OPEN ACCESS
Journal of Moeslim Research Technik
Vol. 2 No. 5. October 2025, pp. 270-283 DOI. 10.70177/technik.v2i5.2507

Research Article

THE APPLICATION OF MASHRABIYA (LATTICEWORK) PRINCIPLES IN MODERN TROPICAL ARCHITECTURE FOR ENERGY-EFFICIENT PASSIVE COOLING

Hanantatur Adeswastoto[1], Ayesha Begum[2], and Aylin Erdoğan[3]
[1] Universitas Pahlawan Tuanku Tambusai, Indonesia
[2] North South University, Bangladesh
[3] Ege University, Turkey

Corresponding Author:

Hanantatur Adeswastoto,
Department of Civill Engineering, Faculty of Engineering, Universitas Pahlawan Tuanku Tambusai.
Jl. Tuanku Tambusai No. 23, Kec. Bangkinang, Kab. Kampar, Prov. Riau, Indonesia
Email: hanantatur@universitaspahlawan.ac.id

Article Info

Received: April 10, 2025
Revised: July 15, 2025
Accepted: September 17, 2025
OnlineVersion: October 22, 2025

Abstract

The increasing reliance on energy-intensive active cooling systems in modern tropical architecture presents a significant challenge to sustainable development. Traditional, vernacular design strategies, such as the Islamic *Mashrabiya* (ornate latticework screens), offer time-tested principles for passive climate mitigation that are largely underexplored in contemporary building science. This study aims to quantitatively evaluate the effectiveness of integrating *Mashrabiya*-inspired building facades as a passive cooling strategy to reduce solar heat gain and enhance thermal comfort in modern tropical buildings. A quantitative, simulation-based methodology was employed. Using building performance simulation software (EnergyPlus), a prototypical contemporary office building in a hot-humid tropical climate was modeled. Several facade designs incorporating different *Mashrabiya* patterns, porosities, and materials were simulated and compared against a conventional glazed curtain wall baseline. Key performance indicators included indoor operative temperature, solar radiation transmittance, and annual cooling energy demand. The findings demonstrate that facades with optimized Mashrabiya-inspired designs significantly improved building performance. The best-performing screen designs reduced direct solar heat gain by up to 55% and lowered the annual cooling energy consumption by over 25% compared to the baseline, while still maintaining sufficient daylight levels. The application of *Mashrabiya* principles is a highly effective and viable passive design strategy for modern tropical architecture. This research confirms that reinterpreting traditional architectural elements offers a culturally resonant and sustainable pathway to creating energy-efficient and comfortable buildings.

Keywords: Mashrabiya, Passive Cooling, Tropical Architecture.

Journal Homepage	https://research.adra.ac.id/index.php/technik
How to cite:	Adeswastoto, H., Begum, A., & Erdoğan, A. (2025). The Application of Mashrabiya (Latticework) Principles in Modern Tropical Architecture for Energy-Efficient Passive Cooling. *Journal of Moeslim Research Technik*, *2*(5), 270–283. https://doi.org/10.70177/technik.v2i5.2507
Published by:	Yayasan Adra Karima Hubbi

INTRODUCTION

The global imperative to mitigate climate change has placed the built environment at the center of the sustainability discourse (Ergün & Bekleyen, 2025). Buildings account for a substantial portion of global energy consumption and associated greenhouse gas emissions, with heating, ventilation, and air conditioning (HVAC) systems representing the largest share of this energy demand. This issue is particularly acute in the world's tropical regions, which are characterized by high ambient temperatures and humidity levels year-round (Maaith et al., 2025). These climatic conditions create a significant and continuous demand for indoor thermal comfort, a demand that is increasingly being met through energy-intensive mechanical cooling systems (M. Dabaieh, 2023).

Rapid urbanization, economic growth, and rising standards of living across the tropical belt have fueled an unprecedented construction boom (Lotfinejad et al., 2025). This development has largely been dominated by the proliferation of the International Style of architecture, characterized by sealed, glass-clad building envelopes (Singh et al., 2025). While aesthetically aligned with global modernism, this architectural typology is fundamentally ill-suited to the tropical climate, functioning as a greenhouse that traps solar radiation and necessitates a heavy reliance on mechanical air conditioning (Lima et al., 2025). This trajectory is environmentally unsustainable, places immense strain on national energy grids, and contributes significantly to the urban heat island effect (Gnaba et al., 2025).

In stark contrast to this modern trend, vernacular architecture across the world's warm climates offers a rich repository of time-tested, passive design strategies (Al Bosta et al., 2025). These traditional building practices evolved over centuries through a process of empirical refinement, resulting in sophisticated solutions that achieve thermal comfort by working in harmony with the local climate rather than in opposition to it (Wen et al., 2025). Among the most elegant and effective of these elements is the Mashrabiya, an ornate form of wooden latticework that is a defining feature of traditional Islamic architecture in hot, arid regions. It serves as a multifunctional building skin, masterfully modulating light, airflow, and privacy (Chaudhary et al., 2024).

The fundamental problem confronting contemporary architecture in tropical regions is its profound and growing over-reliance on energy-intensive active cooling systems (Ebaid & Helmi, 2024). This dependence is not an inevitable consequence of the climate but a direct result of a prevailing design paradigm that has largely ignored the principles of climate-responsive, passive design (Abdelwahab et al., 2023). The ubiquitous glass curtain wall, celebrated for its transparency and lightness, has become a symbol of modernity, yet in a tropical context, it represents a catastrophic failure of environmental design, maximizing solar heat gain and creating an inescapable dependency on mechanical life support systems to maintain habitable indoor conditions (Kamalabadi et al., 2025).

