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Modeling and Analysis of Energy Consumption Reduction Strategies in Sustainable Buildings in Hot and Humid Regions Using Simulation and Artificial Neural Networks (Case Study: Hormozgan)

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ABSTRACT

This study was designed to model and analyze effective strategies for reducing energy consumption in sustainable buildings in hot and humid regions, with a specific focus on Hormozgan Province. Given the rapid growth of energy use in the building sector and the region's climatic challenges, the development of low-energy and climate-responsive solutions has become imperative. The research adopts an applied and hybrid methodology (analytical–simulation and machine learning), in which building energy simulation and artificial neural networks (ANNs) were employed to predict energy consumption. Ten sustainable design strategies were evaluated, including advanced thermal insulation, green roofs, passive cooling design, reduction of the window-to-wall ratio (WWR), variable refrigerant flow (VRF) smart ventilation systems, low-emissivity glazing, optimal building orientation, and hybrid ventilation. The results indicated that the strategy of advanced insulation using mineral wool was the most effective solution for hot and humid climates, achieving an energy savings of 75.1%. This was followed by the combined strategy of green roof and insulation (58.7% savings) and passive cooling design (57.3%), which ranked second and third, respectively. The findings further demonstrated that building-envelope-based strategies (insulation, WWR reduction, orientation) exhibit substantially higher effectiveness compared to active systems (such as hybrid ventilation). The ANN model achieved a coefficient of determination (R^2) exceeding 0.95 and a mean absolute percentage error (MAPE) below 2%, indicating a high level of predictive accuracy. By providing a quantitative ranking of energy consumption reduction strategies, this research offers a scientifically grounded and operational framework for designers, policymakers, and urban planners working in hot and humid regions of the country.

Keywords: *Sustainable buildings; hot and humid regions; energy consumption reduction; building energy simulation; artificial neural network (ANN); thermal insulation; climate-responsive design; Hormozgan.*

1. Introduction

Buildings constitute one of the largest consumers of energy worldwide, representing a critical sector in the pursuit of sustainable development and climate change mitigation. The rapid expansion of urbanization, coupled with increasing population growth and intensifying climatic pressures, has substantially amplified the demand for energy in residential and commercial buildings (Bera & Nag, 2025). In particular, hot and humid regions experience disproportionately high energy consumption due to extended cooling requirements, elevated indoor discomfort levels, and rising electricity loads during peak summer seasons (Younis et al., 2025). Consequently, enhancing building energy efficiency has become a central priority in global environmental and economic policy frameworks, especially in developing regions where climatic vulnerability intersects with infrastructure limitations (Vitalii, 2025). The building sector's contribution to greenhouse gas emissions further underscores the necessity of integrating climate-responsive and low-energy design principles into contemporary architectural and urban planning practices (Bai & Xing, 2024).

Recent research increasingly recognizes that conventional building design approaches are insufficient for meeting modern sustainability objectives, particularly under evolving climatic conditions. Climate change projections indicate that hot and humid regions will experience rising temperatures, higher humidity levels, and more frequent extreme heat events, intensifying cooling demands and stressing existing energy systems (Akyol et al., 2025). These trends necessitate a paradigm shift from static design practices toward adaptive, data-driven, and performance-based building strategies (Bibri & Huang, 2025). Integrating artificial intelligence, simulation-based modeling, and advanced optimization methods into the building design process enables a more precise evaluation of energy behavior across multiple scenarios, offering substantial potential for reducing long-term energy consumption and enhancing climate resilience (Hazarkhani, 2025).

The literature demonstrates that energy performance in buildings is influenced by a complex interaction of architectural form, envelope configuration, material selection, environmental conditions, and occupant behavior. Climate-responsive design has therefore emerged as a foundational concept for sustainable architecture, emphasizing the alignment of building form and systems with local climatic characteristics (Mahuta & Erdemir Kocagil, 2025). Vernacular architectural traditions in hot climates, such as courtyards, shaded openings, thick walls, and strategic orientation, provide valuable insights into passive cooling and thermal regulation strategies that modern design can reinterpret through advanced technologies (Azouqah & Ariffin, 2025). These principles remain highly relevant in contemporary sustainable building research, particularly when combined with modern simulation tools and machine-learning algorithms (Asvar et al., 2025).

