

Integrating Technology and Heritage Design for Climate Resilient Courtyard House in Arid Region

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Abstract

This research has investigated the sustainability and climate resilience of courtyard houses of adobe architecture in the UAE. It analyzed design effectiveness in terms of power consumption, CO₂ emissions, thermal comfort, and daylight use, employing simulations to assess building structures and construction systems. Adopting a three-phase mixed-methods approach, the study began with a literature review on courtyard house design, construction, and environmental performance, emphasizing sustainable design and passive ventilation. The second phase involved a case study of a UAE courtyard house (Al Midfa), including site visits, interviews, and energy consumption and CO₂ emission data collection. The final phase used building energy simulation software to model energy performance and evaluate passive ventilation's role in reducing energy consumption and CO₂ emissions, with simulation results validated against real-world data. Advanced Sefaira simulations with the Energy Plus Engine identified one out of seven modified models (M5) as exceptionally thermally efficient, influencing the architectural design of the Al Midfa house. To transform the Al Midfa house into a sustainable climate-resistant structure, the research suggested retrofitting with new glazing and insulation on the inside of external walls and on the roof surface at a combined U-value of 0.4 W/m² to enhance energy efficiency without altering the exterior. A notable innovation was the use of injected cellulose insulation in wall systems, combining efficient insulation with architectural aesthetics, signifying a shift towards energy-efficient interior modifications. The study's findings contribute to the evolution of traditional house designs toward climate change resilience and a sustainable future.

Keywords: Adobe Architecture; CO₂ Emission; Energy Consumption; Thermal Condition; Traditional Construction; Courtyard House in Hot & Dry Climate.

1. Introduction

This study emerges as a scholarly response to the escalating concerns over climate change and the resultant impact of constructed environments on greenhouse gas emissions, precipitating a heightened emphasis on environmentally sustainable design and energy preservation approaches. The principle of climate resilience underpins the development of architectural structures and infrastructural systems robust enough to endure climate change impacts [1]. While traditional courtyard dwellings are architecturally tailored to the specific climatic challenges of their locations, the integration of climate resilience with these vernacular structures has become a focal area within architectural and environmental design scholarship. Recent trends indicate an increasing inclination to merge these two domains, aiming to establish structures that are both environmentally sustainable and resilient, aligning seamlessly with local ecological contexts.

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The standard traditional courtyard house, especially when constructed using Adobe technology, is characterized by the employment of earthen materials and has historically represented a paradigm of sustainable architecture. In the contemporary context of climate change, such courtyard architectures have been recognized for their inherent sustainability and passive design principles. The thermal mass attributes of adobe materials in these structures significantly contribute to their energy efficiency. Adobe walls, with their capacity to absorb, retain, and subsequently dissipate heat, play a pivotal role in stabilizing indoor temperatures, thereby diminishing the dependence on mechanized temperature regulation systems. This contributes to a reduction in energy consumption while simultaneously elevating the thermal comfort of the inhabitants [2].

Adobe technology not only lends a contextually harmonious and aesthetically pleasing aspect to courtyard houses but also amplifies their eco-friendly characteristics. Utilizing local natural resources like clay, sand, and straw, adobe construction minimizes the environmental impact and carbon emissions associated with building processes [3]. In traditional courtyard houses, the fusion of natural adobe materials is always linked with aesthetic considerations. The case study of Al Midfa House demonstrated how the use of earthen materials fosters a seamless blend between the built environment and its natural surroundings, preserving the cultural and architectural essence of traditional courtyard houses in the UAE and similar arid regions. However, integrating such traditional structures into contemporary urban settings presents considerable challenges.

In the context of the urban setting of courtyard houses, Baiz & Fathulla [4] delved into the incorporation of courtyard housing in Baghdad's urban areas, underscoring the climatic advantages of courtyards, such as enhanced natural ventilation and thermal comfort, and proposing them as sustainable urban housing solutions. Considering the courtyard as a vital outer space in traditional houses of the hot and arid climate of Amiriparyan & Kiani [5], they examined the central courtyard's pivotal role in traditional Iranian houses, particularly in historic cities like Isfahan, Shiraz, and Yazd. The study emphasized the courtyard's importance in both urban planning and intra-house spatial organization, highlighting its contribution to creating cohesive and continuous living spaces, thereby shaping the architectural narrative of 17th- to 19th-century Iranian homes. Regarding the interrelation between design and orientation of courtyards, additional studies have scrutinized the impact of courtyard spatial patterns on microclimate conditions in regions experiencing hot summers and cold winters. These investigations have illuminated the pivotal role of courtyard design and orientation in fostering sustainable and energy-efficient environments [6–8].

Subsequently, continuing on the influence of shape geometry and spatial arrangement over courtyard efficiency, Soflaei et al. [9] have explored how courtyard design and layout impact the microclimate and sustainability of traditional houses in Iran's hot-arid region. The study assessed courtyards' physical and environmental characteristics that enhance energy efficiency, examining six houses in Kerman and Isfahan. The study, using the Koppen climate classification, developed design guidelines and formulas based on courtyard dimensions and proportions, offering a blueprint for sustainable building designs applicable in similar climates. Similarly, another study by Sun et al. [10] investigated the role of enclosed patios in climate adaptation and microclimate regulation in buildings. Their research developed design guidelines to improve thermal comfort, utilizing both qualitative and quantitative methods. The study identified crucial design aspects, such as maintaining proportional dimensions, increasing window numbers, and adding semi-open spaces. Notably, optimal designs for four-sided and three-sided patios were determined, enhancing both the thermal efficiency and aesthetic appeal of these spaces.

In addition, Soflaei et al. [11] and Benoudjafer [12] explored the synergy between natural energy, vernacular architecture, and adobe technology, elucidating the thermal comfort and energy efficiency afforded by adobe in hot arid climates' courtyard houses. Concurrently, Nguyen & Reiter [13] examined passive and low-energy cooling strategies suitable for hot, humid regions, emphasizing Adobe technology's contribution to enhancing thermal performance in courtyard houses. Kamal & Rahman [14] conducted a comprehensive study on the historical, current, and future roles of earth architecture, particularly adobe technology, in courtyard houses. They emphasized the sustainability and energy efficiency prospects of these materials. Investigations into the influence of courtyard geometry on summer microclimate in traditional buildings underscored the imperative of optimizing courtyard dimensions to enhance thermal mitigation capabilities [15, 16]. Additionally, Vellinga [17] offered a historical perspective on courtyard housing, discussing the potential limitations of passive thermal comfort and ventilation in these traditional structures.

The discussion above can be summarized as that the use of adobe technology, along with the implementation of passive ventilation techniques, courtyard spatial morphology, and microclimate considerations, can greatly improve thermal comfort in hot and arid climates. Studies of traditional adobe houses demonstrate the effectiveness of these traditional methods in achieving energy-efficient and sustainable house design. By reviving and incorporating these techniques into modern architecture, we can create comfortable living spaces that minimize the use of energy and promote sustainable living.

In addition to the above research, many simulation experiments and studies have been conducted to measure the design of traditional adobe courtyards towards sustainability, thermal effectiveness, and hybrid living space. Al-Hafith et al. [18] evaluated DesignBuilder's ability to simulate courtyard thermal behavior, uncovering significant discrepancies

between its simulations and real-world measurements. The study found DesignBuilder's modeling often inaccurately predicts heat gain and air temperature due to challenges in replicating the effects of heat radiation, natural ventilation, and shading. This highlights the complexity of accurately simulating courtyard thermal dynamics in software like DesignBuilder. Besides, Abdulkareem [19] investigated the high energy consumption of mechanical air-cooling in the Middle East and proposed the use of traditional architecture for energy efficiency. The study emphasized optimizing courtyard microclimates to enhance thermal comfort and advocated integrating traditional methods with renewable energy strategies for sustainable architecture, moving beyond superficial revivals to a holistic approach combining historical and modern practices.

Saadatjoo et al. [20] have analyzed the microclimatic effects and ventilation in semi-outdoor spaces using computational fluid dynamics (CFD). Their study of various apartment buildings with differing terrace widths and porosity levels showed that porosity increased internal air velocity, although not significantly. Double-sided models were found to be more effective than single-sided or lateral ones in air regulation, with a unique correlation observed between terrace and courtyard air velocities. This suggests double-sided models as balanced designs for optimal airflow. Continuing with experimentation through simulation modeling, Han et al. [21] have explored how different spatial layouts affect courtyard microclimates using field measurements and ENVI-met simulations. Key factors like air temperature, solar radiation, airflow, and humidity were examined. The study found that ground coverings greatly influence temperature and humidity, recommending a specific mix of lawn, marble, water, and trees to optimize courtyard conditions, especially in library courtyards. The study recommends a combination of lawn, marble, water surfaces, and landscape tree coverage in proportions of 25%, 25%, 50%, and 75%, respectively, as optimal design elements for improving the microclimate conditions in the inner courtyards of libraries.

In the context of the courtyard's thermal comfort, Ibrahim et al. [22] have studied optimizing courtyard blocks for thermal moderation in various climates, particularly focusing on Cairo's hot-arid environment. The study used Grasshopper and Ladybug tools in Rhino 3D to analyze design parameters like cooling loads and the Universal Thermal Climate Index. It found that minimizing interspaces in courtyard blocks across three different extension types was most effective for thermal efficiency, offering crucial insights for urban design in hot-arid climates. Similarly, another study through simulation has also explored the issues of thermal comfort and daylight provision and suggested moderation in courtyard design. Besides, Guedouh et al. [23] have investigated the balance between thermal and luminous environments in courtyard buildings in hot, arid regions. Through on-site measurements and DesignBuilder simulations, they analyzed different building morphologies. The study found that while courtyards excel at daylighting, their thermal regulation is less effective. This research helps identify optimal designs for enhancing both daylight and thermal efficiency in challenging hot and arid climates. Continuing with the assessment of thermal comfort of courtyards, another study has presented the concept of ATC (adaptive thermal comfort) in courtyard houses. The study investigated the effect of seasonal occupant movement on thermal comfort in courtyard houses. Their study highlighted that traditional behaviors significantly boost Adaptive Thermal Comfort (ATC), especially during winter in northern courtyard zones, where ATC can increase by 10.1 to 23.7%. This research emphasizes the value of vernacular strategies in enhancing indoor thermal comfort [24]. Furthermore, the Courtyard Thermal Usability Index (CTUI) was developed to improve the thermal efficiency of courtyards in hot climates, focusing on Baghdad. This index calculates the percentage of comfortable hours relative to total use. Analyzing 360 courtyards with Envi-met 4.2, the study found that courtyards in Iraq offer only 38% comfortable hours annually. Key factors affecting thermal comfort include the courtyard's width-to-height ratio and the Mean Radiant Temperature (MRT), providing insights for designing efficient courtyards in hot climates [25].