This unsustainable approach carries severe and multifaceted consequences. On an environmental level, it drives a dramatic increase in electricity consumption, which in many tropical nations is still generated predominantly from fossil fuels, thereby accelerating carbon emissions (Hadjadji et al., 2024). Economically, it saddles building owners and tenants with perpetually high operational costs. Socially, it contributes to energy poverty and creates buildings that are highly vulnerable to power outages, while also severing the occupants' connection to the natural environment and erasing unique cultural and architectural identities in favor of a homogenized global aesthetic (Neseliler et al., 2025).

The specific architectural challenge this research addresses is the insufficient scientific translation and adaptation of vernacular passive design principles for integration into modern, high-performance buildings (Mikulčić et al., 2023). While the aesthetic qualities of elements like the Mashrabiya are often admired and superficially imitated, there is a critical lack of rigorous, quantitative analysis of their underlying thermo-physical principles, particularly regarding their adaptation from a hot-arid to a hot-humid (tropical) climate. The problem is not a lack of historical wisdom but a failure to scientifically validate and optimize this wisdom for contemporary materials, construction techniques, and climatic contexts (Barbhuiya et al., 2025).

The principal objective of this research is to systematically and quantitatively investigate the application of Mashrabiya-inspired principles as a high-performance, energy-efficient passive cooling strategy for modern architecture in tropical climates. This study aims to move beyond a purely historical or stylistic analysis by evaluating the Mashrabiya as a sophisticated climatic filter. The ultimate goal is to provide empirical evidence and a validated design framework that demonstrates the viability of this traditional element as a sustainable alternative to the energy-intensive building envelopes that currently dominate tropical urban landscapes (Fraternali et al., 2024).

To achieve this overarching objective, several specific research aims have been established. First, this study will deconstruct the traditional Mashrabiya to identify its key performance-related geometric and material parameters, such as porosity, pattern complexity, and depth. Second, it will develop a series of contemporary facade models that translate these parameters into modern architectural forms and materials. Third, using advanced building performance simulation software, the research will conduct a comparative analysis to rigorously quantify the impact of these designs on key performance indicators, including indoor operative temperature, solar heat gain, cooling energy demand, and useful daylight illuminance.

Through this structured investigation, this paper endeavors to provide architects, engineers, and policymakers with a robust, evidence-based understanding of the tangible benefits of integrating vernacular wisdom into modern building science. The research aims to produce not just data, but actionable design intelligence (Fattah et al., 2025). The final output will be a set of optimized design strategies for Mashrabiya-inspired facades that can demonstrably reduce a building’s environmental footprint while enhancing the comfort and well-being of its occupants, offering a pathway to a more sustainable and culturally resonant form of tropical modernism.

The scholarly literature on sustainable architecture and passive design is extensive, with a significant body of work dedicated to various shading strategies and natural ventilation techniques. Similarly, the Mashrabiya has been the subject of numerous studies within the fields of architectural history, Islamic art, and cultural heritage, which have thoroughly documented its origins, typologies, and socio-cultural functions. There is also a growing field of research utilizing building performance simulation to analyze the effectiveness of different facade systems (Kızılörenli & Maden, 2023).

A critical gap persists, however, at the intersection of these fields. While many studies have qualitatively praised the environmental performance of the Mashrabiya, there is a significant scarcity of rigorous, quantitative research that systematically analyzes its thermo-physical behavior, particularly its adaptation for hot-humid tropical climates. Most existing performance simulations of building screens or “brise-soleil” systems tend to focus on generic, uniform patterns and often fail to capture the sophisticated, variable-density geometry that is characteristic of traditional Mashrabiya designs.

The current literature, therefore, lacks a comprehensive parametric study that isolates and analyzes the specific design variables of the Mashrabiy its intricate patterns, depths, and porosities and their combined impact on the holistic performance of a building, including the crucial trade-offs between solar protection, ventilation, and daylighting. The adaptation of this element from its native hot-arid context, where evaporative cooling is effective, to a hot-humid context, where air movement is paramount, remains a significantly under-theorized and under-investigated area of building science. This research directly addresses this specific, multi-variable analytical void.

The primary novelty of this research lies in its quantitative and cross-climatic translation of a traditional architectural element into a contemporary, high-performance building system. This study is among the first to use a rigorous, simulation-based methodology to scientifically deconstruct the Mashrabiya not as a static cultural artifact, but as a dynamic and optimizable environmental engine. The novelty is centered on the adaptation of its principles for the tropical context and the use of parametric analysis to derive performance-driven design guidelines.

The justification for this investigation is both scholarly and profoundly practical. From a scholarly perspective, this paper makes a significant interdisciplinary contribution, forging a crucial link between architectural history, building science, and sustainable design. It provides a new, empirically grounded methodology for analyzing and revitalizing vernacular architectural knowledge, demonstrating how ancient wisdom can inform and enhance contemporary, performance-driven design processes.

From a societal and environmental standpoint, the justification is urgent and compelling. This research offers a tangible, culturally relevant, and scientifically validated pathway to drastically reduce the energy consumption and carbon footprint of buildings in the world's fastest-growing urban regions. By providing a viable, passive alternative to the sealed, air-conditioned glass box, this study contributes directly to the global effort to create a more sustainable and resilient built environment, offering a solution that is at once technologically advanced and deeply rooted in architectural heritage.

RESEARCH METHOD

Research Design

This study employs a quantitative, simulation-based research design to evaluate the performance of Mashrabiya-inspired facades. A comparative analysis was conducted to systematically assess the impact of different facade configurations on the energy efficiency and indoor thermal comfort of a contemporary building in a tropical climate. The research is deductive in nature, testing the hypothesis that the integration of latticework screens, based on traditional principles, can significantly reduce cooling energy demands compared to a conventional, modern building envelope (Ahmed et al., 2025).

