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

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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.

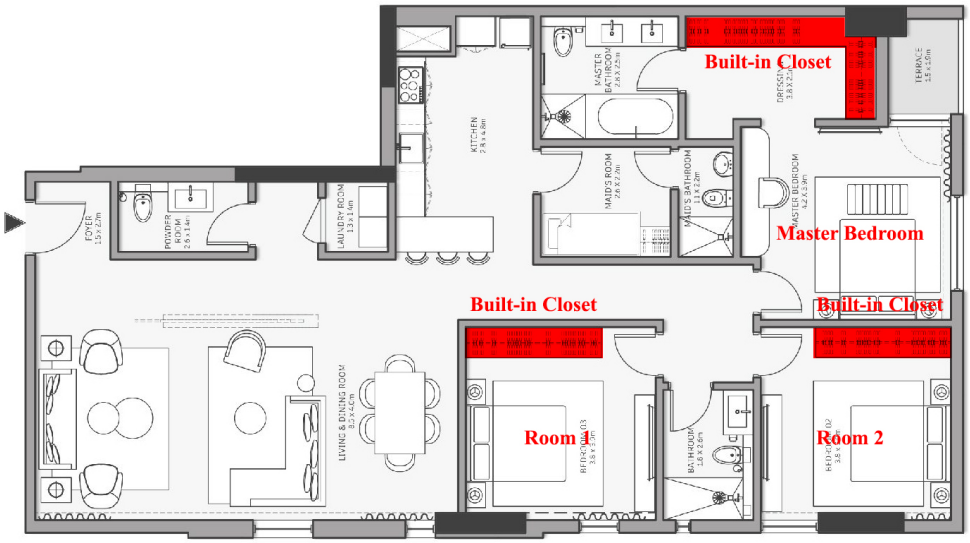


Figure 2. 3-bedroom apartment and locations of built-in closets



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.

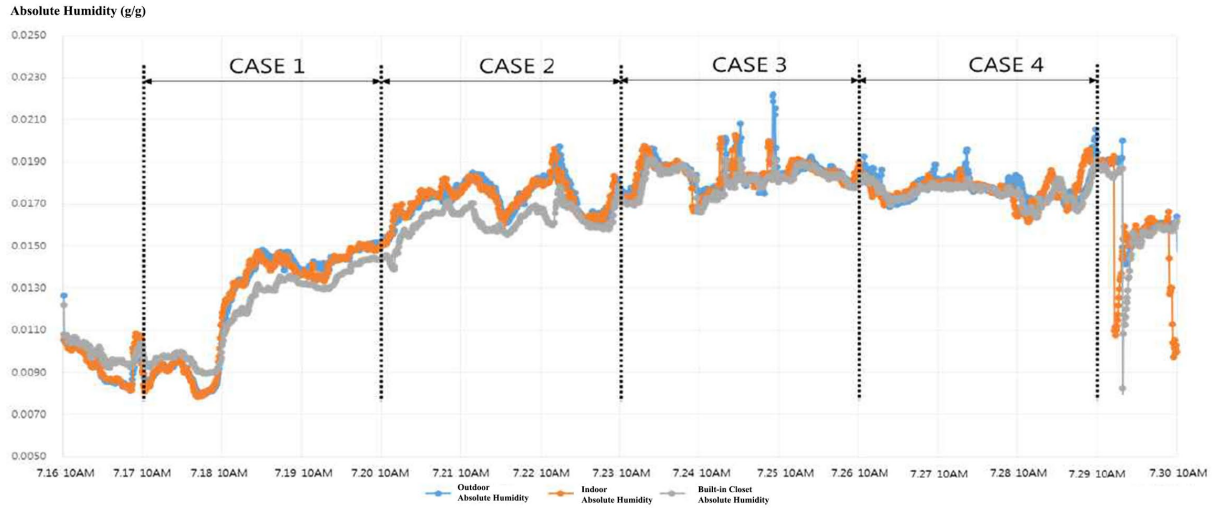


Figure 4. Measurement Result: Absolute Humidity

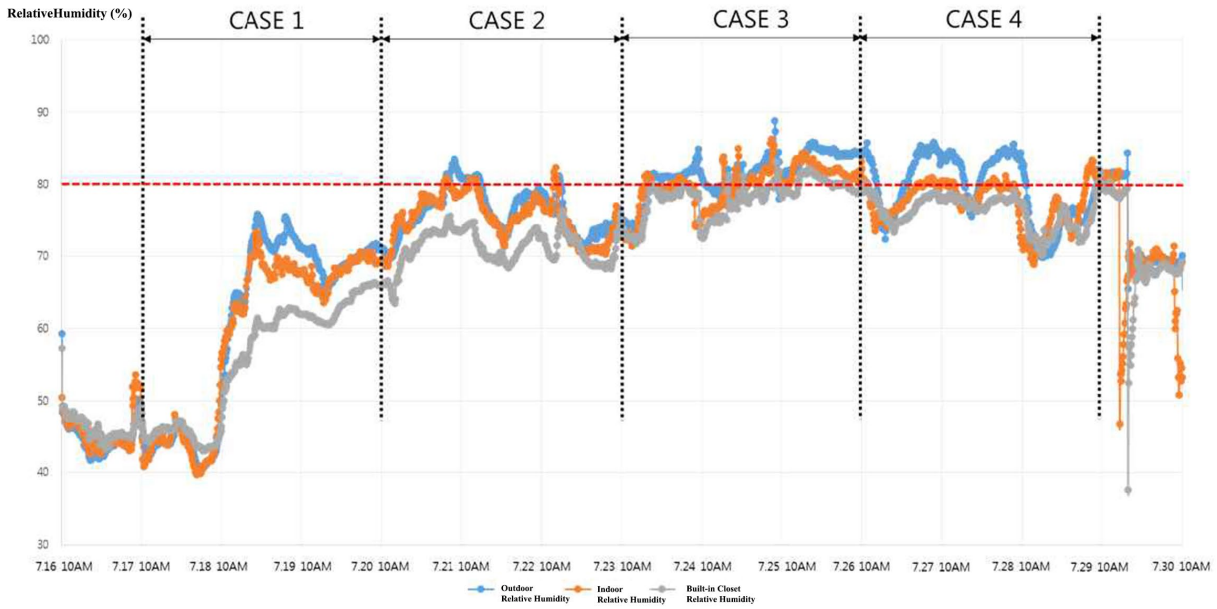


Figure 5. Measurement Result: Relative Humidity

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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