Regarding the interrelationship between the thermal comfort of a courtyard and its design in an urban context, Taleb & Abumoeilak [26] have conducted a study to optimize courtyard designs for thermal performance in urban communities in hot arid regions, focusing on Dubai's sustainable city residential cluster. Utilizing ENVI-met software, they simulated and compared four courtyard layouts: U-shaped, linear, central buildings with square courtyards, and U-shaped buildings with square courtyards. The simulations evaluated outdoor thermal behavior, wind speed, and humidity distribution. Their findings showed that the fourth scenario, U-shaped buildings with square courtyards, significantly improved microclimatic conditions, reducing relative humidity from 56.27 to 48% and temperature from 43.03 to 41.03°C. Whereas, Sahebzadeh et al. [27] explored 11 strategies and tools used traditionally in Iran to establish sustainable, comfortable homes in its extreme climates. These strategies include optimizing density, orientation, introversion, seasonal design, local materials, ground thermal capacity, natural ventilation, wall properties, insulation, native elements, and integrating water and plants. Tools like courtyards, Showādān, and Bahār-khāb were discussed. The research provides a comprehensive guideline for sustainable building practices in Iran and the Middle East's harsh climates.

The discussion above asserts that a courtyard in a hot and arid region acts as an ecological battery, severing its occupants both in summer and winter. However, its importance cannot be ignored in humid climates as well. It has been explored that, despite courtyards' declining use in new housing in tropical regions, their potential for promoting passive ventilation and daylight is significant. The study from a humid region found that in courtyards, polycarbonate shading

elements hinder ventilation while increasing shade. Utilizing simulations, the research examined the configurations of various courtyard terrace houses in Penang, Malaysia. Results indicated that a semi-enclosed courtyard with shading devices optimizes environmental conditions, contributing to the design of modern terrace houses in hot-humid climates [28].

The review above about courtyard houses has been conducted in the context of their thermal comfort, shape, orientation, material application, and adaptive applications. This review suggests that a low-energy consumption strategy in courtyard houses has the potential to significantly reduce energy consumption and improve sustainability. Passive solar design, natural ventilation and cooling, and the use of renewable energy sources can all contribute to achieving low energy consumption. However, careful consideration of various factors such as climate, site location, thermal mass, and occupant behavior is necessary to maximize the effectiveness of these strategies. Overall, the design of low-energy-consumption courtyard houses is a promising approach to sustainable housing design. To summarize the review above, Table 1 has been assembled to extract the key findings of previous studies.

Table 1. Literature Review Key Findings

No	Study	Key Findings
1.	[18]	DesignBuilder struggles with accurate simulation of courtyard thermal behavior, especially in replicating heat radiation, natural ventilation, and shading.
2.	[19]	Investigated high energy use of mechanical air-cooling in the Middle East and advocated for traditional architecture for better energy efficiency.
3.	[20]	Studied microclimatic effects in semi-outdoor spaces, finding porosity slightly increases air velocity; double-sided models are more effective.
4.	[9]	Explored courtyards' impact on microclimate in Iran's BWks region, providing sustainable building design guidelines based on courtyard properties.
5.	[21]	Examined how various ground coverings in courtyards affect microclimates, suggesting specific material combinations for optimal conditions.
6.	[22]	Focused on optimizing thermal efficiency of courtyard blocks in Cairo's hot-arid climate using Grasshopper and Ladybug-tools.
7.	[23]	Investigated the balance between thermal and luminous environments in hot, arid courtyard buildings, finding courtyards excel in daylighting but not in thermal regulation.
8.	[10]	Developed design guidelines for enclosed patios to enhance thermal comfort, identifying key design elements for optimal thermal efficiency.
9.	[5]	Highlighted the central courtyard's role in traditional Iranian houses, emphasizing its importance in urban planning and intra-house spatial organization.
10.	[24]	Investigated how seasonal occupant movement affects thermal comfort in courtyards, finding it significantly enhances Adaptive Thermal Comfort (ATC).
11.	[25]	Developed Courtyard Thermal Usability Index (CTUI) for Baghdad courtyards, showing courtyards in Iraq offer 38% comfortable hours annually.
12.	[28]	Explored ways to enhance environmental conditions in terrace house courtyards in hot-humid climates, finding semi-enclosed courtyards with shading devices most effective.
13.	[27]	Provided a comprehensive guideline of 11 strategies and tools for sustainable, comfortable homes in Iran's extreme climates.
14.	[26]	Studied courtyard design optimization for thermal performance in hot arid regions, identifying U-shaped buildings with square courtyards as best for microclimatic conditions.

In the context of climate resilience in traditional courtyard houses, Table 2 highlights specific research gaps that have been instrumental in shaping the direction of this study. While existing research provides a substantial foundation on the role and design of traditional courtyard houses in mitigating climate impacts, there remain unexplored areas that hold significant potential for enhancing our understanding of climate resilience in these structures. Recognizing these gaps, this study aims to delve deeper into aspects that have been overlooked or insufficiently addressed in previous research.

Table 2. Research Focus and Gaps in Comparative Studies

Research focus	Comparative studies addressing the focus	Identified gaps in research
Design and Adobe Construction Courtyard House	[5, 9]	Limited exploration of adobe construction techniques in courtyard houses.
Courtyard House as Low Energy Model	[19, 26, 28]	Need for more studies on the adaptation of courtyard designs in modern low-energy models.
Inner Thermal Comfort of Courtyard House	[10, 18, 20, 24]	More research on specific strategies to enhance inner thermal comfort in different climatic conditions is required.
Adaptation to Climate Resilient Design Techniques	[10, 19, 27]	Further exploration of adapting traditional design techniques for modern climate resilience is needed.
Transforming Existing Courtyard House in UAE as Low Energy Climate Resilient Living.	[26]	A gap exists in comprehensive studies specifically focused on transforming existing courtyard houses in the UAE for energy efficiency and climate resilience.

2. Research Validation

This research comprehensively addresses the identified gaps in Table 2 by integrating traditional and contemporary design philosophies. It aims to expand the exploration of adobe construction techniques in courtyard houses, considering their natural insulation properties and suitability for hot climates. The study focuses on courtyard houses as low-energy models, investigating how their traditional design can be adapted to modern sustainable practices. This includes enhancing inner thermal comfort through innovative, climate-responsive strategies, particularly in diverse climatic conditions.

Moreover, the research delves into adapting traditional design techniques for modern climate resilience. This involves exploring how these age-old methods can be synergized with advanced technologies to create sustainable, climate-resilient living spaces. A significant part of the study is dedicated to transforming existing courtyard houses in the UAE into models of low-energy, climate-resilient living. This includes detailed case studies and practical implementations, considering the unique environmental and cultural context of the UAE. The findings contribute to sustainable urban development, offering insights into preserving architectural heritage while meeting contemporary environmental challenges.

3. Factors Contributing to Climate Change in Gulf Countries

Climate change is a global issue that affects every nation, and Gulf countries are no exception. The Gulf region is home to several countries, including the UAE, that are highly vulnerable to climate change due to their geographic location, extreme weather conditions, and dependence on fossil fuels [29]. This section aims to assess the factors contributing to climate change in Gulf countries and provide an understanding of their impact on the environment.

The Gulf region is known for its high temperature and humidity levels, which can contribute to the increased use of air conditioning and, thus, higher energy consumption. The energy sector in Gulf countries is heavily reliant on fossil fuels, leading to high levels of greenhouse gas emissions [30]. Additionally, rapid urbanization and industrialization have increased the demand for energy and transportation, further exacerbating the environmental impact of these activities [31]. Some other studies outline the other factors contributing to climate change in Gulf countries, including desertification, soil degradation, and water scarcity. The lack of sustainable farming practices, coupled with excessive use of water resources, has resulted in a decline in soil fertility and productivity. The Gulf region is also one of the most water-scarce areas in the world, with high levels of water consumption and low levels of renewable water resources [32, 33].

To address these environmental challenges in GCC countries, various potential solutions have been proposed. One solution is to diversify the energy mix by promoting renewable energy sources such as solar and wind power [34]. The implementation of sustainable farming practices, such as drip irrigation and the use of drought-resistant crops, can help reduce water consumption and improve soil fertility [35]. Additionally, the promotion of public transportation and the use of electric vehicles and hydrogen fuel cells can help reduce the environmental impact of transportation [36–38].

The above studies can be summarized as, the Gulf countries face significant challenges regarding climate change, including high levels of greenhouse gas emissions, energy consumption, and water scarcity. These challenges require a comprehensive and coordinated approach involving the government, private sector, and civil society. Solutions such as the promotion of renewable energy, sustainable housing, farming practices, and public transportation can help address these challenges and ensure a sustainable future for the Gulf region.

4. Research Aims and Objectives

The concept of low energy consumption in courtyard houses has gained popularity in recent years due to its potential for reducing energy usage and improving sustainability in housing design. This study aims to explore the effectiveness of courtyard house design in climate resilience and change scenarios. By evaluating energy consumption, CO₂e emission materials, their thermal performance, daylighting usability, and resilience factors, the research seeks to provide valuable insights into designing environmentally friendly and energy-efficient buildings.

The primary objectives of this research are to:

- Investigate the Emirati courtyard house in the context of adobe architecture design and construction.
- Analyze the challenges of courtyard house design and its effectiveness as a sustainable model and climate resilience.

Evaluate the effectiveness of power consumption and CO₂e, thermal comfort, daylight utility, and climate resilience of building structures and construction systems through simulation.

5. Methodology

The research employs a mixed-methods approach, combining both quantitative and qualitative data collection and analysis. This research is conducted in three phases. In the first phase, a comprehensive literature review is conducted to gather information on the design and construction of courtyard houses, their historical and cultural contexts, and their environmental performance. The review focuses on the principles of sustainable design, passive ventilation, and wind catcher effectiveness. In the second phase, a case study was conducted in a selected courtyard house in the UAE, and its architectural design and construction were analyzed to identify key design elements that contribute to low energy consumption. Besides this qualitative case study, analysis involved site visits, interviews with architects, engineers, and building occupants, and the collection of data on energy consumption and CO₂ emissions.