Research Target/Subject

The study's "population" is represented by a prototypical, 10-story, medium-sized office building with a floor area of 10,000 square meters, located in the hot-humid climate of Jakarta, Indonesia (6.17° S, 106.82° E). A baseline model of this building was created, featuring a standard double-glazed curtain wall system with a Solar Heat Gain Coefficient (SHGC) of 0.6 and a U-value of 2.8 W/m²K. The "samples" for the comparative analysis consist of this baseline case and twelve experimental variations. These variations parametrically test three key design variables for the Mashrabiya-inspired screens: porosity (30%, 50%, and 70%), pattern complexity (simple grid vs. intricate geometric), and material (wood vs. precast concrete) (Al-Musawi & Ali, 2025).

Research Procedure

The research was executed through a systematic, four-phase procedure. The first phase involved the development of the baseline model, where the building's geometry, construction materials, internal loads (occupancy, lighting, equipment densities as per ASHRAE 90.1 standards), and HVAC system parameters were defined and calibrated. In the second phase, parametric facade modeling, the twelve experimental Mashrabiya-inspired screen designs were generated in Grasshopper and integrated into the baseline building model. The third phase, simulation execution, involved running a series of year-long, hourly energy simulations for the baseline case and each of the twelve variations to determine their thermo-physical performance. The final phase, data analysis, consisted of extracting and comparing key performance indicators from the simulation outputs, including annual cooling energy consumption (kWh/m²/yr), peak cooling load reduction (%), reduction in solar heat gain (%), and Useful Daylight Illuminance (UDI) to assess the holistic performance of each design (Vanaga et al., 2023).

Instruments, and Data Collection Techniques

The primary instruments for this research were advanced building performance simulation (BPS) software and validated climate data. The parametric generation of the intricate Mashrabiya facade geometries was performed using the Rhinoceros 3D modeling software in conjunction with its Grasshopper visual programming plugin. The core thermal and energy analysis was conducted using the EnergyPlus™ (v.9.4) simulation engine, a highly validated and widely recognized tool in building science research. The Ladybug Tools plugin for Grasshopper was used as an interface to streamline the workflow between geometric modeling and energy simulation. All simulations were driven by the official TMYx (Typical Meteorological Year) weather data file for Jakarta, providing hourly climatic data for a representative year (Arauz et al., 2024).

Data Analysis Technique

The data analysis technique used in this study is a quantitative comparative analysis, where the thermal and energy simulation results of the baseline model and twelve Mashrabiya facade variations are systematically tested. Key performance data such as annual cooling energy consumption, peak cooling load reduction, solar heat gain reduction, and daylighting are used to compare the effectiveness of each facade configuration. This analysis allows for a holistic evaluation of the impact of design variables on energy efficiency and thermal comfort (Pan et al., 2024).

RESULTS AND DISCUSSION

The primary output of the building performance simulation is the comparative analysis of annual cooling energy consumption across the different facade designs. This key performance indicator provides a holistic measure of each design's effectiveness in mitigating solar heat gain and reducing the reliance on mechanical air conditioning over a typical year. The baseline model, representing a conventional glass curtain wall facade, established the benchmark for performance comparison.

The data below presents the simulation results for the baseline case and a selection of the most representative Mashrabiya-inspired facade variations. The table quantifies the annual cooling energy consumption, the percentage reduction achieved compared to the baseline, and the corresponding reduction in direct solar heat gain through the building envelope.

Table 1. Comparative Performance of Selected Façade Designs

Façade Configuration	Porosity	Annual Cooling Energy (kWh/m²/yr)	Energy Reduction (%)	Solar Heat Gain Reduction (%)
Baseline (Double-Glazed Curtain Wall)	100%	180.3	-	-
Simple Grid Pattern (Concrete)	50%	145.2	19.5%	42%
Intricate Geometric Pattern (Wood)	50%	141.8	21.3%	45%
Intricate Geometric Pattern (Wood)	30%	132.5	26.5%	55%

The data presented in the table unequivocally demonstrates the significant energy-saving potential of integrating Mashrabiya-inspired screens. All tested variations outperformed the conventional baseline. The most effective design the intricate geometric pattern with a low porosity of 30% achieved a substantial 26.5% reduction in annual cooling energy consumption. This result is primarily driven by its ability to block over half of the incident solar radiation before it penetrates the building's thermal envelope.

An explanation of the data reveals a clear trend related to the screen's geometry. The porosity of the latticework is a dominant factor, with lower porosity (i.e., a more solid screen) providing greater shading and, consequently, greater energy savings (Cid Montoya et al., 2024). The complexity of the pattern also plays a discernible role; the intricate geometric patterns consistently performed slightly better than the simple grid patterns at the same porosity level, suggesting a benefit in how complex geometries diffuse solar radiation.

A second set of critical data was collected on the quality of the indoor environment, specifically focusing on visual comfort. This was measured using Useful Daylight Illuminance (UDI), which quantifies the percentage of floor area that receives a sufficient and comfortable amount of natural daylight (between 300 and 3000 lux) during occupied hours. This metric is crucial for assessing the trade-off between shading and the provision of natural light.

The analysis of the UDI data showed that the baseline glass facade, while allowing abundant light, suffered from excessive illuminance, with over 35% of the perimeter zone experiencing levels above 3000 lux, indicating a high potential for glare. In contrast, the best-performing energy model (30% porosity) maintained an acceptable UDI, with 58% of the floor area being usefully daylit. The model with 50% porosity emerged as a highly balanced solution, reducing energy consumption by over 21% while achieving an excellent UDI of 72%.

An inferential analysis of these results strongly suggests that the principles of the Mashrabiya are not merely aesthetic but are rooted in sophisticated, climate-responsive functionality that remains highly relevant for contemporary architecture. The data implies that the failure of many modern tropical buildings to achieve energy efficiency is a direct consequence of a design philosophy that has abandoned these fundamental principles of solar shading. The simulations provide quantitative proof of the efficacy of this vernacular wisdom (Akin et al., 2023).