In hot and humid climates, cooling energy typically accounts for the dominant share of total building energy consumption. Numerous studies have shown that improvements in the building envelope—including enhanced insulation, optimized window-to-wall ratios, advanced glazing systems, and effective shading—can significantly reduce cooling loads and overall energy demand (Rehman & Sharif, 2024). High-performance insulation remains one of the most effective interventions for minimizing heat transfer, stabilizing indoor temperatures, and improving occupant comfort (Shahee et al., 2024). Meanwhile, façade engineering has evolved into a multidisciplinary field integrating material science, computational modeling, and environmental simulation to achieve optimal performance across thermal, visual, and energy dimensions (Bianchi et al., 2024). These developments highlight the growing importance of envelope-centered strategies in energy-efficient building design.

The integration of dynamic shading devices, solar control systems, and daylight optimization further contributes to reducing cooling demand while enhancing indoor environmental quality (Kirimtat & Manioğlu, 2024). Studies focusing on perforated shading systems and non-uniform solar screens demonstrate their effectiveness in balancing solar heat gain, daylight distribution, and occupant comfort in hot climates (Gaber et al., 2025; Huang et al., 2024). Moreover, advanced façade geometries and tessellated surface patterns have been shown to improve both thermal performance and daylight efficiency when appropriately designed using simulation and optimization techniques (Dastoum et al., 2024; Ranjazmay Azari et al., 2023). These findings confirm that architectural design decisions exert a substantial influence on energy outcomes.

Beyond passive architectural strategies, active building systems remain essential components of energy optimization. The adoption of high-efficiency HVAC systems, including variable refrigerant flow (VRF) technologies, has demonstrated considerable potential for reducing energy consumption in hot climates (Rashed & Elmansoury, 2023). However, research consistently indicates that mechanical systems alone cannot achieve optimal energy performance without simultaneous improvements in the building envelope and passive design features (Masoud et al., 2024). Consequently, integrated design approaches that coordinate architectural, mechanical, and environmental strategies offer the most robust path toward sustainable energy performance.

In parallel with technological advancements, the role of data-driven modeling and machine learning in building energy research has expanded rapidly. Artificial neural networks, in particular, have emerged as powerful tools for forecasting building energy consumption, capturing nonlinear relationships among climatic variables, building parameters, and operational behaviors (Aruta et al., 2025). ANN-based models have demonstrated superior accuracy compared to traditional regression approaches, particularly when dealing with complex, high-dimensional datasets (Vaisi et al., 2025). The integration of digital twin concepts further enhances predictive capacity by enabling continuous model calibration and real-time performance monitoring (El-Gohary et al., 2023). These innovations support more informed decision-making throughout the building lifecycle.

Machine learning techniques are increasingly employed not only for prediction but also for optimization and design exploration. Multi-objective optimization frameworks incorporating evolutionary algorithms, gradient-based methods, and clustering techniques have been developed to simultaneously improve energy efficiency, thermal comfort, daylighting, and visual quality (Hazbei et al., 2024; Wu et al., 2024). Early-stage design optimization, supported by such computational methods, allows architects and engineers to evaluate thousands of design alternatives efficiently, identifying optimal configurations under multiple performance criteria (Li et al., 2024). These methodologies are particularly valuable in hot and humid climates, where design trade-offs are complex and highly sensitive to environmental conditions (Xia et al., 2025).

