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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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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.

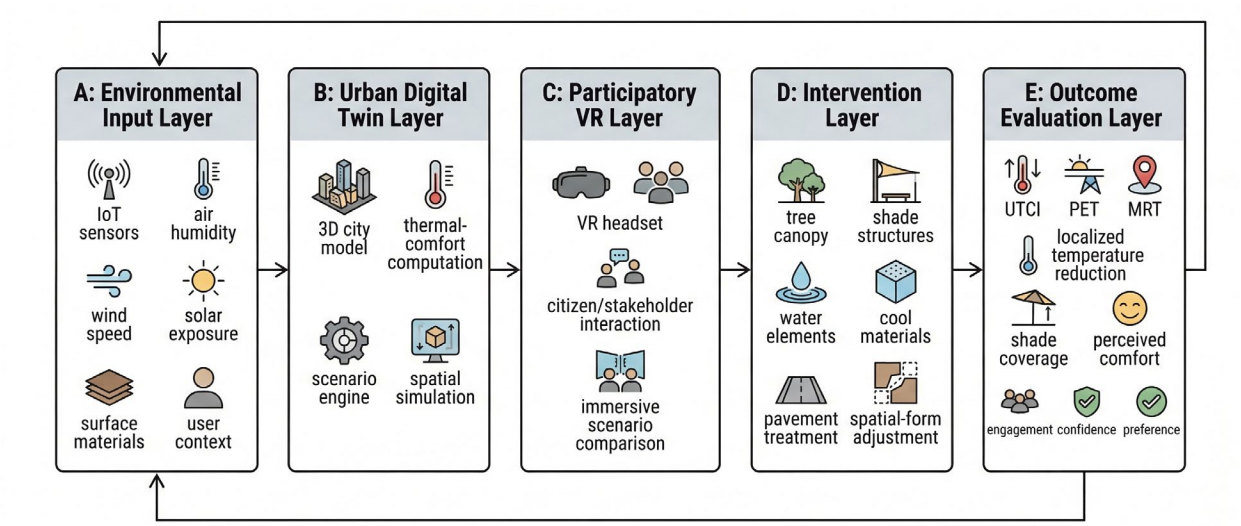


Fig. 1. Human-centered closed-loop framework integrating IoT sensing, urban digital twin modelling, participatory VR, intervention testing, and objective-subjective evaluation for heat-resilient public-space co-design.

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.