The data collected through the literature review and case study analysis was filtered to identify trends and relationships between the variables of interest. The third phase involves the creation of a simulation model to evaluate the energy consumption and CO₂ reduction potential of courtyard houses. This involves the use of building energy simulation software, such as Sefaira, to model the energy performance of a typical courtyard house. A building performance simulation is carried out to assess the effectiveness of passive ventilation in reducing energy consumption and CO₂ emissions in courtyard houses. The simulation is based on energy usage and CO₂ emissions, thermal comfort, and daylighting Plus software and considers various scenarios for ventilation and insulation. In the final phase, the simulation results are analyzed and compared to real-world data to determine the accuracy and validity of the simulation model. Figure 1 shows the flow diagram of the research methodology.

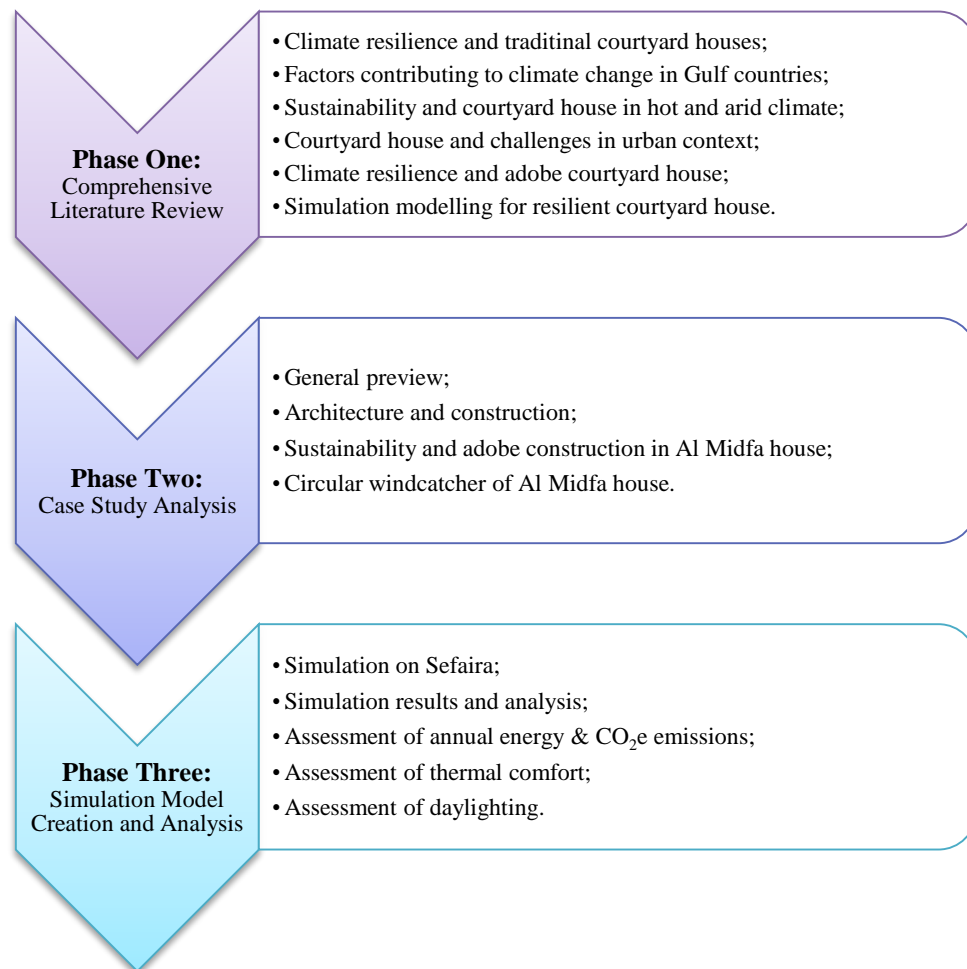


Figure 1. Research Flow Diagram

5.1. Phase One: Comprehensive Literature Review

At the very outset, the research emphasizes the importance of laying a strong foundational understanding of the subject matter. Therefore, the first phase involves an exhaustive literature review. This review intends to mine relevant information on the design and construction methodologies of courtyard houses, considering their deeply rooted historical and cultural contexts. Moreover, the environmental performance of these structures is of utmost importance to this research. Special attention is given to the principles of sustainable design, understanding the nuances of passive ventilation, and gauging the effectiveness of wind catchers. This phase offers insights into existing academic knowledge and presents a coherent framework for the subsequent phases of the study.

5.2. Phase Two: Case Study Analysis

In the succeeding phase, the spotlight shifts to an empirical exploration of a selected courtyard house located in the UAE. The choice of this region is significant, given its historical ties and architectural relevance to courtyard houses [39]. This case study, through a qualitative lens, delves deep into understanding the architectural design and construction practices employed. The primary aim is to ascertain the key design elements pivotal to ensuring low energy consumption. However, this investigation is not limited to merely analyzing architectural blueprints. A more holistic approach has been adopted, which encompasses site visits, stakeholder interviews including architects, engineers, and the very occupants of the building, and rigorous data collection focusing on metrics like energy consumption and CO₂ emissions. This comprehensive approach ensures that the research captures the full essence and complexities of the subject.

Following the collection of data, meticulous efforts were directed towards its analysis. The objective was to discern patterns, trends, and any significant relationship between the variables of interest that emerged from both the literature review and the empirical case study.

5.3. Phase Three: Simulation Model Creation and Analysis

With the foundation laid and empirical data at hand, the third phase transitions to a more technical realm. Here, the research introduces the concept of a simulation model. This model's central goal is to evaluate the potential of courtyard houses in terms of energy consumption reduction and CO₂ mitigation. To achieve this, the study harnesses the capabilities of advanced building energy simulation software like Sefaira. This software recreates the energy performance dynamics of a quintessential courtyard house. Key aspects of this simulation include assessing the role of passive ventilation in energy and CO₂ emission reduction. The process incorporates other software tools, focusing on parameters like energy utilization, CO₂ emissions, thermal comfort, and daylighting. The simulation, while rigorous, is also versatile, considering multiple scenarios encompassing different ventilation and insulation strategies.

Concluding this phase, the resultant simulation data undergoes a thorough analysis. The essence of this analysis is not just understanding the simulation's results but comparing them against real-world data. This juxtaposition aims to determine the simulation model's accuracy, ensuring its validity and applicability in real-world contexts. In summation, this research, through its phased approach, endeavors to provide a holistic understanding of courtyard houses, from historical relevance to future sustainability potential, as shown in Figure 2.

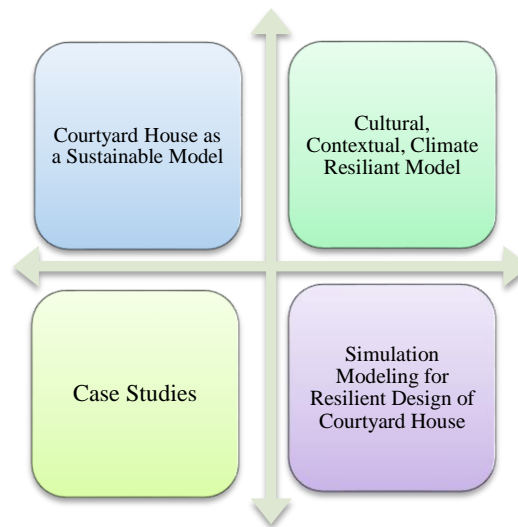


Figure 2. Research Matrix

6. Sustainability and Courtyard House in Hot and Arid Climate

This study considers that the integration of traditional Adobe technology and passive ventilation techniques in courtyard house design is exciting. The central courtyard is not only aesthetically pleasing but also contributes to the building's sustainability by enhancing ventilation and cooling. The consideration of microclimate factors and the use of natural materials further promote sustainable living. The traditional courtyard house is an architectural typology that has been prevalent in various cultures and geographical locations for centuries [40, 41]. By examining the literature on this topic, this review highlights the inherent characteristics of traditional courtyard houses, which provide an embedded sustainable approach and foster the potential for adaptation to future climatic changes. In addition, its design presents an accurate blend of passive design, cultural adaptability, and urban context. Many studies have examined the correlation between a courtyard with sustainability and investigated various parameters defining the role of a courtyard in promoting sustainability in a courtyard house.

The courtyard house design showcases the importance of sustainable architecture. The incorporation of natural adobe materials and passive ventilation techniques, such as wind catchers and courtyard spatial morphology, contributes to energy efficiency and sustainable living. The central courtyard also enhances the aesthetics of the building while providing functional benefits [42]. The integration of traditional adobe technology and passive ventilation techniques, along with the consideration of microclimate factors, promotes energy-efficient and sustainable living. The central courtyard provides a functional and sustainable design solution [43]. According to Fernandes et al. [44], courtyard houses are a great example of how sustainable architecture can be achieved using traditional techniques. The use of natural adobe materials and passive ventilation techniques, such as wind catchers and courtyard spatial morphology, contributes to energy efficiency and sustainable living. The central courtyard provides an aesthetically pleasing and sustainable design feature [45].

The sustainable features of the courtyard house design are noteworthy because of the incorporation of natural adobe materials and passive ventilation techniques, along with the consideration of microclimate factors, which promote energy-efficient and sustainable living; moreover, the central courtyard also provides functional and sustainable design solutions [46]. House design became admirable because of the courtyard and its sustainable features. The integration of traditional adobe technology and passive ventilation techniques, along with the consideration of microclimate factors, contributes to energy efficiency and sustainable living. The central courtyard also enhances the aesthetics of the building while providing sustainable design solutions [47]. Whereas the study of Friess & Rakhshan [48] emphasized that courtyard houses in the Middle East use local materials, architectural elements such as wind towers, and cultural context are important in achieving sustainability and energy efficiency. In addition, the courtyard shapes and designs play a crucial role in achieving sustainable thermal comfort and energy efficiency by employing, as mentioned, the shading performance of various polygonal courtyard forms [49].

Discussion under this section can be précised as that the sustainability features of courtyard houses are outstanding. The incorporation of natural adobe materials and traditional passive ventilation techniques, including wind catchers and courtyard spatial morphology, creates a comfortable and energy-efficient living space. The central courtyard not only adds to the visual appeal of the building but also provides functional benefits, such as improved air quality and cooling. The combination of these sustainable features showcases the potential of traditional design techniques in modern architecture. In terms of passive design strategies, traditional courtyard houses consistently emphasize the significance of their design principles in providing climate resilience. A key element is the central courtyard, which acts as a microclimate regulator, improving thermal comfort and allowing for natural ventilation. Furthermore, the compact layout, combined with thick walls and small openings, minimizes heat gain during hot periods and retains warmth during cold periods, enhancing energy efficiency. Additionally, the use of local materials with high thermal mass and insulation properties contributes to the overall climate adaptability of the courtyard house.

