Washing" that may further exacerbate the already vulnerable condition of architectural heritage in the Sharqiyah region.

Selecting three main practices, varying from mere reconstruction of old architecture to more complex conservation practices, it is possible to generally exemplify the variegated approach in preserving the local architecture heritage.

Several scholars have recently examined how urban revival is increasingly employed to reinforce local identity [13][14][15][16]. However, when heritage sites are reshaped under the pressure of tourism and real estate development, this process may lead to architectural falsification.

In architectural restoration and conservation, such practices can be interpreted as forms of "Architectural Heritage Washing", where historical identity is selectively reconstructed and re-interpreted.

This can be understood as problematic and potentially dangerous actions through which an architectural artifact is reconfigured by selectively altering its aesthetic, material, or symbolic features. In doing so, it risks rewriting the documentary nature of the building and erasing its authenticity. This irreversible loss of the historical and cultural significance of the site/building is often masked by a form of reconstruction that reinterprets the past and narrates an alternative reality through rhetorical operations that do not correspond to the real artifact's materiality and design characteristics, distorting its scale, typology along with its corresponding layout.

Rapid urban development and tourism-related pressures often require accelerated interventions in the built environment, including regeneration, rehabilitation, and valorization projects. These conditions may contribute to the emergence of destructive heritage practices, not only through demolitions but also through a Disneyfication or faux-historic reconstruction. "Architectural Heritage Washing" can be understood as a paradoxical condition in which historical imagery is used to legitimize new architectural developments, while more rigorous forms of research, documentation, and conservation are neglected, preventing the emergence of a genuinely preservation-oriented project. Within this framework, priorities are often directed toward visual branding and economic regeneration instead of substantive heritage conservation [17].

The effort to foster the local architectural identity has been accompanied by some problematic conservation practices in the GCC countries. Some of these conservation and restoration attempts has been deeply analyzed, as demonstrated by a growing body of recent literature [18][19][20][21]. These cases differed in terms of scale, intensity, and impact and may be evaluated according to their degree of adherence to rigorous conservation approaches informed by recent international protocols, particularly UNESCO principles and widely recognized best practices.

Dubai Old Town, developed between 2014 and 2017, as mainly a commercial project, can be considered one of the most evident examples of Architectural Heritage Washing. The project reveals several critical issues, particularly in the way historical architectural forms were freely reinterpreted to produce an imaginary and picturesque image of the past, rather than a scientifically grounded reconstruction of the original urban and architectural fabric. In doing so, it created a simulated perception of what historic Dubai may have looked like

By extensively reconstructing a historical appearance without preserving the original proportions, material authenticity, or documentary basis of the historic buildings, the project recalls, to some extent, a scenographic and consumable representation of the past. Elements such as artificial cracks and the reconstruction of wind towers as merely decorative features, detached from their original indoor climatic function, further intensify this process of architectural heritage falsification.

The final objective of this project seems to be the development of a mere commercial/real-estate-driven project, where heritage is employed as a superficial visual layer rather than grounded in a comprehensive scientific, historical, and documentary framework where the false heritage image survive without community continuity.

Another widely discussed important case in the scientific literature concerns the transformation of Souq Waqif and Msheireb in Doha [22]. These interventions sought to reconstruct local identity

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through the rehabilitation and selective conservation of historic urban areas, although in some parts only limited traces of the original urban fabric remain visible after extensive redevelopment [23].

In the case of Souq Waqif, the rehabilitation process was based on the removal of inappropriate additions accumulated over previous decades, which had obscured the reading of the original architectural character of the historic marketplace. In order to avoid a radical falsification of the site, the intervention was supported by deep historical documentation and by studies of the social use of the space. This approach helped preserve the souq as an integrated part of everyday urban life, rather than transforming it into a merely staged image of the past [24][25][26]. In order to avoid the result of a theme park, the project preserved its role as a traditional open-air public space and working market, actively used by residents, merchants, shoppers, and tourists. In contrast to the Dubai Old Town project, the rehabilitation of Souq Waqif relied on the reintroduction of traditional materials and construction techniques, including wood, bamboo, clay, and straw. These were combined with passive climatic strategies rooted in local architectural practice, thereby reinforcing the material and environmental continuity of the historic marketplace.