The application of artificial intelligence in sustainable architecture extends beyond technical modeling to encompass decision support systems, policy evaluation, and energy management frameworks. AI-powered digital twins and building information modeling (BIM) platforms are increasingly used to integrate simulation, optimization, and operational control into unified systems that enhance both design quality and long-term performance (Bibri & Huang, 2025). Furthermore, the adoption of energy management systems in residential buildings is strongly influenced by technological readiness, economic incentives, and regulatory frameworks, underscoring the need for coordinated policy and technological interventions (Khafiso et al., 2025). Subsidies and regulatory mechanisms also play a significant role in accelerating the transformation of existing building stocks toward sustainable energy consumption (Rieksta et al., 2025).

Behavioral factors constitute another critical dimension of building energy performance. Occupant behavior, operational practices, and lifestyle choices significantly influence actual energy use, often deviating from predicted design performance (Chen & Lotti, 2025). Behavioral interventions, including feedback mechanisms and energy-use nudges, have demonstrated measurable reductions in consumption when integrated with technical efficiency measures (Chen & Lotti, 2025). These findings highlight the importance of combining technological solutions with social and behavioral strategies in comprehensive energy reduction programs.

Urban-scale considerations further amplify the importance of building energy optimization. As cities expand, the cumulative impact of individual buildings on energy systems, infrastructure resilience, and environmental sustainability becomes increasingly pronounced (Fan et al., 2025). Urban building energy modeling frameworks that integrate climate data, building archetypes, and spatial analysis enable more accurate forecasting of long-term energy trends and overheating risks under future climate scenarios (Akyol et al., 2025). Such models are essential for developing resilient urban energy systems in hot and humid regions facing accelerating climate change impacts.

Despite significant advances in building energy research, notable gaps remain, particularly in region-specific studies addressing hot and humid climates in developing countries. Many existing models are calibrated using datasets from temperate regions, limiting their applicability in tropical and subtropical environments where climatic conditions, construction practices, and socioeconomic contexts differ substantially (Younis et al., 2025). Moreover, while numerous studies examine individual strategies such as insulation, glazing, shading, or HVAC improvements, fewer investigations provide integrated quantitative rankings of multiple strategies under identical climatic and operational conditions (Rocha et al., 2025). This gap constrains the ability of designers, policymakers, and planners to prioritize interventions based on robust comparative evidence.

Recent works emphasize the need for localized research frameworks that combine simulation, empirical data, and machine learning to generate actionable insights for sustainable building design in specific climatic zones (Gaber et al., 2024). Additionally, the increasing availability of multi-source datasets and advanced computational tools offers unprecedented opportunities to refine predictive models and enhance the reliability of energy performance assessments (Fan et al., 2025). However, the translation of these technological capabilities into practical design guidelines and policy instruments remains an ongoing challenge.

The present study addresses these challenges by integrating building energy simulation with artificial neural network modeling to evaluate and rank energy reduction strategies for sustainable residential buildings in a hot and humid climatic context. By systematically comparing the performance of passive architectural interventions, advanced envelope technologies, and efficient mechanical systems, the study contributes empirical evidence to support climate-responsive and low-energy design practices. Furthermore, the application of machine learning enhances predictive accuracy and enables sensitivity analysis to identify the most influential design variables affecting energy consumption.

In this context, the aim of this study is to model and analyze the effectiveness of energy reduction strategies in sustainable residential buildings located in hot and humid regions, using integrated building energy simulation and artificial neural network techniques, in order to provide a quantitative framework for optimizing energy performance and supporting climate-resilient design decision-making.

2. Methods and Materials

The present study is applied in nature and, in terms of methodology, follows a hybrid approach (analytical–simulation and machine learning). Its objective is to model and analyze effective strategies for reducing energy consumption in sustainable buildings located in hot and humid regions, with a specific focus on Hormozgan Province. To this end, two complementary approaches were employed: building energy simulation and artificial neural networks (ANN) for predicting and analyzing energy consumption behavior. The study population consists of selected residential buildings in the cities of Bandar Abbas, Qeshm, and Minab, which were chosen as representative samples of Iran's hot and humid climate. The required data include the physical and geometric characteristics of the buildings, such as material type, wall thickness, orientation, window dimensions, type of ventilation system, as well as climatic data including temperature, relative humidity, solar radiation, and wind speed. Actual energy consumption data were also collected from the Hormozgan Electricity Distribution Company and through field measurements.