Thus, it could be concluded that the design principles and passive strategies employed in traditional courtyard houses offer a sustainable and contextually adaptable approach to addressing current and future climatic challenges. As such, the traditional courtyard house can serve as an inspiration for contemporary urban design, promoting climate resilience and fostering a more sustainable built environment.

6.1. Courtyard House and Challenges of Urban Context

While traditional courtyard houses exhibit various sustainable characteristics, they also face certain challenges that warrant further examination. This section of the study explores literature sources that critically discuss the problems associated with traditional courtyard houses, focusing on aspects such as privacy, maintenance, and adaptation to contemporary needs. According to Al Kodmany [50] and Bekleyen & Dalkiliç [51], the level of privacy is a major concern in traditional courtyard houses. The study highlights issues related to visual and acoustic privacy, which arise due to the shared nature of courtyards and the proximity of living spaces. The study of Wang et al. [52] has discussed the challenges of urbanization and its impact on building energy consumption and efficiency, emphasizing the difficulties of integrating traditional courtyard houses into rapidly growing modern cities while maintaining their sustainable features.

Maintenance and tidiness are major challenges in traditional Iranian courtyard houses of Iran. The authors emphasize the complexity of preserving and restoring historical structures while addressing the evolving needs of contemporary occupants [53]. However, various other studies have investigated factors influencing occupants' window opening behavior in a naturally ventilated building. The authors highlight that the reliance on natural ventilation in traditional courtyard houses may not always result in optimal indoor air quality, as occupant behavior and preferences can be unpredictable [54, 55]. Moreover, studies by Al Surf et al. [56] and Ghaffarianhoseini et al. [57] have discussed the challenges of integrating traditional courtyard houses with modern green building concepts. The authors emphasize the need for balancing the preservation of cultural heritage with the adoption of contemporary sustainable and smart building technologies.

Whereas cultural and contextual adaptability is profoundly present, traditional courtyard houses are not a one-size-fits-all solution. Various literature points out their adaptability to different cultural and climatic contexts. In regions with

hot arid climates, such as the Middle East, the courtyard houses often feature wind towers and water elements to increase the cooling effect of air movement [58, 59]. In contrast, in regions with cold climates, such as Northern China, the courtyard houses employ a south-facing orientation to maximize solar gain and heat retention [60, 61]. These examples showcase the adaptability and versatility of courtyard houses in addressing specific climatic challenges.

While the courtyard house is also being presented as an example of urban context and contemporary relevance. Some studies emphasized courtyard geometry and layout; the traditional courtyard house is increasingly recognized for its relevance in urban contexts and contemporary living. Research underscores the capacity of these structures to significantly contribute to sustainable urban development. The unique design of courtyard houses, characterized by their high-density living spaces intertwined with communal green areas, cultivates a robust sense of community. Such architectural arrangements not only promote social interaction among residents but also play a crucial role in mitigating the urban heat island effect. This blend of traditional design and communal living space offers a model for modern urban development that harmoniously balances private living with communal engagement [62, 63]. Furthermore, the courtyard house model's inherent flexibility allows for the integration of modern technologies, such as photovoltaic panels and rainwater harvesting systems, to further enhance its environmental performance [64, 65].

The discussion above has revealed several challenges associated with traditional courtyard houses, such as privacy concerns, maintenance issues, and adaptation to contemporary needs. These critical perspectives highlight the importance of considering both the advantages and disadvantages of courtyard houses when assessing their suitability for modern urban environments. Further research and innovative approaches are necessary to address these challenges and maximize the potential of traditional courtyard houses as sustainable architectural models.

6.2. Climate Resilience and Adobe Courtyard House

Climate change has become a significant concern globally, with the increase in the frequency and severity of natural disasters such as rising temperatures, storms, floods, and wildfires. Traditional courtyard houses have been recognized for their ability to provide climate resilience and offer a sustainable solution to climate change. The traditional courtyard house has been found to offer several benefits, including natural ventilation, shading, and thermal comfort. Studies have shown that traditional courtyard houses can reduce energy consumption by up to 50% compared to modern buildings [66, 67]. The use of traditional building materials such as adobe and mud bricks has also been found to have a positive impact on the environment, with a low carbon footprint but Adobe construction is vulnerable to climate change and poses a threat to the cycle of life [68].

However, there are also several challenges associated with traditional courtyard houses. For instance, some studies have noted the susceptibility of these houses to earthquakes and the precedent rate of rainfall [69] and the difficulty in adapting them to changing social needs and lifestyles [70]. Additionally, the use of traditional building materials may lead to maintenance and durability issues in extreme weather and seismic conditions [71, 72]. To address these challenges, various potential solutions have been proposed, one solution is to integrate modern building technologies with traditional building methods, such as using lightweight and earthquake-resistant materials. Another proposed solution is to introduce green roofs and walls to improve insulation and reduce heat absorption [73, 74]. Additionally, the integration of renewable energy systems, such as solar panels and wind turbines, can enhance the climate resilience of traditional courtyard houses [75].

One of the key benefits of traditional courtyard houses is that they provide natural ventilation and cooling, which can help to reduce energy consumption and greenhouse gas emissions. For example, in studies conducted by Du et al. [76] and Subramanian et al. [77] it was found that traditional houses with courtyards have significantly lower indoor temperatures than modern houses without courtyards. This is because the courtyard provides a shaded outdoor space that allows for natural air circulation and reduces heat gain.

However, while traditional courtyard houses can be effective in reducing energy consumption and increasing resilience to climate change, there are also challenges associated with their design and construction. For example, traditional materials and building techniques may not meet modern safety standards, and the cultural significance of these structures may make it difficult to implement changes that are necessary for climate resilience. One approach to addressing these challenges is to incorporate modern materials and technologies into the design of traditional courtyard houses. In the studies conducted by Manioğlu & Yılmaz [78] and Cabeza et al. [79], it was found that the use of modern materials and technologies such as insulation and double-glazed windows can improve the energy efficiency of traditional courtyard houses without compromising their cultural significance.

Another challenge associated with traditional courtyard houses is the need to adapt them to changing environmental conditions. For example, in areas that are prone to flooding or sea level rise, it may be necessary to raise the elevation of the house or modify the design of the courtyard to accommodate rising water levels. The studies suggest that the use of adaptive design strategies such as elevated ground, amphibian construction, and building water barriers can help to increase the resilience of traditional courtyard houses to climate change [80, 81].

Discussion under this section can be resolved as the combination of traditional courtyard houses and climate resilience has the potential to create sustainable and resilient buildings that are adapted to local environmental conditions. However, it is important to address the challenges associated with their design and construction and to incorporate modern materials and technologies to improve their energy efficiency and resilience. However potential solutions such as integrating modern building technologies, introducing green roofs and walls, and integrating renewable energy systems can address these challenges.

7. Case Study of Al Midfa House Sharjah

In this section of the case study, an examination of numerous factors was conducted in the research, along with obtaining crucial information. Aspects such as tangible dimensions, design aspects, materials properties, techniques for building with adobe, and weather-related data were meticulously scrutinized. To collect vital details, an exhaustive examination of the location was carried out, followed by sifting and handling the data to develop a three-dimensional representation needed for the climate resilience simulation process.

Al Midfa House, also known as Majlis Al Midfa, stands as a testament to traditional Emirati architecture in the heart of the Sharjah heritage district, near Souk Al Arsa (Al Arsa bazaar) and a short walk from Sharjah Corniche, in the United Arab Emirates, as shown in Figure 3. This historic building, over a century old, is constructed using adobe, comprising clay, sand, and date palm fonds and barks, a material prevalent in the Middle East. It claims the UAE's only circular wind tower, "barjeel" differing from the common square designs of most wind towers, adding a unique architectural feature to the site. The house, named after Ibrahim Bin Mohammed Al Midfa who established the nation's first newspaper in 1927, has been a significant cultural hub for scholars and traders. Serving as a meeting point for discussions on poetry, literature, and politics, the Majlis Al Midfa has played an integral role in the UAE's cultural and historical narrative [81-83].

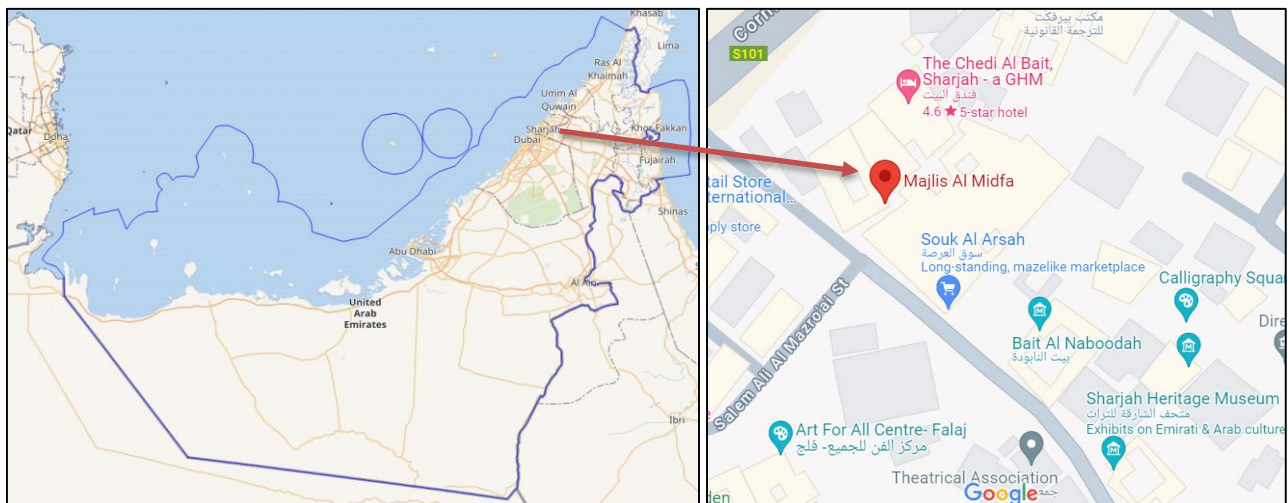


Figure 3. Location Al Midfa House [83]