It is important to emphasize that one of the most relevant recent examples of architectural conservation in the GCC can be found in Saudi Arabia. Ushaiger Village represents a significant attempt to preserve the original materiality and traditional construction techniques of its architectural heritage, while simultaneously reinforcing local identity and integrating environmental sustainability into the conservation process. The academic literature has recently started to identify Ushaiger as one of the most notable cases in the region across the Najdi settlements [27][28], particularly due to the restoration of more than one hundred houses over a long period, initially supported by volunteer-based initiatives promoted by local residents.

The restored mud and limestone houses, many of which were preserved or rehabilitated after years of abandonment, demonstrate the importance of material continuity and the reactivation of living heritage as core elements of contemporary conservation practice. In this sense, Ushaiger offers a comprehensive model in which architectural restoration, community participation, tourism development, and local economic revitalization converge with the broader objectives of Saudi Vision 2030 [29].

The attempt to recall and reintegrate historical identity within the contemporary global cities of the GCC reveals a broad spectrum of conservation approaches. At one end are commercially driven and scenographic reconstructions, where heritage is reduced to a visual or symbolic device. At the other are more rigorous practices grounded in scientific documentation, historical research, material authenticity, and internationally recognized conservation principles. These more robust approaches move closer to established international benchmarks, particularly in contexts where conservation protocols and legal frameworks have been consolidated over several decades.

For the Sharqiyah region of Saudi Arabia, especially its historic coastal settlements, these examples offer an important lesson. Future conservation projects should move beyond superficial revival, nostalgic imagery, or selective aesthetic reconstruction. Instead, they should be based on systematic documentation, historical evidence, community participation, and sustainable development strategies. Only through such an integrated framework can conservation resist the risk of becoming a rhetorical instrument of heritage washing and instead function as a genuine process of cultural preservation, architectural continuity, and urban regeneration.

3.2 The role of the universities: a pedagogical approach

Following the principles of a sustainable approach to conservation projects, participation is increasingly recognized as an essential pillar. Community involvement and the inclusion of multiple stakeholders should be accompanied by the development of awareness-raising programs capable of stimulating students' curiosity, particularly at the university level. Across Saudi Arabia, there are increasing initiatives, especially at the administrative and voluntary levels, including associations, forums, conferences, and debates on cultural heritage, aimed at strengthening efforts

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to recognize authentic and unique sites. The establishment of the National Urban Heritage Register and national forums testifies to this growing interest

Beside this phenomena, it is important to foster that university students could play a transformative role in documentation, awareness-raising, and cultural heritage preservation, particularly in emerging contexts such as Saudi Arabia, where these actions are relatively new but rapidly developing. Students represent the next generation of professionals, especially in faculties of architecture and engineering, and should be encouraged to act with greater responsibility, particularly when dealing with cultural heritage that requires preservation.

Experiences of heritage documentation in these geographical areas have recently been organized at universities such as King Abdulaziz University in Jeddah, through fruitful collaboration with international institutions, to develop structured methodologies for documenting architectural heritage.

Such types of initiatives, developed as workshops for staff and students in historic centers, particularly in places such as Al-Balad in Jeddah, have proven effective in training participants in methods and techniques for building archaeology and architectural surveys of typical examples of traditional architecture [30][31]. The use of recent innovative survey methods, such as laser scanning, enriches the experience of metric surveys through the most up-to-date techniques currently appreciated in this field.

Direct measurement combines theoretical knowledge with architectural learning experiences [32], fostering attention to precise record collection, direct observation, and the discovery of details. These aspects are useful for developing a more comprehensive understanding of building characteristics, degradation, damage, and future project actions, while supporting a progressive transition to digital tools [33]. This passage between traditional and innovative tools allows students to experiment with the intersections between critical analysis and the physical manifestation of their ideas, from documentation to the final project, with deeper engagement with building materials and spatial understanding.

Moreover, the value of metric surveys conducted through drawings and sketches maintains a crucial role in the practice of measuring an architectural site. This approach goes beyond mere technical competence [34], revealing that fieldwork can enhance soft skills such as teamwork, leadership, and communication, which are difficult to develop through classroom-based teaching alone.