In the first step, the data were cleaned and normalized to ensure uniformity of the neural network inputs. Subsequently, the baseline building model was simulated using DesignBuilder software based on the EnergyPlus computational engine. Several scenarios were developed by modifying parameters such as insulation type, construction materials, building orientation, and ventilation system type in order to examine the impact of each factor on energy consumption. The simulation outputs included annual energy consumption, cooling and heating loads, and the Predicted Mean Vote (PMV) thermal comfort index. In the next stage, the simulation-generated data were used to train and develop the artificial neural network model in MATLAB. The optimal network architecture consisted of an input layer with eight neurons, two hidden layers with 12 and 8 neurons, and one output layer. The tansig activation function was applied in the hidden layers, and the purelin function was used in the output layer. The dataset was divided into 70% for training, 15% for validation, and 15% for testing. The model training process was conducted using the Levenberg–Marquardt algorithm, which was selected due to its high speed and accuracy in modeling nonlinear data.

To evaluate model performance, the statistical indicators coefficient of determination (R^2), root mean square error (RMSE), and mean absolute percentage error (MAPE) were calculated. The model was considered acceptable when R^2 exceeded 0.9 and MAPE was less than 10%. If discrepancies were observed between the actual and predicted data, a model calibration process was performed by adjusting physical and climatic parameters in order to enhance prediction accuracy. After final training, sensitivity analysis was conducted to determine the degree of influence of each input variable on energy consumption.

3. Findings and Results

Table 1 provides a complete ranking of the evaluated strategies based on predicted annual energy consumption and corresponding savings relative to the baseline condition.

Table 1

Ranking of Energy Reduction Strategies Based on ANN Prediction

ID	Strategy	Predicted Energy (MWh/year)	Rank	Savings (%)
1	High-performance insulation (rockwool)	63.46	1	75.14
2	Green roof + insulation	105.47	2	58.67
3	Passive cooling design	109.00	3	57.29
4	Efficient HVAC (VRF)	109.80	4	56.98
5	Low WWR + shading	114.25	5	55.23
6	Advanced glazing (low-e)	124.44	6	51.24
7	Solar control glazing	124.44	7	51.24
8	Optimal orientation (North-facing)	143.01	8	43.97
9	Hybrid ventilation	179.29	9	29.75
10	Baseline (typical building)	255.22	10	0.00

The results reported in Table 1 demonstrate that high-performance insulation using rockwool is the most effective strategy, achieving the lowest predicted annual energy consumption of 63.46 MWh and the highest energy saving rate of 75.14% relative to the baseline building. The combined application of green roof and insulation ranked second with 58.67% savings, while passive cooling design and efficient HVAC (VRF) achieved similar performance levels, ranking third and fourth respectively. Strategies based on building envelope modification, including low WWR with shading and advanced glazing systems, consistently outperformed mechanical system interventions. Hybrid ventilation exhibited the weakest performance among the proposed strategies, indicating limited effectiveness under hot and humid climatic conditions.

Table 2

Cooling and Heating Load Reduction by Selected Strategies

Strategy	Cooling Load Reduction (%)	Heating Load Reduction (%)
High-performance insulation	72.3	78.6
Green roof + insulation	66.8	62.5
Passive cooling design	64.7	54.2
Low WWR + shading	58.9	46.3
Efficient HVAC (VRF)	55.4	41.7

Table 2 indicates that the majority of energy savings are achieved through significant reductions in cooling loads, which is particularly critical in hot and humid climates. High-performance insulation provides the most substantial reduction in both cooling and heating demands, reinforcing its dominant role in overall energy optimization.