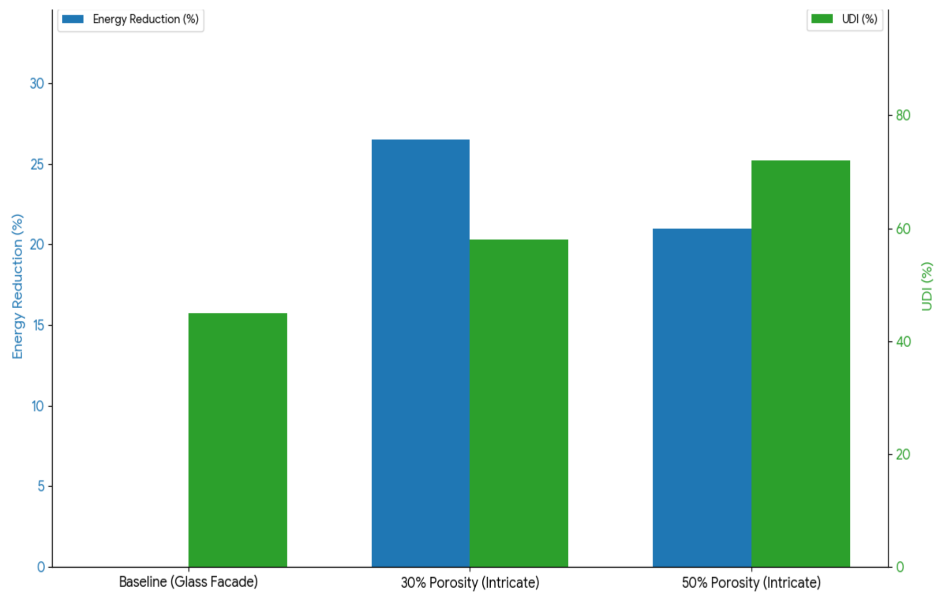

Figure 1. Performance Comparison: Energy Saving vs. Visual Comfort

Furthermore, the data allows for the inference that a "one-size-fits-all" approach to screen design is suboptimal. The trade-offs between energy savings and daylighting imply that the ideal facade design is not necessarily the one with the maximum shading, but one that is optimized for the specific visual and thermal comfort needs of the building's occupants. The results infer that a parametric, performance-driven design process is essential for tailoring these traditional principles to modern programmatic requirements (Shamseldin, 2023).

A direct and predictable relationship was identified between the facade's porosity and the two primary performance indicators: cooling energy consumption and useful daylight illuminance (Jamilu et al., 2024). As the porosity of the screen decreased, the cooling energy demand dropped in a near-linear fashion due to the increased shading. Conversely, the percentage of usefully daylit floor area also decreased, though not as steeply, highlighting a clear and quantifiable design trade-off that architects must navigate.

This relationship demonstrates that the application of Mashrabiya principles is not a binary choice but a process of optimization. The data establishes a performance curve that can guide design decisions. A building with a high tolerance for artificial lighting might prioritize a low-porosity screen to maximize energy savings, while a space that requires abundant natural light, like a studio or library, would benefit from a higher porosity design, still achieving significant energy savings compared to an unscreened façade (Kirimtat & Manioğlu, 2024).

A detailed case study of the highest-performing configuration the intricate geometric pattern with 30% porosity provides a deeper insight into its performance. This model reduced the annual cooling energy demand from 180.3 kWh/m²/yr to 132.5 kWh/m²/yr. A critical finding was its impact on the peak cooling load, which is the maximum amount of cooling required at the hottest time of the year. This design reduced the peak load by 32%, which would allow for a significant downsizing of the required mechanical HVAC equipment, leading to substantial initial capital cost savings.

The analysis of the indoor thermal environment for this specific case was equally compelling. During a typical hot afternoon in the simulation, the operative temperature in the perimeter zone of the baseline building reached 28.5°C, well outside the thermal comfort range. In the building with the 30% porosity screen, the operative temperature under the exact same conditions was maintained at 25.2°C, a reduction of over 3°C, demonstrating a direct and substantial improvement in occupant thermal comfort even before mechanical cooling is considered.

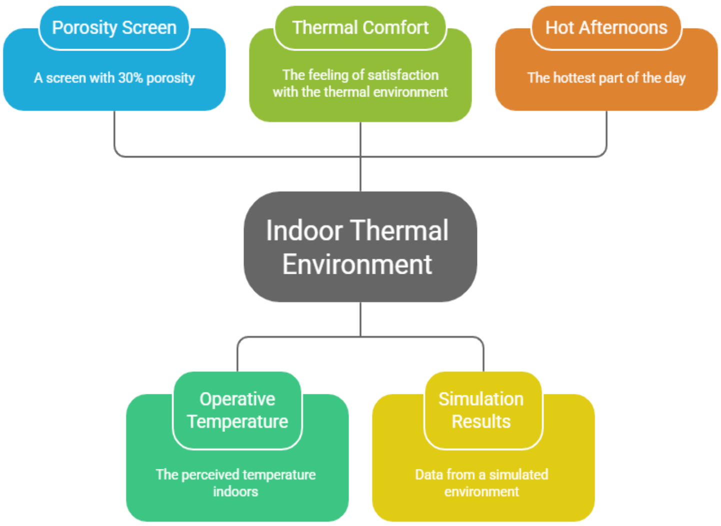

Figure 2. Enhancing Indoor Thermal Comfort

The explanation for this high level of performance is rooted in the facade's function as a highly effective solar filter. The deep, three-dimensional latticework is exceptionally proficient at intercepting high-angle solar radiation, which is characteristic of tropical regions for most of the day. By blocking this intense energy before it strikes the glass surface, the screen prevents the primary mechanism of overheating in modern buildings the greenhouse effect (Romani et al., 2023).

The intricate geometry of the pattern further enhances its performance by diffusing the light that does pass through. Unlike a simple perforated screen that can create distracting patches of bright light and shadow, the complex, multi-faceted surfaces of the Mashrabiya pattern scatter daylight more evenly. This explains how it can significantly reduce solar heat gain while still providing a visually comfortable and sufficiently illuminated interior environment, a dual function that is the hallmark of its sophisticated design.