Ultimately, by empowering university students to participate in heritage documentation and conservation processes, institutions equip them with the skills needed to facilitate inclusive heritage planning and mediate between community interests and conservation needs. This process encourages students to become active promoters of cultural preservation within their communities, while helping to shape a new generation of architects and professionals deeply committed to safeguarding architectural heritage [35].

4. Smart Survey Methods for Architectural Heritage

A comprehensive review of recent advances in digital survey technologies shows how the integration of laser scanning, HBIM, and GIS-based environments is reshaping the documentation and management of architectural heritage through increasingly accurate, data-driven and interoperable workflows. The study by Conor Dore and Maurice Murphy highlights how the integrated workflow between laser scanning, HBIM, and CityGML represents an advanced approach for the documentation, modeling, and management of cultural heritage, enabling the acquisition of highly accurate data through digital surveying, the automation of modeling and conservation documentation through HBIM, and the integration of 3D models into GIS platforms through CityGML, thereby improving the analysis, monitoring, and management of historic sites [36].

However, as noted by S. Logothetis, A. Delinasiou, and E. Stylianidis (2015), current HBIM methodologies still face limitations in representing the complexity and variability of historic buildings, as existing BIM libraries often rely on predefined components with restricted adaptability to the multiple states and irregular geometries characteristic of fragile cultural heritage [37]. According to S. Logothetis, A. Delinasiou and E. Stylianidis, HBIM is an increasingly important tool for the documentation and conservation of cultural heritage because it integrates geometric and semantic data into intelligent 3D models. Through the analysis of several case studies, the authors show that the HBIM workflow typically relies on laser scanning and photographic data, point cloud processing, and the creation of parametric objects to build detailed historical models enriched with information on materials, deterioration, and conservation management. The study concludes that the field is rapidly evolving and still offers significant potential for further development, particularly in open-source environments [38].

6. Conclusion

In Gulf cities, a growing effort to recover and reinterpret the historical past has led to a wide range of interventions, often shaped by the limited presence of consolidated heritage conservation regulations. This regulatory gap has encouraged experimentation in restoration practices and, in some cases, highly flexible approaches to reconstruction. As a result, there is a clear need to establish a structured conservation framework that integrates legal protection, economic incentives, community engagement, and technological monitoring [39] into a coordinated system. Future initiatives should prioritize community participation and authentic heritage education over commercial interests [40], ensuring that preservation strategies strengthen rather than weaken cultural continuity. In the GCC context, the strong educational base, knowledge exchange networks, and international standing of local universities provide a solid foundation for developing effective conservation frameworks. Through these structures, it becomes possible to combine technical standards with multi-level community involvement, particularly via educational programs, helping to safeguard the architectural and cultural heritage that defines Gulf identity.

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About the Editors

Dr. Dr. Jamal F. Nayfeh



Dr. Jamal Nayfeh is the Dean of the College of Engineering and Professor of Mechanical Engineering at Prince Mohammad Bin Fahd University (PMU), a position he has held since 2009. He brings more than 35 years of experience in higher education as an academician, professor, researcher, and academic administrator. Prior to joining PMU, he served as Associate Dean for Academics, Marketing, and Outreach in the College of Engineering and Computer Science at the University of Central Florida (UCF), where he was also a Professor in the Department of Mechanical, Materials, and Aerospace Engineering. Dr. Nayfeh earned his Ph.D. in Engineering Mechanics from Virginia Tech in 1990. He is a member of several leading professional organizations, including the American Society of Mechanical Engineers (ASME), the Society of Automotive Engineers (SAE), the American Society for Engineering Education (ASEE), and the Society of Petroleum Engineers (SPE), and is also a member of Tau Beta Pi Engineering Honor Society. His research encompasses design optimization, digital manufacturing, and energy systems. Dr. Nayfeh's research portfolio includes over 180 peer-reviewed journal articles and conference proceedings, reflecting a sustained and impactful scholarly record. His work has garnered significant citation recognition within the engineering community, with a strong and growing citation footprint as documented in his Scopus profile. The broader impact of his research is clearly aligned with global sustainability priorities, with measurable contributions to several of the United Nations Sustainable Development Goals. His work has been linked to Goal 6 (Clean Water and Sanitation) with 1 indexed contribution, Goal 7 (Affordable and Clean Energy) with 20 contributions, Goal 8 (Decent Work and Economic Growth) with 2 contributions, Goal 9 (Industry, Innovation and Infrastructure) with 7 contributions, Goal 11 (Sustainable Cities and Communities) with 4 contributions, and Goal 13 (Climate Action), reflecting a diversified and impactful research portfolio addressing energy, environment, and digital manufacturing challenges. Throughout his career, Dr. Nayfeh has supervised numerous graduate students at the master's and doctoral levels, secured substantial research funding from state, federal, and industrial sources, and played an active role in organizing and chairing national and international technical conferences and symposia. He also serves as a reviewer for leading international engineering journals and continues to contribute to the advancement of engineering education, research, and innovation.