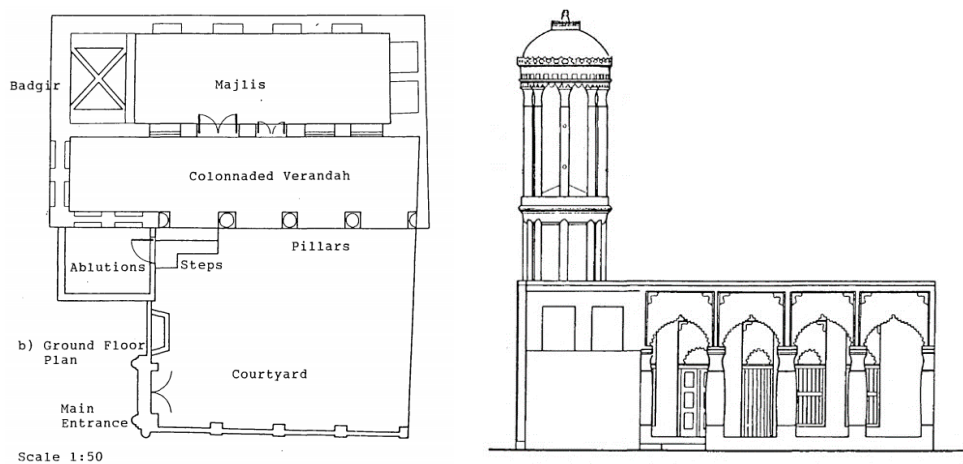


Figure 4. The Al Midfa House plan (left) and elevation from the courtyard (right) [84]

7.1. Architectural Planning

As depicted in Figures 4 and 5, Al Midfa House is situated on a 10 x 13-meter land parcel in Sharjah's heritage district. Originally, the ground floor was designed as a male guest house or "Majlis" for the Al Midfa family. The house's facade faces west and is bordered by narrow passages on the west, south, and north sides. Differing from typical traditional designs, Al Midfa House features only one entrance, which is positioned on the northern side. The house's design incorporates a straightforward geometric configuration consisting of one square and two rectangles: the courtyard, the veranda, and the Majlis or guest room respectively.

The primary offset entrance opens into a courtyard, which connects to a colonnaded veranda that leads to the Majlis hall. The house is arranged with the ground floor courtyard as the foremost space, the veranda as an intermediate area, and the Majlis guest room, equipped with a wind catcher, situated at the rear. The only wet space in the house, the ablution and toilet room for guests, is located along the western external wall adjacent to the entrance. An elegantly circular wind catcher, or "brajeel," is vertically extended over the first-floor roof. However, no physical access has been designed to reach the rooftop.

The ground floor house of Al Midfa features an intelligent design with a wind catcher positioned in the guest room, facing a west-north orientation. Entry to the guest room is through Mughal Arch colonnaded verandas, which run along the guest room's length and effectively block direct heat and light from entering the rooms from the south. Additionally, the ablution and toilet facilities are conveniently located in the courtyard, ensuring easy access and privacy.

Overall, Al Midfa House exemplifies a well-designed traditional UAE residence that embodies cultural sensitivity in its entrance and gathering spaces. The courtyard, positioned in front of the colonnaded veranda, serves as the home's focal point, providing a sense of openness and connection to the outdoors. The guest room is strategically located to optimize functionality. Overall, the Al Midfa guest house is thoughtfully designed to offer comfort, privacy, and convenience, with the verandas, courtyard, and toilets placed in strategic locations to ensure the guest room remains well-ventilated and protected from direct heat and light.

7.2. Sustainability and Adobe Construction

Adobe architecture provides a distinctive visual and cultural appeal, contributing to a sense of belonging and community cohesion in hot, arid environments. Nevertheless, it is vital to strike a balance between preserving cultural heritage and adhering to contemporary building codes and safety standards [85]. While adobe structures may exhibit a degree of resilience to extreme weather occurrences, it is essential to examine the possibilities for reinforcement and retrofitting to bolster their capacity to cope with evolving climatic conditions [86, 87]. Exploring the materials and construction methods employed in traditional UAE houses yields significant insights into eco-friendly design principles and the conservation of architectural cultural heritage. The construction techniques used in traditional UAE houses, which incorporate adobe and coral stone masonry, exhibit durability and resistance, having been honed over centuries to withstand severe environmental challenges.

Examining the materials and construction techniques applied in Al Midfa houses reveals considerable knowledge about environmentally conscious design strategies and the preservation of architectural cultural heritage. Al Midfa houses utilize building methods such as adobe and coral stone masonry, which have been developed and refined over generations to withstand harsh environmental conditions. The construction process involves using sun-dried mud bricks and coral stones bonded with mud mortar, which are then reinforced by palm fronds. These locally sourced materials not only symbolize the region's cultural identity but also promote ecological sustainability. Conversely, the use of gypsum plaster and decorative wood carvings in Al Midfa house interiors highlights the area's rich artistic and cultural traditions.

The inclusion of load bearing, thick walls, and small windows in Al Midfa house designs helps to minimize heat absorption and maximize natural airflow, resulting in comfortable living spaces well-adapted to the region's hot and arid climate. Roof construction studies have indicated that traditional house roof designs in hot, arid climates often feature elements such as high-pitched roofs made of palm barks tied together, covered with palm thatches, and sealed with mortar surfaces. Overhangs and shading devices are also incorporated to shield interiors from direct sunlight and decrease heat gain [88, 89]. Additionally, the use of reflective roofing materials, like white or light-colored paints or limestone mortar coverings, can help diminish heat absorption and enhance energy efficiency in hot, arid climates [90, 91].

Al Midfa house's roof design and construction embody several features suited to Sharjah's hot and arid climate. High-pitched roofs are built using palm barks fastened together and covered with palm thatches, then reinforced with mortar surfaces to ensure water resistance. Overhangs, verandahs, and shading devices are incorporated into the design to safeguard interiors from direct sunlight and reduce heat gain. Furthermore, reflective roofing materials, such as white or light-colored paints or limestone mortar coverings, are employed to minimize heat absorption. These elements guarantee that Al Midfa House maintains a comfortable living environment even in Sharjah's hot and humid climate.

7.3. Circular Windcatcher of Al-Midfa House

Wind towers serve as a distinctive cultural and architectural feature in the Gulf region, signifying the interconnection between time-honored construction methods and modern urban settings. Researchers advocate for the ongoing

importance of wind towers in preserving the architectural heritage of the region while fostering environmentally sustainable urban design. Integrating wind tower design concepts into contemporary architecture is vital for promoting eco-friendly living in hot, arid climates [92-94].

The Al Midfa house showcases a distinct circular, multi-faceted wind tower with an innovative 'X' blade configuration. Positioned on a circular plan over a square base, the wind tower is situated on the eastern side of the dwelling to capture winds from the southwest and northwest. This strategic placement enables the wind tower to make the most of prevailing breezes, offering a natural ventilation solution for the guest room.

The 'X' blade structure of the wind tower excels in capturing air currents from various directions, channeling them into the home, and delivering a consistent flow of cool air. By placing the wind tower on the eastern side of the property, it can effectively utilize wind from the most advantageous directions, maximizing its ability to provide natural ventilation [95]. The inclusion of a cylindrical, multi-faceted wind tower with an 'X' blade design in the Al Midfa house presents an efficient strategy for establishing a natural ventilation system. The wind tower's well-considered placement and design ensure that it can optimally harness prevailing winds, creating a comfortable and refreshing living environment for the inhabitants.

7.4. Research Challenges

This study on design, adobe construction, and climate resilience in courtyard houses faced various challenges. Accessing case studies and analyzing traditional Adobe structures was difficult due to their private ownership or heritage status. Additionally, replicating traditional construction methods required specialized knowledge of historical architecture, which varied regionally and lacked comprehensive documentation. Proving courtyard houses as low-energy models were complicated by diverse architectural styles and climatic adaptations, requiring an extensive review and comparison of scattered data. Simulating indoor thermal comfort and climate resilient design adaptations in UAE encountered limitations in capturing complex dynamics of traditional buildings and uncertainty in future climate scenarios. Moreover, developing guidelines for transforming existing Emirati courtyard houses into energy-efficient, climate-resilient structures involved balancing cultural heritage with modern sustainability requirements, posing challenges in retrofitting while maintaining architectural integrity.

8. Simulation Modelling for Climate Resilient House

Simulation modelling is an essential tool for architects and engineers to design climate-resilient houses that can withstand the impacts of climate change. Climate-resilient houses are designed to reduce energy consumption and minimize the environmental impact of buildings while providing comfortable living conditions for occupants. This critical review aims to assess the effectiveness of simulation modelling for designing climate-resilient houses and provide examples of its successful application.

Simulation modeling is a crucial tool in designing climate-resilient houses, allowing for the evaluation of building performance under different climatic conditions. Simulation modeling enables architects and designers to optimize the building design, leading to energy efficiency and reduced environmental impact [96]. Simulation modeling can aid in the selection of appropriate materials, systems, and technologies, ensuring that the house is resilient and sustainable [97]. Various case studies have demonstrated the effectiveness of simulation modeling in designing climate-resilient houses. For example, in Australia, the use of simulation modeling was instrumental in the design of a sustainable house that can withstand bushfires and extreme weather events [98]. Similarly, in the United States, simulation modeling was used to optimize the design of a net-zero energy house that can generate electricity and minimize its carbon footprint [99, 100]. To address the challenges of climate change, various potential solutions have been proposed. One solution is to promote the use of renewable energy systems such as solar panels, wind turbines, and geothermal systems [101]. The implementation of green roofs and walls can enhance the thermal performance of the building and mitigate the urban heat island effect. Furthermore, the use of natural ventilation, shading devices, and daylighting can improve indoor air quality and reduce energy consumption [102, 103].

Successful application of simulation modelling for climate-resilient houses can be seen in various case studies. For example, in the United Kingdom, simulation modelling was used to design a passive solar house that achieved a 60% reduction in energy consumption compared to conventional houses [104]. In India, simulation modelling was used to design a low-cost, energy-efficient house for low-income families that reduced energy consumption by 50% [105]. Similarly, in Japan, simulation modelling was used to design a sustainable house that reduced energy consumption by 80% [106].

This section can be précised as, that simulation modelling plays a critical role in designing houses that are resilient to climate change, as it allows architects and designers to optimize building performance across various climatic conditions. By integrating renewable energy systems, green roofs and walls, and natural ventilation, the sustainability and resilience of the house can be improved. As a result, simulation modelling offers an effective approach to designing climate-resilient houses and mitigating the impacts of climate change.