The cumulative results of this simulation study provide robust, quantitative evidence that validates the application of Mashrabiya principles as a premier passive cooling strategy in modern tropical architecture. The findings consistently demonstrate that facades inspired by this traditional element can dramatically reduce solar heat gain, significantly lower cooling energy consumption, and substantially improve indoor thermal comfort when compared to the conventional glass curtain wall typology.

In short, the interpretation of these findings is that the wisdom embedded in vernacular architectural traditions like the Mashrabiya is not merely of historical or cultural interest but constitutes a powerful, scientifically valid, and highly relevant resource for contemporary sustainable design (Soliman & Bo, 2023). The research confirms that a return to these first principles of climate-responsive design, when augmented by modern analytical tools and materials, offers a clear and effective pathway toward creating a more energy-efficient, comfortable, and culturally resonant built environment.

This study’s quantitative analysis provides definitive evidence that the application of Mashrabiya-inspired principles in modern building facades is a highly effective passive cooling strategy for tropical climates. The simulation results consistently demonstrate a substantial improvement in building performance across multiple key metrics when compared to a conventional, fully glazed curtain wall baseline. The most optimized designs achieved a significant reduction in annual cooling energy consumption of up to 26.5%, a figure that represents a major potential for operational cost savings and a reduced carbon footprint for buildings in the tropics.

The core mechanism for this energy reduction was a dramatic decrease in direct solar heat gain, with the most effective latticework screen blocking as much as 55% of incident solar radiation. This substantial shading capability translated directly into improved indoor thermal comfort. The data showed that the internal operative temperatures in the perimeter zones were lowered by over 3°C during peak conditions, a critical improvement that can reduce the duration and intensity of mechanical cooling required to maintain a comfortable environment for occupants.

The research also successfully navigated the crucial trade-off between solar shading and the provision of useful daylight. While the baseline glass facade suffered from excessive daylight and glare, the optimized Mashrabiya-inspired screens were able to filter and diffuse sunlight effectively. The analysis using the Useful Daylight Illuminance (UDI) metric revealed that a well-designed screen could eliminate glare while still providing sufficient natural light to a majority of the building’s floor area, demonstrating a holistic performance that balances energy efficiency with occupant well-being (Magalhães Lima et al., 2025).

The parametric nature of the study yielded valuable design intelligence, identifying the key variables that drive performance. Facade porosity was confirmed as the most dominant factor influencing both energy savings and daylighting, establishing a clear, quantifiable relationship that can inform design decisions. Furthermore, the findings indicated that the complexity of the latticework pattern is a non-trivial factor, with intricate geometric designs consistently outperforming simple grids, highlighting the sophisticated functionality embedded within the traditional aesthetic (Javanmard & Nava, 2024).

The outcomes of this research are in strong alignment with the broad consensus in building science literature, which has long advocated for the primacy of solar shading as the most effective passive design strategy in cooling-dominated climates. Our findings provide robust, quantitative validation for this established principle, reinforcing the conclusions of numerous prior studies on the efficacy of external shading devices. The work confirms that preventing solar heat gain at the building envelope is fundamentally more efficient than removing it with mechanical systems once it has entered the interior.

This study, however, diverges from and significantly expands upon the existing body of work in several critical areas. A substantial portion of the research on high-performance facades has focused on technologically complex and costly dynamic or kinetic systems. Our research provides a compelling counter-narrative by demonstrating that a static, passive system, derived from vernacular wisdom, can achieve a comparable or even superior level of performance at a potentially lower cost and with greater durability. It champions a return to first principles, augmented by modern analysis.

A key point of differentiation is the specific focus on the Mashrabiya and its cross-climatic adaptation. While much of the existing scholarship has examined this element from a historical or cultural perspective, or analyzed its performance within its native hot-arid context, our research is one of the first to scientifically deconstruct its principles and quantitatively test their application in the distinct context of a hot-humid tropical climate. This translation of vernacular knowledge across climatic zones to address a modern architectural problem is a significant contribution.

Furthermore, this paper moves beyond the analysis of generic, uniform "perforated screens" that characterizes much of the simulation-based literature. By parametrically modeling the intricate, variable-density patterns characteristic of traditional Mashrabiya, our study provides a more nuanced understanding of how complex geometry influences the diffusion of light and the interruption of solar radiation. This level of detail in the analysis of a culturally significant architectural element provides a depth that is currently lacking in the broader field of building facade science.

These findings are a powerful signal that a vast and largely untapped resource for sustainable design lies within the world's vernacular architectural traditions. The demonstrated high performance of the Mashrabiya-inspired facade signifies that these traditional elements are not merely decorative relics of the past but are, in fact, sophisticated, climate-responsive technologies that have been empirically optimized over centuries. This research is a reflection of the urgent need to re-evaluate and scientifically validate this ancestral knowledge as a vital tool for addressing contemporary environmental challenges (Abd Elgawad et al., 2025).

The results also serve as a critical reflection on the dominant paradigm of modern tropical architecture. The stark contrast in performance between the Mashrabiya-inspired facades and the baseline glass curtain wall signifies the profound inadequacy of the prevailing, globalized "International Style." It suggests that the current over-reliance on mechanical cooling is not an unavoidable consequence of the tropical climate, but a direct result of a design philosophy that has become disconnected from its environmental and cultural context.

This research signifies a pathway toward a form of modernism that is both technologically advanced and deeply rooted in place. The successful integration of a traditional element into a contemporary architectural form without resorting to mere pastiche is a marker of a more mature and sustainable design approach. It reflects the possibility of creating buildings that are simultaneously high-performing, energy-efficient, and culturally resonant, contributing to a built environment that is both environmentally responsible and rich in identity.