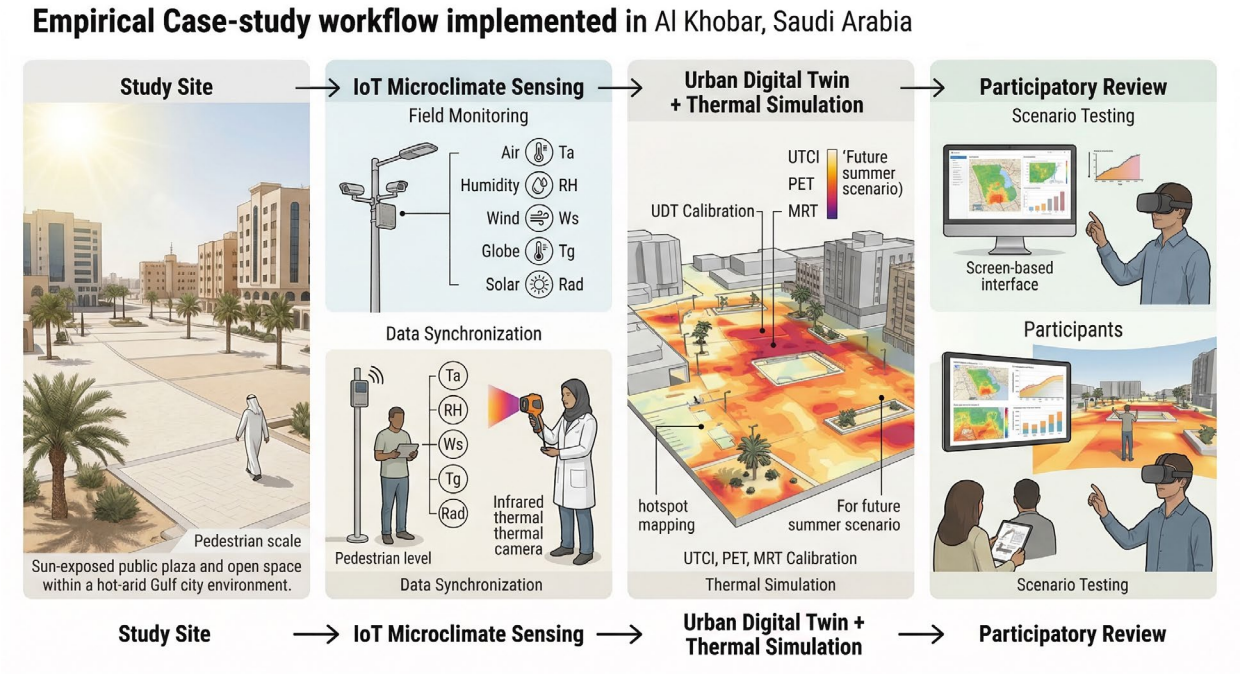


Fig. 2. Mixed-method empirical workflow showing site-based microclimate sensing, data synchronization, urban digital twin calibration, thermal simulation, and immersive/non-immersive participatory review.

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.

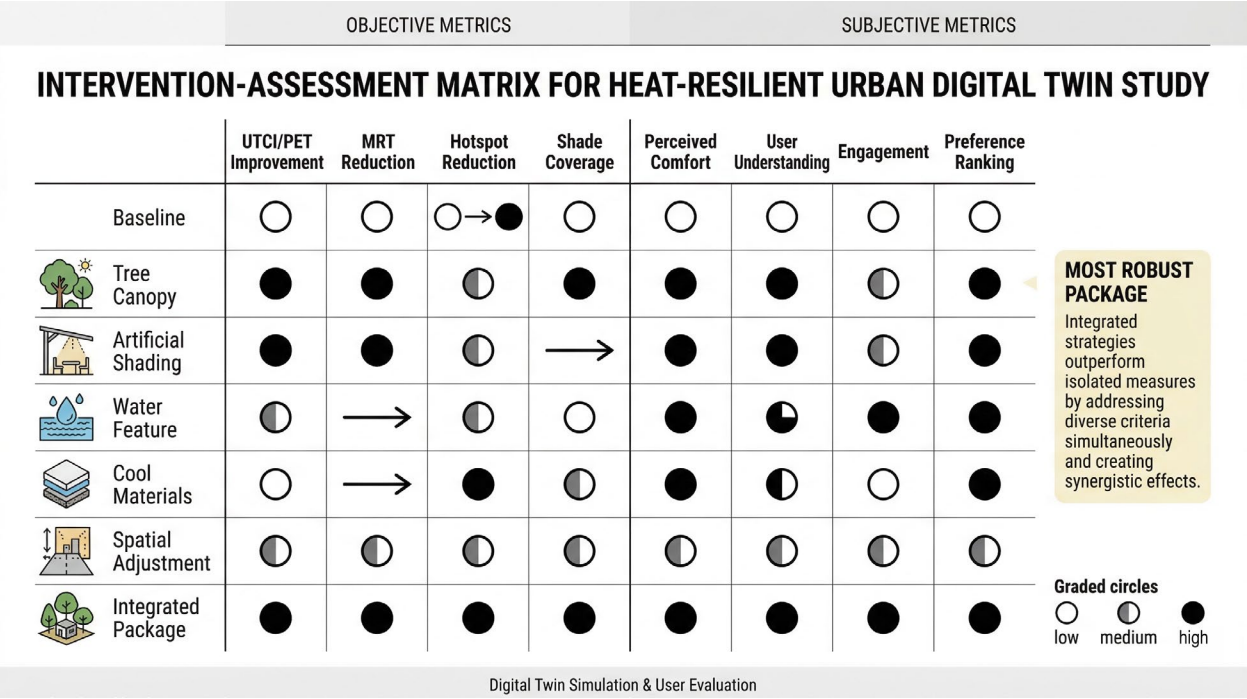


Fig. 3. Conceptual intervention-assessment matrix integrating objective thermal indicators and subjective user evaluation for comparing baseline, single-intervention, and integrated mitigation scenarios.

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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