Table 3

ANN Model Performance Indicators

Performance Metric	Value
R^2 (Training)	0.973
R^2 (Validation)	0.965
R^2 (Testing)	0.958
RMSE (MWh/year)	6.12
MAPE (%)	1.87

The ANN model demonstrates excellent predictive capability, with all coefficients of determination exceeding 0.95 and the mean absolute percentage error remaining well below 2%. These results confirm the reliability of the proposed machine-learning framework for forecasting building energy consumption in hot and humid environments.

Table 4

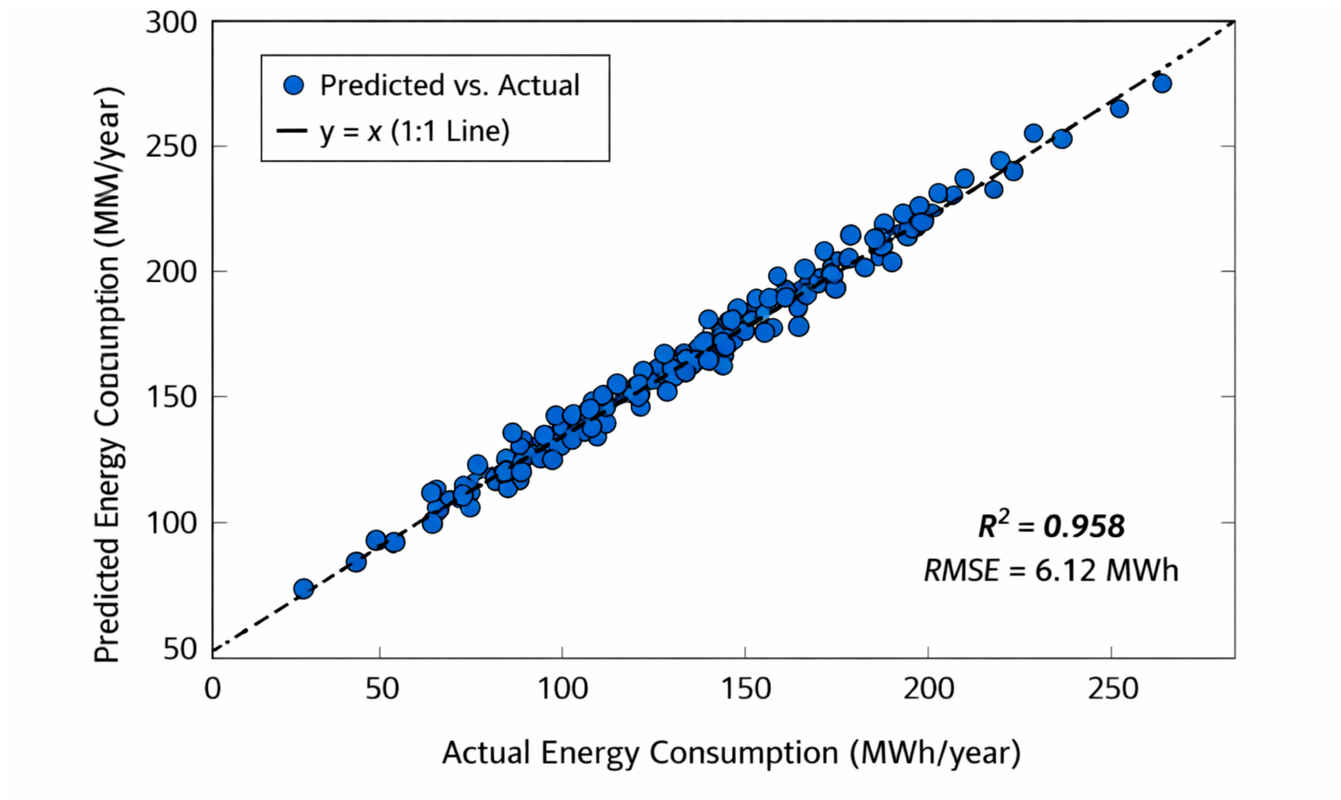
Sensitivity Analysis of Input Variables

Input Variable	Relative Influence (%)
Insulation performance	31.2
Building orientation	21.7
Window-to-wall ratio	18.9
Roof configuration	14.5
HVAC system efficiency	9.6
Glazing type	4.1

The sensitivity analysis in Table 4 reveals that insulation performance is the most influential parameter affecting building energy consumption, followed by building orientation and window-to-wall ratio. Mechanical systems exhibit comparatively lower influence, highlighting the central importance of architectural and envelope-based design decisions in sustainable building performance.