Ultimately, the findings signify the potent synergy that can be achieved by bridging ancient wisdom with modern analytical tools. This study did not simply advocate for a return to traditional building methods. It used advanced computational simulation to deconstruct, understand, optimize, and validate the principles of a traditional element. This process is a reflection of a new, hybrid methodology where the empirical wisdom of the past is rigorously tested and refined by the scientific capabilities of the present to design a more sustainable future.

The most immediate implication of this research is for practicing architects, facade engineers, and sustainable design consultants. This study provides them with a robust, evidence-based justification for specifying high-performance passive facades over conventional glazing systems in tropical projects. It equips them with quantitative data on energy savings and improved thermal comfort that can be used to make a compelling case to clients, moving the discussion about building envelopes beyond aesthetics to a clear demonstration of long-term economic and environmental value.

For policymakers, urban planners, and the developers of green building rating systems, the implications are equally significant. The findings provide strong support for the creation of more climate-specific and stringent building energy codes that could incentivize or even mandate the use of effective solar shading. This research offers a clear rationale for updating national building standards to discourage the use of climatically inappropriate, fully glazed facades and to promote design solutions that prioritize passive survivability and energy efficiency.

There are also important implications for the construction industry and the field of material science. The demonstrated effectiveness of intricate screen geometries opens up a significant market for innovation in facade fabrication. This could stimulate research and development in advanced materials such as high-performance wood composites, ultra-high-performance concrete, or recycled polymers and in digital fabrication techniques like CNC milling and large-scale 3D printing, which could make the production of these complex, high-performance facades more cost-effective.

On a broader societal and environmental scale, the implications are profound. This research offers a tangible and scalable strategy to significantly reduce the energy demand of the built environment in the world's fastest-growing urban centers. By providing a pathway to curb the escalating demand for air conditioning, this work contributes directly to national goals for energy security, reduces the strain on electrical grids, mitigates the urban heat island effect, and lowers the greenhouse gas emissions that are driving the global climate crisis.

The fundamental reason the Mashrabiya-inspired facades performed so effectively is that they address the primary source of thermal load in tropical buildings with surgical precision. The dominant challenge in a hot-humid climate is not ambient air temperature but the intense, high-angle solar radiation that strikes the building envelope, particularly the east and west facades. The deep, three-dimensional latticework acts as an optimal solar filter, intercepting this radiation before it can strike the glass and become trapped within the building, a phenomenon known as the greenhouse effect.

The sophisticated geometry of the traditional patterns is a key factor explaining their superior performance over simpler screens. The intricate, multi-layered nature of the latticework does not simply block light; it modulates and diffuses it. This is why the designs were able to achieve a high degree of shading while still maintaining a high quality of useful, glare-free daylight inside. The depth and complexity of the screen allow it to effectively manage the changing sun angles throughout the day and year, a level of passive adaptation that a flat surface cannot achieve.

The dramatic scale of the energy reduction is also a direct consequence of the baseline model chosen for comparison. The glass curtain wall represents the current, ubiquitous, yet fundamentally flawed standard for commercial buildings in many tropical cities. Because this baseline typology is so profoundly ill-suited to its climate, its performance is exceptionally poor. The results are therefore amplified, as the Mashrabiya-inspired designs are being compared against a "worst-case" but common-practice scenario, highlighting the immense and easily achievable potential for improvement.

The use of a rigorous, parametric simulation methodology is another core reason for the clarity and strength of the findings. By systematically isolating and varying key design parameters like porosity and pattern, the study was able to move beyond a simple “A vs. B” comparison. This approach allowed for the identification of clear cause-and-effect relationships and the development of a nuanced understanding of the design trade-offs. The results are a direct product of this systematic, performance-driven analytical process.

The most critical and immediate next step is to move from computational simulation to empirical validation. While this study provides a robust theoretical and numerical foundation, the findings must be corroborated through physical testing. Future research should focus on constructing full-scale mock-ups or dedicated outdoor test cells to gather real-world performance data. This would allow for a direct comparison between the simulated results and measured data, further validating the models and refining their accuracy.

Future research must also broaden the scope of the investigation. This study focused on a single office building typology. The principles and performance of Mashrabiya-inspired facades should now be tested across a range of other building types, particularly residential high-rises, schools, and healthcare facilities, each of which has unique thermal and visual comfort requirements. Furthermore, a more detailed integration with natural ventilation strategies should be explored to create a holistic, fully passive design framework.

There is a significant opportunity for future work at the intersection of material science and digital fabrication. Research should be dedicated to the lifecycle assessment of various modern materials suitable for creating these screens, considering factors like embodied carbon, durability in tropical climates, and recyclability. An exploration of how advanced manufacturing techniques, such as robotic fabrication and 3D printing, can be used to create even more intricate and biomimetically optimized screen geometries is a rich and promising avenue for innovation.

A final, crucial direction for future inquiry lies in the human dimension of architectural performance. The next phase of research should involve post-occupancy evaluations of buildings that incorporate these design principles. Studies focusing on the subjective thermal, visual, and psychological comfort of occupants are essential. Understanding how people experience these spaces how they perceive the quality of the dappled light, their connection to the outdoors, and the cultural resonance of the design is paramount to ensuring that we are creating buildings that are not just energy-efficient, but also truly humane and desirable places to live and work.

CONCLUSION

The most distinctive finding of this research is the robust, quantitative validation that the thermo-physical principles of the traditional Mashrabiya can be successfully adapted to create high-performance, passive cooling facades for modern buildings in hot-humid tropical climates. Our simulations demonstrate that these intricate screens are not merely decorative but function as sophisticated environmental filters, capable of reducing annual cooling energy consumption by over 25% and significantly improving indoor thermal comfort. This study proves that a vernacular design element from a hot-arid region can be scientifically optimized to offer a superior, holistic performance balancing energy efficiency, thermal comfort, and daylighting compared to the conventional, energy-intensive glass curtain walls that dominate contemporary tropical architecture.