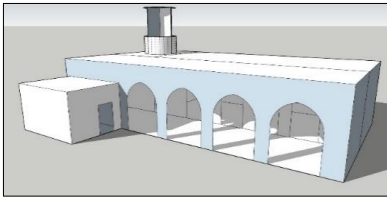
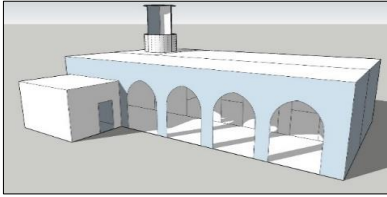
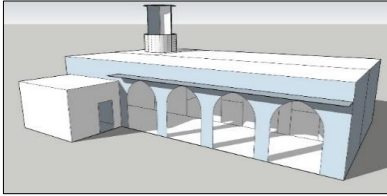
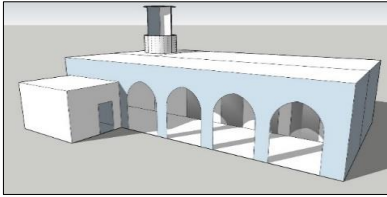
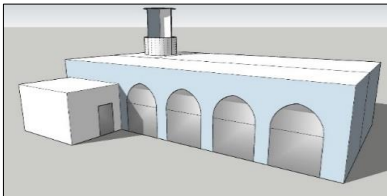
8.1. Simulation on Sefaira

A simplified Sketchup model was created according to Sefaira's requirements. External and internal walls, roof, operable glass, and shading were assigned to each surface. Sefaira was then launched to perform daylighting and energy

studies. The building specifications were based on U-values for uninsulated walls and roofs [107, 108]. Standard values were used as the authors lacked access to laboratory equipment to calculate the actual combined U-value of the mud wall and roof constructions. Sefaira is used to analyse the daylighting performance, energy consumption and thermal comfort based on ASHRAE 55 predicted mean vote (PMV) standard.

The baseline Sefaira model was then uploaded to the Sefaira System for additional analysis and specification changes. The baseline model was initially configured to use natural ventilation (free running) instead of air conditioning. Except for the M7, air conditioning was chosen to run with a 20°C to 25°C setpoint indoor temperature and full occupancy throughout the year. To adapt to the severe desert climate, air conditioning integration is critical in the UAE. The Sefaira simulation was run for each of the seven alterations listed in Table 3. The changes are modest in nature, intending to increase the basic model's resilience to climate change. Sefaira's energy analysis is powered by the dependable Energy Plus engine and displays all energy expenditure components. Renewable energy generation via PV can also be factored into the study to further minimize energy consumption. A thermal comfort study based on the ASHRAE 55 PMV standard is included in the same simulation to determine whether internal zones (rooms) are thermally comfortable.

Table 3. Simulated models, designs and specification

Simulation model	Model design	Specifications/modifications
Base model (BM)		<ul style="list-style-type: none"> ▪ Mud walls throughout at 1.2 W/m² U-value ▪ Mud roof with timber rafters at 1.2 W/m² U-value ▪ No glazing and naturally ventilated
Modification 1 (M1)		<ul style="list-style-type: none"> ▪ 0.6 m deep shading device and air-conditioned
Modification 2 (M2)		<ul style="list-style-type: none"> ▪ 0.9 m deep shading device and air-conditioned
Modification 3 (M3)		<ul style="list-style-type: none"> ▪ Operable glazing to enclose the <i>Majlis</i> (main room) and air-conditioned
Modification 4 (M4)		<ul style="list-style-type: none"> ▪ 2 m high operable glazing to enclose the colonnade with shading at a high level ▪ Operable glazing to enclose the <i>Majlis</i> (main room) and air-conditioned
Same exterior design for M4, M5, M6 and M7		
Modification 5 (M5)		<ul style="list-style-type: none"> ▪ Insulation on the inside surface of external walls surface at a combined U-value of 0.4 W/m² ▪ Insulation on the roof surface at combined U-value of 0.4 W/m² ▪ 2 m high operable glazing to enclose the colonnade with shading at a high level ▪ Operable glazing to enclose the <i>Majlis</i> (main room) and air-conditioned
Modification 6 (M6)		<ul style="list-style-type: none"> ▪ All M5 modifications ▪ 90 m² roof mounted PV solar system
Modification 7 (M7)		<ul style="list-style-type: none"> ▪ The same as M6 but naturally ventilated

The simulation parameters (design loads, design temperatures, annual diversity factors, ventilation and outside air, HVAC and day schedules) for the baseline model are set to closely resemble the actual case study. Similar parameters are used for the modified models to isolate the effects of physical design and specification changes, renewable energy generation addition and natural ventilation. The HVAC system specified for the simulation is fan coil unit with central plant for all models. The authors did not consider any overhead or underfloor systems as these would greatly alter the case study interior architecture. Further, the use of variable refrigerant flow (VRF) fan coils and packaged terminal heat pump (PTHP) split system are not considered as they would result in 20% and 27% increase respectively in baseline model annual net electricity use, despite their perceived savings in electricity.

To complete the analysis, all seven alterations are compared to the base model in Sefaira and carefully assessed for a more precise comparison. Finally, the authors suggest the best chance for implementation.

8.2. Simulation Results and Analysis

Figure 5 demonstrates that the suggested modern improvements to the traditional UAE house resulted in improved energy results. The EUI decreases from 90 kWh/m²/yr for the base model (BM) to -77 kWh/m²/yr for the Modification 6 (M6) model, which includes operable windows, better insulated walls and roof (0.4W/m²), and a 90m² solar PV system. This solar PV system was sized depending on available roof space for the installation of 45 units of 2.0m² solar PV modules. Its installation not only offsets the whole energy consumption for the house, but it also generates 15,688 kWh of surplus electricity (nearly 100% extra) that can be profitably exported into the national power grid. Minimally, to counteract the M5 76 kWh/m²/yr EUI and 15,569 kWh annual electricity usage, just 23 units of identically sized solar PV modules are required. Interestingly, the M1, M2 and M3 with shading devices and internal glass between the Majlis and veranda had a somewhat reduced EUI than the base model at 88 kWh/m²/yr, indicating that they were ineffective in lowering annual energy use.

8.3. Annual Energy Use and CO₂e Emissions

The energy demand for M1-M6 is computed using a fan coil unit with a central plant air-conditioning system, which is the worldwide default cooling system for a Sefaira residential building. On the contrary, VAV with central plant is the default for healthcare and laboratories, while packaged rooftop VAV with reheat is the default for offices, schools, retail, and anything else [109]. The fan coil with a central plant system was kept for the energy use simulation since it is equivalent to systems utilized in UAE residential structures. Lighting and plug load defaults were also preserved. All simulated models' design loads (50 m²/person occupant density, 5 W/m² equipment power density, and 10 W/m² lighting power density) are based on Sefaira's default values for residential buildings [110]. For both the base model and the M7, the air conditioning is programmed to always be turned off.

The annual energy use comparison in Table 4 shows that as additional modifications are made to the base model, the energy demand rises from 18,004 kWh (base model) to 18,330 kWh (M4). This is primarily due to the advent of operable windows, which separates rooms into different zones that require their air-conditioning, resulting in reduced efficiency. When insulation is added, however, the total annual energy demand drops to 15,569kWh, which is approximately 13.5% less than the base model.

Table 4. Overall simulation results showing the peak cooling load, energy usage intensity (EUI), annual net electricity use, annual net CO₂e emissions and the annual energy cost for all eight simulated models

Model	EUI (kWh/m ² /yr)	Annual net electricity use (kWh)	Annual net CO ₂ e emission	DEWA Electricity Tariff				Annual energy cost (AED)
				1 to 2000 kWh	2001 to 4000 kWh	4001 to 6000 kWh	6000+ kWh	
BM	90	18,004	9,060	150.00	179.91	209.90	1500.50	2040.31
M1	88	17,606	8,857	150.00	179.91	209.90	1450.75	1990.56
M2	88	17,583	8,846	150.00	179.91	209.90	1447.88	1987.68
M3	88	17,664	8,887	150.00	179.91	209.90	1458.00	1997.81
M4	91	18,330	9,228	150.00	179.91	209.90	1541.25	2081.06
M5	76	15,569	7,785	150.00	179.91	209.90	1196.13	1735.93
M6	-77	-15,688	-7,844	150.00	179.91	209.90	1211.00	1750.81
M7	40	8,162	4,081	150.00	179.91	209.90	270.25	810.06

Annual energy cost is calculated based on Dubai Electricity & Water Authority (DEWA) 2019 residential sector electricity tariff for UAE nationals [111].

This annual energy demand is greatly reduced when the house is naturally ventilated (M7), as shown in Table 4. The total energy cost for this form of ventilation is also significantly cheaper, at AED810.06 (USD220.55) per year,

compared to AED1,735.93 (USD472.63) for the M5, and AED2,040.31 (USD555.50) for the base model. M5 and M7 lead to 14.9% and 60.3% cost savings per year compared to the base model. Operating the Al Midfa house on natural ventilation mode translates to significant electricity cost savings but at the expense of thermal comfort. In addition, the yearly CO₂e emission for M7 that runs on natural ventilation is the lowest at 4,081 kgCO₂e/year, compared to 9,228 kgCO₂e/year for M4 and 7,785 kgCO₂e/year for M5.

Referring to Table 5, the cooling energy use for the M4 is 9,081 kWh per year, compared to 9,130 kWh for the standard model and 7,045 kWh for the M5 with insulation. These correspond to approximately 48.8% (M4), 50.0% (base model), and 45.3% (M5) of total yearly energy consumption. The remaining annual energy use is accounted for by lighting, equipment use, and pumps. With the addition of insulation, the total peak cooling coil load is reduced from 18.1 kW (M4) to 10.8 kW (M5).

Table 5. Cooling energy analysis in comparison to the total electricity use for all simulated models

Model	Annual net electricity use (kWh)	Yearly cooling energy (kWh)	Percentage of the annual electricity use	Total peak cooling coil load (kW)
BM	18,004	9130	50.71%	15.8
M1	17,606	8498	48.27%	16.9
M2	17,583	8483	48.25%	16.9
M3	17,664	8540	48.35%	17.1
M4	18,330	9081	49.54%	18.1
M5	15,569	7045	45.25%	10.8
M6	-15,688	7045	44.96%	10.8
M7	8,162	838	10.27%	0.9

As previously stated, M6, with similar modifications to M5 but a 90 m² solar PV system, can generate 31,257 kWh of electricity per year and fully offset M5's 15,569 kWh per year energy demand, while potentially producing approximately 100% excess electricity that can be fed into the power grid for profit at AED1,750.81. This aligns with the UAE's goal of generating up to 75% of its energy from renewable sources by 2050 [112]. However, this 90 m² PV system may be too heavy for the roof. To counteract the overall energy consumption for M5, a smaller system with only 23 modules (46 m²) at 21 kg per module [113], equivalent to 483 kg (10.5 kg per square meter or nearly 1 pound per square foot) can be used instead. This smaller system would be lighter on the vernacular structure and would cause no structural harm.