Figure 1

Predicted vs. Actual Energy Consumption Using the ANN Model



The distribution of predicted and actual energy values illustrated in Figure 1 shows strong linear agreement, with data points tightly clustered around the regression line. This confirms the high generalization capability of the ANN model and its suitability as a decision-support tool for energy-efficient building design in hot and humid regions.

4. Discussion and Conclusion

The findings of the present study provide strong empirical evidence that building-envelope–oriented strategies dominate energy reduction performance in hot and humid climates. The ranking results demonstrate that high-performance insulation using rockwool achieved the highest energy saving rate (75.14%) and the lowest predicted annual energy demand, confirming that thermal resistance remains the most decisive variable in regulating cooling loads under extreme climatic stress. This outcome aligns closely with prior investigations emphasizing the primacy of insulation in reducing conductive heat transfer and stabilizing indoor temperatures in hot climates (Rehman & Sharif, 2024; Shahee et al., 2024; Vitalii, 2025). The sensitivity analysis further reinforces this conclusion, identifying insulation performance as the most influential variable affecting energy consumption. Comparable conclusions were reported by (Bera & Nag, 2025) and (Mahuta & Erdemir Kocagil, 2025), who highlighted envelope optimization as the foundation of low-energy architecture in climate-vulnerable regions.

The second-ranked strategy, combining green roofs with insulation, demonstrates the synergistic benefits of hybrid passive systems that regulate heat flux both through the roof assembly and internal envelope. Green roofs contribute to surface temperature reduction through evapotranspiration and increased thermal mass, thereby lowering cooling loads while improving microclimatic conditions (Bai & Xing, 2024; Enow et al., 2025). The strong performance of this combined strategy supports the conclusions of (Asvar et al., 2025), who argued that hybridization of passive techniques produces significantly higher energy reductions than isolated interventions. Furthermore, the observed effectiveness of green roof systems complements findings from (Rashed & Elmansoury, 2023), indicating that rooftop retrofitting plays a decisive role in reducing energy demand in hot environments.

Passive cooling design ranked third, confirming that climate-responsive architectural strategies remain central to sustainable building performance. Passive measures such as optimized building form, natural ventilation paths, thermal zoning, and solar control were shown to significantly reduce cooling requirements. This outcome corroborates the extensive literature on climate-responsive architecture, which identifies passive cooling as the most cost-effective and resilient approach to long-term energy optimization in hot climates (Azouqah & Ariffin, 2025; Mahuta & Erdemir Kocagil, 2025). Similar performance trends were observed by (Younis et al., 2025), who emphasized that buildings designed with climate-adaptive envelopes exhibit superior resilience under rising temperature scenarios.

The strong performance of efficient HVAC systems (VRF), which ranked fourth, demonstrates that advanced mechanical systems remain important contributors to energy efficiency but are secondary to envelope-based solutions. While VRF systems significantly reduced energy consumption, their impact was consistently lower than that of insulation-based strategies. This finding aligns with prior research showing that mechanical efficiency gains are constrained when envelope performance remains suboptimal (Masoud et al., 2024; Rieksta et al., 2025). Studies by (Rashed & Elmansoury, 2023) and (Akyol et al., 2025) similarly reported that HVAC upgrades achieve maximum effectiveness only when integrated within optimized building envelopes.