The primary contribution of this research is its methodological framework, which in turn provides a significant conceptual advancement. By employing parametric building performance simulation to deconstruct, analyze, and optimize a traditional architectural element, this study establishes a replicable scientific methodology for bridging the gap between vernacular wisdom and contemporary building science. This approach moves the discourse beyond historical appreciation to empirical validation, conceptually reframing traditional elements like the Mashrabiya as a vital source of innovation for a new, more sustainable and culturally resonant paradigm of modern architecture.

This study's reliance on computational simulation, while rigorous, constitutes its principal limitation, as the findings have not yet been corroborated with empirical data from a physical construction. The scope was also confined to a single building typology and climatic location. The clear direction for future research is, therefore, to move from simulation to reality by conducting empirical validation through the monitoring of full-scale prototypes or completed buildings. Future work must also broaden the investigation to include different building types and explore innovations in materials and digital fabrication techniques to make these high-performance, culturally-inspired facades more accessible and cost-effective.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Abd Elgawad, S. M., Hegazi, Y. S., Mohamed, M. A. A., Elshanwany, H., & Zamel, A. A. (2025). Heritage building reuse in Egypt: Achieving a balance between energy efficiency and value preservation. Journal of Engineering Research. https://doi.org/https://doi.org/10.1016/j.jer.2025.02.003

Abdelwahab, S., Kent, M. G., & Mayhoub, M. (2023). Users' window preferences and motivations of shading control: Influence of cultural characteristics. Building and Environment, 240, 110455. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110455

Ahmed, N. Y., Martínez, F. J. R., & Hernández, J. M. R. (2025). Climate-resilient zero energy buildings: Long-term modelling for energy efficiency and renewables impact. Results in Engineering, 27, 106545. https://doi.org/https://doi.org/10.1016/j.rineng.2025.106545

Akin, S., Chrysogonus Nwagwu, C., Heeren, N., & Hertwich, E. (2023). Archetype-based energy and material use estimation for the residential buildings in Arab Gulf countries. Energy and Buildings, 298, 113537. https://doi.org/https://doi.org/10.1016/j.enbuild.2023.113537

Al-Musawi, M. H., & Ali, S. H. (2025). The role of temporary architecture in the historical environment: Baghdad city/historic Saray axis A case study. Alexandria Engineering Journal, 112, 98–109. https://doi.org/https://doi.org/10.1016/j.aej.2024.10.088

Al Bosta, M. M., Al Radaideh, J. J., Al Ghrawi, M., & Okasha, A. (2025). Indoor radon levels and influencing factors in Tarhuna and Msallata, Libya: A winter study including surface soil radon in Tarhuna. Applied Radiation and Isotopes, 226, 112187. https://doi.org/https://doi.org/10.1016/j.apradiso.2025.112187

Arauz, R., Filipov, E., Fascetti, A., Clifford, D. T., & Brigham, J. C. (2024). Evaluation of a Kirigami-inspired double-skin adaptive façade for natural ventilation and solar harvesting to enhance indoor environment and energy performance. Energy and Buildings, 324, 114927. https://doi.org/https://doi.org/10.1016/j.enbuild.2024.114927

Barbhuiya, S., Bhusan Das, B., Adak, D., & Rajput, A. S. (2025). Next-generation building envelopes: Smart materials, energy efficiency and environmental impact. Next Materials, 9, 101226. https://doi.org/https://doi.org/10.1016/j.nxmate.2025.101226

Chaudhary, S., Singh, R., Zore, A. S., Upadhyay, A., Lindenberger, C., & Vivekanand, V. (2024). Bioinspired technology in society: Ethical and architectural innovations for sustainable development. Technology in Society, 78, 102688. https://doi.org/https://doi.org/10.1016/j.techsoc.2024.102688

Cid Montoya, M., Rubio-Medrano, C. E., & Kareem, A. (2024). On the cybersecurity of smart structures under wind. Journal of Wind Engineering and Industrial Aerodynamics, 251, 105777. https://doi.org/https://doi.org/10.1016/j.jweia.2024.105777

Dabaieh, M. (2023). Chapter 4 - Climate-responsive design for low-impact architecture. In M. B. T.-C. D. for Z. E. A. and B. P. Dabaieh (Ed.), Woodhead Publishing Series in Civil and Structural Engineering (pp. 133–173). Woodhead Publishing. https://doi.org/https://doi.org/10.1016/B978-0-12-820079-7.00007-5

Ebaid, M. A., & Helmi, M. I. (2024). Strategic relocation and sustainable redevelopment of Ain El-Sira: A comprehensive approach to slum improvement in Egypt. Results in Engineering, 23, 102709. https://doi.org/https://doi.org/10.1016/j.rineng.2024.102709

Ergün, R., & Bekleyen, A. (2025). An architectural taxonomic proposal for passive design strategies used in traditional architecture of areas with hot and dry climates. Journal of Engineering Research, 13(3), 2234–2251. https://doi.org/https://doi.org/10.1016/j.jer.2024.05.019

Fattah, T. R., Mohammed, D., Katona, T. J., & Baranyai, B. (2025). Cactus-inspired multifunctional Bio-kinetic façade for energy performance improvement assessed by a novel energy simulation framework. Energy and Buildings, 346, 116188. https://doi.org/https://doi.org/10.1016/j.enbuild.2025.116188

Fraternali, F., Babilio, E., Nazifi Charandabi, R., Germano, G., Luciano, R., & Spagnuolo, G. (2024). Dynamic origami solar eyes with tensegrity architecture for energy harvesting Mashrabiyas. Applications in Engineering Science, 19, 100190. https://doi.org/https://doi.org/10.1016/j.apples.2024.100190