Overall, both the installation of insulation that reduces the building envelope U-value (resulting in significant annual energy use reduction) and the installation of a solar PV system are in line with Sharjah's declaration as a conservation city, to reduce energy use and use cutting-edge power conservation technologies [114].

8.4. Thermal Comfort

Sefaira evaluates predicted mean vote (PMV) based on ASHRAE 55. All simulated models were created with four zones based on existent rooms. If the PMV is between a -0.5 and 0.5 range for more than 98% of the occupied hours, the zone is considered passed. The PMV results for all models are summarized in Table 6.

Table 6. PMV results summary from Sefaira based on ASHRAE 55

Model	# of pass zone	# of failed zone	Worst zone	Remark
BM	0	4	PO3 (ablution)	59.1% under target
M1	0	4	PO3 (ablution)	42.8% under target
M2	0	4	PO3 (ablution)	42.5% under target
M3	0	4	PO3 (ablution)	42.9% under target
M4	0	4	PO2 (verandah)	51.8% under target
M5	0	4	PO2 (verandah)	33.2% under target
M6	0	4	PO2 (verandah)	33.2% under target
M7	0	3	PO2 (verandah)	78.3% under target

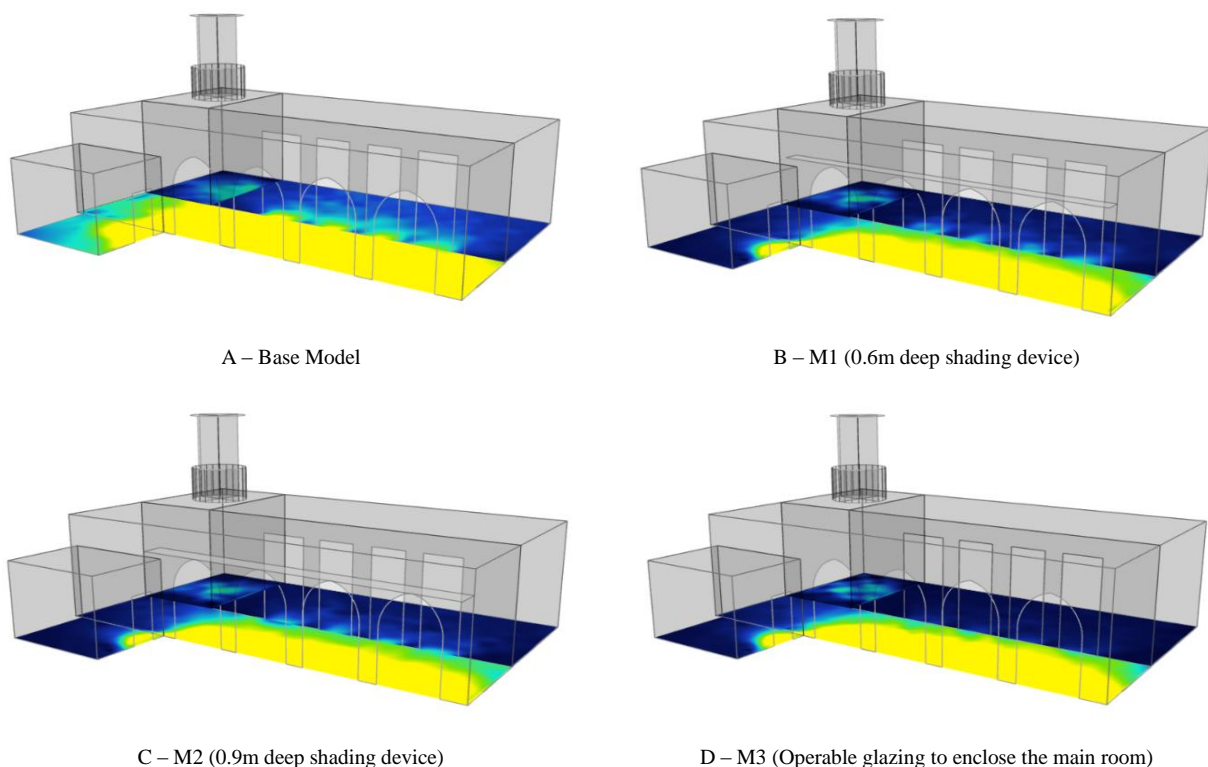
Clearly, the M5 and M6 outperformed all other models, with more than 75% of hours being thermally comfortable at PO1, PO3, and PO4 (see Table 6). Ultimately, all zones failed because they were outside of the -0.5 and 0.5 range for more than 98% of the occupied hours (see Table 7). PO4 or the guest room below the wind catcher is the best zone since it gets plenty of fresh air. Nonetheless, this situation is undesirable because the majority of people will be in zones PO1 (*Majlis*), PO2 (veranda), and PO3 (ablution), necessitating constant air-conditioning. PMV results for M7 are worse, since zones PO1-PO3 are only comfortable for about 25% of the time (see Table 7). Only the guest room passed this test with a score of 99.4%. This problem may be improved if big openings were provided between each zone to allow air brought down through the wind catcher to circulate freely. M7 simulation was rerun with only one zone per floor (no sub-divisions) and the results were a failure (74.5% under target) since this zone is only thermally pleasant for 23.5% of the time, too hot for 67.5% of the time, and too cold for 9.1% of the time. As a result, air conditioning is essential to maintain thermal comfort.

Table 7. ASHRAE 55 PMV evaluation failure results for M5, M6 and M7

Zones	M5 and M6				M7			
	Comfortable (% of hours)	Too hot (% of hours)	Too cold (% of hours)	Under target (%)	Comfortable (% of hours)	Too hot (% of hours)	Too cold (% of hours)	Under target (%)
PO1 (<i>Majlis</i>)	84.9	8.5	6.6	13.1	20.1	79.4	0.5	77.9
PO2 (verandah)	64.8	33.1	2.1	33.2	19.7	70.6	9.7	78.3
PO3 (ablution)	76.4	17.4	6.2	21.6	23.6	65.2	11.3	74.4
PO4 (guest room)	89.9	16.0	8.5	8.1	99.4	0.0	0.6	1.4 (over target)

8.5. Daylighting

Daylighting in the UAE's hot and arid climate is always a challenge for any style of structure. This issue is caused by excessive heat input through windows or openings in the building envelope that allow natural light to enter. As a result, shading mechanisms are required to prevent direct sunlight from entering through openings, while internal surface colours and reflecting materials can diffuse sunshine over a larger area and deeper into the building. This paper's case study house, Al Midfa, includes large openings along the front length of the veranda (PO2) and comparable openings into the *Majlis* (PO1). Furthermore, the wind catcher tower features small openings to allow air to move while yet allowing some natural lighting into zone PO4. The same Sefaira models (base model, M1, M2, M3, and M4) were utilized to analyse the inside daylighting conditions. Figure 5 depicts the Sefaira simulation results, which make use of the Radiance and DAYSIM engines [115].



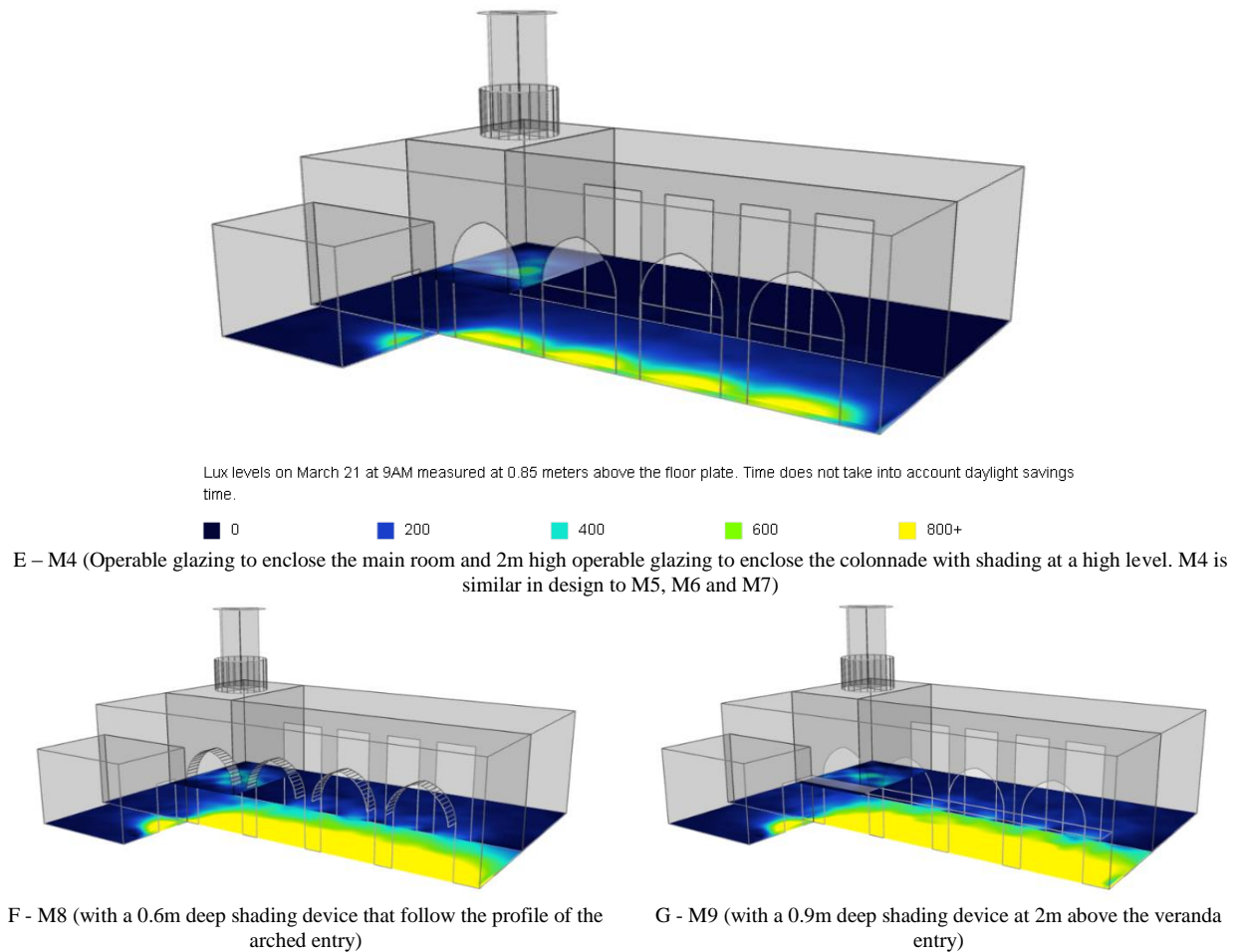


Figure 5. Lux levels for A – Base Model, B – M1, C – M2, D – M3, E – M4, F – M8, and G – M9

According to the simulation, the base model has the best natural daylight penetration, with the veranda (PO2) being primarily over lit at 7.91% average sunshine factor. Meanwhile, the Majlis is generally dark, with an average daylight factor of 0.77%. The majority of the daylight enters through the veranda. The remaining zones are generally dark as well. This daylighting pattern is shared by M1 (which has a 0.6 m deep shading device above the veranda entrance) and M2 (which has a deeper 0.9 m shading device in the same area). The shading mechanisms had little effect on the amount of daylight that entered the veranda and ablution. On the contrary, the addition of glazing along the aperture into the *Majlis* in M3 successfully reduced daylight penetration into the Majlis, which was already mostly dark. Furthermore, new external glazing along the veranda obstructed more sun penetration, resulting in an underlit veranda (PO2) with a 1.28% average daylight factor (see Table 8).