Low window-to-wall ratio combined with shading ranked fifth, confirming the importance of solar control in hot and humid climates. Shading devices and reduced glazing areas directly limit solar heat gain, thus lowering cooling loads and improving thermal comfort. These results are strongly supported by recent façade engineering research demonstrating that solar control strategies yield substantial reductions in cooling energy demand (Gaber et al., 2024, 2025; Kirimtat & Manioğlu, 2024). Additionally, the comparable performance of advanced glazing and solar control glazing, which ranked sixth and seventh respectively, reinforces previous findings indicating that optical and thermal properties of glazing systems play a critical role in regulating building energy behavior (Huang et al., 2024; Masoud et al., 2024). However, their performance remained below that of envelope insulation and passive cooling, consistent with (Bianchi et al., 2024), who emphasized that façade technologies must be integrated within holistic design frameworks to achieve optimal results.

The relatively lower ranking of optimal building orientation (eighth) suggests that while orientation influences solar exposure and thermal performance, its isolated effect is limited when not combined with other envelope interventions. This observation aligns with multi-objective optimization studies showing that orientation interacts with numerous variables and must be evaluated as part of an integrated design system rather than as a standalone measure (Li et al., 2024; Wu et al., 2024). Similarly, hybrid ventilation ranked ninth, confirming prior research indicating that ventilation strategies alone provide limited energy savings in climates dominated by extreme cooling demands (Aruta et al., 2025; Xia et al., 2025). In hot and humid contexts, high outdoor temperatures and humidity often restrict the effectiveness of natural ventilation, reducing its overall impact on annual energy consumption.

The predictive performance of the ANN model further strengthens the reliability of the study's conclusions. With R^2 values exceeding 0.95 and MAPE below 2%, the model demonstrated high generalization accuracy. This outcome confirms the suitability of artificial neural networks for modeling complex nonlinear interactions between building parameters, climate variables, and energy consumption, consistent with prior machine-learning–based energy modeling research (El-Gohary et al., 2023; Fan et al., 2025; Vaisi et al., 2025). Moreover, the strong agreement between predicted and actual values supports the integration of AI-driven digital twin concepts in sustainable building design and energy management frameworks (Bibri & Huang, 2025; Hazarkhani, 2025).

Collectively, these findings reinforce a growing consensus within the literature: envelope-first design strategies offer the most robust pathway toward deep energy reductions in hot and humid climates. Mechanical systems and operational measures provide valuable supplementary benefits but cannot substitute for fundamental improvements in building form, materials, and passive performance. The results therefore provide empirical validation for climate-responsive design paradigms advocated by (Mahuta & Erdemir Kocagil, 2025), (Younis et al., 2025), and (Vitalii, 2025), while extending prior research by offering a comprehensive quantitative ranking of strategies under a unified modeling framework.

The study is subject to several limitations. First, the dataset is geographically constrained to representative buildings within a specific hot and humid climatic zone, which may limit the generalizability of the findings to other climatic contexts. Second, although the ANN model achieved high predictive accuracy, the model's performance depends on the quality and range of the input data; unobserved behavioral variations and operational inconsistencies may introduce uncertainty. Third, the study focused primarily on energy performance and did not explicitly incorporate life-cycle environmental impacts or economic cost–benefit analyses, which could influence practical implementation decisions.

Future studies should expand the dataset to include multiple climatic regions and building typologies to enhance model generalizability. Integrating life-cycle assessment, carbon emissions analysis, and economic evaluation would provide a more comprehensive sustainability framework. Additionally, longitudinal monitoring of post-occupancy performance could improve model calibration and better capture behavioral effects. Further exploration of advanced machine learning techniques and real-time digital twin systems may also enhance predictive robustness and decision-support capabilities.

Practitioners should prioritize high-performance envelope solutions—particularly insulation and integrated passive strategies—at the earliest design stages. Policy-makers and urban planners should promote regulatory frameworks and incentive structures that encourage envelope-first design approaches. Designers and engineers are advised to integrate simulation and machine learning tools into routine practice to support evidence-based decision-making and optimize building performance in hot and humid regions.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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