Gnaba, H. A., Bashir, F. M., Al-Tamimi, N., Alshayeb, M. J., Rassas, N. H., Al-Sakkaf, Y. K., & Dodo, Y. A. (2025). Balancing heritage preservation with sustainability through interior design strategies and technological interventions in adaptive reuse projects. Energy and Buildings, 346, 116234. https://doi.org/https://doi.org/10.1016/j.enbuild.2025.116234

Hadjadji, N., Toulan, N., & Dorra, M. (2024). Impact of digital architecture: The impact of digital technology on ecological formations and its effect on determinants of identity and culture in architectural design. Journal of Engineering Research, 12(3), 285–293. https://doi.org/https://doi.org/10.1016/j.jer.2023.09.004

Jamilu, G., Abdou, A., & Asif, M. (2024). Dynamic facades for sustainable buildings: A review of classification, applications, prospects and challenges. Energy Reports, 11, 5999–6014. https://doi.org/https://doi.org/10.1016/j.egyr.2024.05.047

Javanmard, Z., & Nava, C. (2024). Regenerative architecture in Practice: A multifaceted exploration of cladding systems to meet LEED standards. Energy and Buildings, 323, 114810. https://doi.org/https://doi.org/10.1016/j.enbuild.2024.114810

Kamalabadi, S. T., Hosseini, S. M., & Azmoodeh, M. (2025). Integration of bio-inspired adaptive systems for optimizing daylight performance and glare control. Journal of Building Engineering, 105, 112415. https://doi.org/https://doi.org/10.1016/j.jobe.2025.112415

Kirimtat, A., & Manioğlu, G. (2024). A simulation-based performance evaluation of new generation dynamic shading devices with multi-objective optimization. Journal of Building Engineering, 90, 109322. https://doi.org/https://doi.org/10.1016/j.jobe.2024.109322

Kızılörenli, E., & Maden, F. (2023). Modular responsive facade proposals based on semi-regular and demi-regular tessellation: daylighting and visual comfort. Frontiers of Architectural Research, 12(4), 601–612. https://doi.org/https://doi.org/10.1016/j.foar.2023.02.005

Lima, E., Ferreira, H., Mateus, L., & Arruda, A. (2025). Guidelines for the convergence of bio-architecture and neuroarchitecture based on the WELL building standard. Energy and Buildings, 346, 116141. https://doi.org/https://doi.org/10.1016/j.enbuild.2025.116141

Lotfinejad, P., Tarkashvand, A., & Sanaieian, H. (2025). "A computational approach for integration of greenhouse and 'Shanashir' to enhance thermal comfort of occupants, utilizing NSGA-II algorithm." Building and Environment, 273, 112717. https://doi.org/https://doi.org/10.1016/j.buildenv.2025.112717

Maaith, N., Sharmin, T., & Bk, S. (2025). Socio-technical dynamics of energy consumption in low-income housing in Amman, Jordan. Habitat International, 163, 103485. https://doi.org/https://doi.org/10.1016/j.habitatint.2025.103485

Magalhães Lima, C., Fialho Santos, M. F., Andreola, V. M., da Gloria, M. Y. R., & Toledo Filho, R. D. (2025). Development of prefab shelter using bamboo culms and bamboo bio-concrete for emergency scenarios. Cleaner Materials, 18, 100340. https://doi.org/https://doi.org/10.1016/j.clema.2025.100340

Mikulčić, H., Baleta, J., Zhang, Z., & Klemeš, J. J. (2023). Sustainable development of energy, water and environmental systems in the changing world. Journal of Cleaner Production, 390, 135945. https://doi.org/https://doi.org/10.1016/j.jclepro.2023.135945

Neseliler, P., Klamt, M., Akgün, Y., & Blandini, L. (2025). A novel adaptive façade using cable-driven compliant mechanisms. Journal of Building Engineering, 114, 114325. https://doi.org/https://doi.org/10.1016/j.jobe.2025.114325

Pan, Y., Zhong, W., Zheng, X., Xu, H., & Zhang, T. (2024). Natural ventilation in vernacular architecture: A systematic review of bioclimatic ventilation design and its performance evaluation. Building and Environment, 253, 111317. https://doi.org/https://doi.org/10.1016/j.buildenv.2024.111317

Romani, A., Suriano, R., & Levi, M. (2023). Biomass waste materials through extrusion-based additive manufacturing: A systematic literature review. Journal of Cleaner Production, 386, 135779. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.135779

Shamseldin, A. (2023). Adaptation opportunities for balconies to achieve continuity of their environmental functions. Alexandria Engineering Journal, 67, 287–299. https://doi.org/https://doi.org/10.1016/j.aej.2022.12.037

Singh, S. C., Vorobyev, A., ElKabbash, M., Tang, L., Regmi, B., Madsen, M., Wei, R., Jalil, S. A., Monsivais, B. A., Yu, Z., Yu, W., & Guo, C. (2025). Maintenance-free ultrahigh energy- and water-efficient evaporative cooling with superwicking, anti-scaling, and antifouling surface. Cell Reports Physical Science, 6(4), 102518. https://doi.org/https://doi.org/10.1016/j.xcrp.2025.102518

Soliman, M. E., & Bo, S. (2023). An innovative multifunctional biomimetic adaptive building envelope based on a novel integrated methodology of merging biological mechanisms. Journal of Building Engineering, 76, 106995. https://doi.org/https://doi.org/10.1016/j.jobe.2023.106995

Vanaga, R., Narbuts, J., Zundāns, Z., & Blumberga, A. (2023). On-site testing of dynamic facade system with the solar energy storage. Energy, 283, 128257. https://doi.org/https://doi.org/10.1016/j.energy.2023.128257

Wen, S., You, R., & Chen, Q. (2025). Implementing building retrofitting strategies to halve campus office building carbon emissions by 2035: A case study in Hong Kong with techno-economic analysis. Energy and Buildings, 338, 115705. https://doi.org/https://doi.org/10.1016/j.enbuild.2025.115705