Table 8. Daylighting Radiance simulation results from Sefaira

Model	Zones	Daylight Factor		
		Average	Minimum point	Uniformity ratio
BM	PO1	0.77%	0.10%	0.13
	PO2	7.91%	0.40%	0.05
	PO3	0.97%	0.20%	0.21
	PO4	1.36%	0.20%	0.15
M1	PO1	0.72%	0.1%	0.14
	PO2	6.96%	0.4%	0.06
	PO3	0.94%	0.2%	0.21
	PO4	1.34%	0.20%	0.15
M2	PO1	0.69%	0.10%	0.14
	PO2	6.17%	0.30%	0.05
	PO3	0.85%	0.20%	0.24
	PO4	1.35%	0.20%	0.15

M3	PO1	0.30%	0.00%	0.00
	PO2	7.89%	0.40%	0.05
	PO3	1.01%	0.20%	0.20
	PO4	1.36%	0.20%	0.15
M4 (the same as M5, M6 and M7)	PO1	0.01%	0.00%	0.00
	PO2	1.28%	0.10%	0.08
	PO3	0.43%	0.10%	0.23
	PO4	1.32%	0.20%	0.15
M8	PO1	0.58%	0.10%	0.17
	PO2	5.23%	0.36%	0.06
	PO3	0.95%	0.20%	0.21
	PO4	1.43%	0.20%	0.14
M9	PO1	0.68%	0.10%	0.15
	PO2	6.00%	0.30%	0.05
	PO3	0.88%	0.20%	0.23
	PO4	1.20%	0.20%	0.17

Two more models were also simulated. M8 has a 0.6m deep shading device that follows the profile of the arched entry, while M9 has a 0.9 m horizontal shading device that is situated 2 m above the veranda entry. Similar to the base model, these new improvements enabled great sunshine penetration onto the veranda. Overall, the Majlis (PO1) is mostly dark, the veranda (PO2) is mostly bright, and the guest room (PO3) and ablution (PO4) are mostly dark. This summarized finding is consistent across all models studied. Furthermore, for all examined models, the spatial daylight autonomy (sDA) and annual sunlight exposure (ASE) are both 0.00%.

9. Discussion

In the realm of sustainable architecture and energy-efficient design, the utilization of cutting-edge simulation tools, such as the Sefaira simulations, offers crucial insights into the thermal performance of different building models. Among the investigated models, the M5 version emerged as a leading contender, exhibiting impressive thermal efficiency characteristics that surpassed its counterparts. This article provides an in-depth analysis of the M5 model, focusing on its key attributes and potential implications for the architectural design of the Al Midfa house.

The triumph of the M5 model in the context of thermal performance primarily hinges on its strategic implementation of additional insulation within the building envelope. This enhancement has led to a commendable 13.5% decrease in annual energy consumption in comparison to the original prototype. Moreover, the M5 design requires a reduced amount of energy for cooling purposes, a crucial factor in optimizing energy efficiency. However, the advantages of M5 are not devoid of complications. A significant challenge emerged from the ASHRAE 55 PMV examination, where all the rooms within the M5 model were found to fail the test. In particular, an alarming 33.2% of the 203 m² dwellings were found to fall short of the expected standard. Despite this drawback, the dry bulb temperature measurements demonstrated a reassuring consistency, with all four designated zones adhering to the setpoint range 100% of the time.

The intricacies of M5's design further extend to its daylighting characteristics. Comparable in its design approach to M4, the M5 model necessitates a substantial utilization of artificial illumination to maintain adequate visibility. Energy simulations accurately mirror this necessity, revealing an energy expenditure of 4,811.37 kWh/year, accounting for 30.9% of the total annual energy demand for artificial lighting alone. While this figure might appear significant, it is important to acknowledge that M5's energy consumption for cooling and artificial lighting can be effectively neutralized by employing a solar photovoltaic (PV) system. The solar solution proposed involves the mounting of 23 solar panels, each measuring 2.0m², effortlessly accommodated on the flat roof. This strategic initiative not only enhances energy self-sufficiency but also harmonizes with the architectural aesthetics of the Al Midfa house.

However, the introduction of M5's recommended changes will inevitably influence the architectural identity of the Al Midfa house. Such alterations necessitate careful selection of building materials, emphasizing the choice between framed or frameless windows, and insulation panels mounted on the interior surfaces of the walls and roof. The desired method aims to minimize alterations to the exterior architecture, thus preserving the building's visual integrity.

Injectable cellulose insulation represents an innovative solution to diminish the impact on interior architecture, but its compatibility with Adobe wall and roof constructions remains an area of uncertainty. The integration of the solar PV system on the roof presents no challenge concerning the weight-bearing capacity of the existing roof structure. Additionally, the concealed positioning of the panels ensures that they remain invisible from an eye-level external view.

The M5 model, as revealed through Sefaira simulations, offers a compelling solution in terms of thermal performance. Although accompanied by some challenges, the model proposes a visionary approach to energy efficiency and architectural integration. Its reliance on enhanced insulation, balanced artificial lighting, and the strategic incorporation of a solar PV system provides a resilient pathway towards future-proofing the Al Midfa house. The careful consideration of material selection and aesthetic coherence further underscores the holistic nature of the M5 design, promising a sustainable and harmonious coalescence of form and function.

10. Conclusions

Al Midfa House exemplifies the creativity and expertise of traditional Emirati builders and architects. The house exemplifies the use of sustainable and eco-friendly materials, as well as the use of traditional design aspects that take into account the climate and cultural setting of the region. Today, many architects and builders in the UAE draw inspiration from Emirati architecture's rich legacy. They are aiming to conserve and promote this distinctive architectural style. Therefore, this house must be resistant to climate change to last for many more generations. The conclusion of the study on the M5 model's implementation in the Al Midfa house presents a synthesis of various elements that reflect the complex balance between architectural integrity, sustainability, and resilience towards climate change. The success of such an approach lies in its ability to respond adeptly to the multifaceted challenges of contemporary living while prioritizing the environment.

The findings of the ASHRAE 55 PMV examination were not favorable for the M5 model, with all rooms failing to meet the required standards. Despite this drawback, the implications of the M5 model go far beyond this singular aspect. The changes recommended by M5 extend to the very core of the Al Midfa house's architecture, shaping its character and enhancing its resilience against climate change. More importantly, these modifications are aligned with the global movement towards sustainable living, positioning the Al Midfa house on a trajectory toward becoming a zero-carbon residence.

The transformation of the Al Midfa house into a model of sustainability is not a simplistic endeavor but a process replete with challenges and opportunities. It demands a meticulous exploration of new building materials and retrofits, focusing on windows (both framed and frameless) and insulation panels to be mounted on the interior surfaces of the walls and roof. These specific changes were identified as the most effective means of improving energy efficiency without altering the exterior architecture. The aim here is not just to make superficial adjustments but to infuse the building with features that enhance its performance and aesthetics.

The idea of utilizing injected cellulose insulation in the wall system represents a significant innovation in this direction. The potential benefits of this material are considerable, offering efficient insulation without compromising the architectural aesthetics of the building. It exemplifies a new way of thinking about insulation, one that acknowledges the importance of interior alterations in achieving energy efficiency.

Yet, the journey towards a zero-carbon Al Midfa house and its climate resilience does not stop with insulation and window modifications. The integration of a solar photovoltaic (PV) system within the existing roof structure is a key aspect of this transformation. What is remarkable about this initiative is that it transcends mere technical feasibility. By confirming that adding solar panels to the roof will not pose any weight-related problems to the existing structure, it reassures stakeholders that this ambitious goal is within reach. The introduction of solar energy not only symbolizes the house's commitment to renewable energy but also establishes it as a frontrunner in the transition towards a sustainable future. The Al Midfa House's transformation through the M5 model's recommendations is not an isolated case but rather a reflection of a broader societal shift towards sustainability. It showcases a pathway to resilience and adaptability that is cognizant of the imperatives of climate change and a world where energy efficiency is no longer a choice but a necessity.

In conclusion, the complex yet harmonious interplay of the M5 model's recommendations for the Al Midfa house presents a roadmap towards a future where architecture is not merely a static entity but a dynamic force in the fight against climate change. It transcends conventional boundaries, integrating innovation in materials, design, and technology to create a living space that is both practical and sustainable. The lessons learned from this study are not confined to a single dwelling but extend to the broader architectural community, providing insights and inspiration for a new generation of buildings that embody the principles of sustainability, resilience, and beauty. The Al Midfa house stands as a testament to what is achievable when creativity and responsibility converge, creating a home that is not just a shelter but a beacon of sustainable living in a rapidly changing world.

11. Declarations

11.1. Author Contributions

Conceptualization, A.H.C., J.A., M.A.I., and M.S.A.; methodology, A.H.C.; formal analysis, M.A.; investigation, M.A.; resources, M.S.A.; data curation, A.H.C. and J.A.; writing—original draft preparation, A.H.C.; writing—review and editing, J.A. and M.S.A. All authors have read and agreed to the published version of the manuscript.

11.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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11.5. Conflicts of Interest

The authors declare no conflict of interest.

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