Dr. Chuloh Jung



Dr. Chuloh Jung is a South Korean working as a professor in the Department of Architecture at PMU, KSA. He received his Bachelor of Architecture from Yonsei University in Seoul, South Korea, in 1994, his Master of Architecture from Harvard University in 1997, his Master in Design Studies from Harvard University, in 2001, and his Ph.D. from Yonsei University in Seoul, South Korea, in 2007. Dr. Chuloh Jung has 24 years of experience teaching, research, and curriculum development at graduate and undergraduate levels. He has developed and taught design studios, urban design and planning studios, sustainable design, environmental design, modern & contemporary architectural theory, research methodology, and specialized courses in design computation, often integrating my design projects into the curriculum, during his tenure at the American University of Dubai and Ajman University in the United Arab Emirates. His practical design experience includes collaborations with renowned architects like Lord Richard Rogers, Daniel Liebeskind, UN Studio, Zaha Hadid, and Massimiliano Fuksas. His portfolio on Archidaily.com demonstrates a convergence of building culture, technology, sustainability, and innovative design methodologies. Over the past three academic years, my scholarly endeavors have yielded 76 SCI/SSCI, 10 ESCI papers (69 Scopus Q1 and 2 Scopus Q2), and 15 conference proceedings. His teaching effectiveness is reflected in a high instructor evaluation score of an average of 4.84/5 in the annual faculty evaluation, having supervised 35 thesis projects in the last five years. Additionally, he led the Ajman University Innovation Center, nurturing technology startups aligned with the Fourth Industrial Revolution. Dr. Chuloh Jung hopes to contribute to preparing an outstanding young generation of architects and engineers who will help shape the future of cutting-edge and sustainable architecture in KSA and the region and collaborate to establish a more preeminent College of Architecture and Design in PMU.

Dr. Nadine Fayad



Dr. Nadine Fayad is an architect and urban scholar whose work integrates architectural practice with critical urban planning theory. Holding a Ph.D. in urban planning, she examines how cities evolve under shifting socio-economic and political conditions, with particular attention to governance structures, regulatory frameworks, and their spatial implications. She currently serves as an Assistant Professor and Associate Chair in the College of Architecture and Design at Prince Mohammad Bin Fahd University, where she contributes to both academic leadership and the development of architectural and urban planning education. Her role extends beyond teaching to shaping academic programs, fostering interdisciplinary collaboration, and supporting strategic initiatives within the college. Dr. Fayad's professional experience in the Saudi public sector informs her academic perspective, grounding her theoretical work in real-world institutional contexts. Through consultancy with municipalities, she has contributed to drafting urban regulations and guidelines, mediating between policy frameworks and spatial outcomes. This engagement reflects a nuanced understanding of how institutional mechanisms and governance systems shape urban development, particularly within rapidly transforming environments. In teaching and supervision, she focuses on urban regeneration, cultural preservation, and socio-economic analysis, encouraging students to adopt a multidimensional and critical approach to urban interventions. Her pedagogical approach frames design not merely as a formal exercise, but as a process embedded within broader political, economic, and cultural systems. Her research further examines urban transformation through neoliberal policy frameworks, analyzing how market-driven reforms influence spatial organization, governance, and social equity. By bridging theory and practice, her work contributes to ongoing debates on urban change, positioning her scholarship within a critical discourse on the socio-spatial implications of contemporary urbanization.