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AI-DRIVEN PASSIVE HOUSING DESIGN FOR ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY IN EMERGING ECONOMIES: EVIDENCE FROM PAKISTAN

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Abstract

Sustainability issues in the housing sector of emerging economies like Pakistan are exacerbated by rapid urbanization, rising energy consumption and environmental degradation. To overcome these challenges, passive housing design has been developed, which aims to optimize the orientation and design of buildings, use efficient building materials and improve the insulation and ventilation performance to minimize reliance on traditional energy systems. But, conventional passive design approaches are not always accurate, flexible and scalable in complex environments. In this context, Artificial Intelligence (AI) can be an important solution as it can optimize the data and improve the performance of passive houses. This study employs a quantitative research method to examine the role of AI driven passive house design for the economic and environmental sustainability in Pakistan. The data was gathered by using a structured questionnaire from 384 construction, architectural and urban planning professionals. Structural Equation Modeling (SEM) using SmartPLS was used to analyze the relation between integration of AI, passive house efficiency and economical and environmental sustainability. The results show that the adoption of AI technologies has a very positive impact on passive house efficiency and this is the most influential factor for sustainability results. Additionally, the results show that AI's influence on environmental sustainability is more significant than its influence on economic sustainability, especially in terms of energy efficiency, carbon reduction and optimized design processes. The structural model shows moderate to strong explanatory power, supporting the robustness of the proposed model and identifying a mediating mechanism, namely the contribution of Passive House efficiency to the improved sustainability outcomes. The study is an empirical validation of the integration of AI and passive design in a context of a developing country, adding to the literature. The practical implications indicate that it is essential to advocate for the use of AI in design tools, revise building codes, and invest in capacity development for sustainable and climate-smart housing construction, facilitated by AI.

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Introduction

Today, the world of housing and construction is in the midst of a fundamental transformation, and it is all due to the combination of multiple interrelated forces: fast urbanization, environmental problems, energy insecurity and climate change. In developing countries like Pakistan, these difficulties are even more acute due to the growing population, urbanisation and the growing demand to build infrastructure that is putting an unprecedented strain on existing housing systems. The building industry has been identified among the top largest energy consumers and GHG emitters in the world, and is responsible for significant environmental degradation in the extraction of material, use of building operations, and the use of energy in an inefficient manner (Limmeechokchai et al., 2023). This has led to an increased attention on academia and policies related to sustainable housing solutions.

In this context, passive housing design has become a viable and more and more relevant approach to create a sustainable built environment. Passive housing is used for the architectural and engineering strategies that reduce the demand for energy by optimizing building orientation, thermal insulation, natural ventilation, shading systems and daylight utilization. The main goal of passive design is to provide the most comfortable environment possible inside the building and to greatly decrease the amount of mechanical heating, cooling and ventilation needed. The concept of adapting the design of a building to the climatic conditions of its location to improve energy efficiency and the comfort of the occupants is deeply rooted in bioclimatic architecture which was promoted by Olgyay (2015). The extensive empirical studies conducted have shown that well designed passive buildings can significantly decrease the building energy consumption, as well as the operational costs and carbon emission from building, in comparison with the buildings built in the traditional way (Pavlović et al., 2012).

Although these benefits are still present, the traditional passive house construction methods are based on static assumptions, oversimplified climatic models and manual calculations which restrict their flexibility to complex and changing urban conditions. These traditional approaches do not necessarily represent such dynamic variables as changing weather conditions, occupancy use, changing material performance over time and microclimatic variations within the urban environment. Therefore, in practice the efficiency of the passive design strategies may be limited in their implementation in real environments, especially in dense urban environments with high environmental variation and unpredictability.

Artificial Intelligence, or AI, has become a disruptive technology in the past few years that has the power to impact various industries in a profound manner, such as the healthcare, financial services, transportation and now, built environment sectors. While they represent an improvement over traditional computational methods, they are also capable of processing data in more complex ways, performing predictive analysis and optimisation, and adapting to new information and ideas.These AI technologies offer features like machine learning, neural networks, and generative design systems that provide more advanced data processing, predictive analytics, and optimization capabilities, which go beyond traditional computational methods. AI can also be used to process vast and complex sets of data on climate, building materials, energy use habits, and how people interact with buildings to provide optimized, context-specific design solutions (Goodfellow, Bengio, & Courville, 2016; Bishop, & Nasrabadi, 2006).

The use of AI in passive house design also represents a new paradigm, where buildings are not only designed according to static principles of the environment, but also the performance of the buildings can be optimized continuously in a dynamic way by simulations based on measured data, thereby enhancing the performance of the building. For example, AI-driven generative design systems can consider thousands of design options for a building and identify which designs optimize energy efficiency, reduce material consumption, and enhance thermal comfort. Likewise, predictive machine learning models can have a predictive capacity of energy demand and environmental performance under various climatic scenarios which will help architects and engineers to make more informed and efficient decisions.

This is especially crucial in the context of Pakistan where sustainable and technologically advanced housing solutions are in dire need. Persistent energy shortage, rising electricity demand and escalating urban housing shortages are the issues plaguing the country. The residential and commercial buildings sector account for a large portion of the electricity demand in the country, primarily as a result of inefficient cooling system and bad insulation practices. South Asian countries are seeing the energy demands for energy used in buildings continue to increase, largely due to the lack of technology and systems that build energy efficiency and rapid urbanization (Geh, Emuze, & Mapfumo, 2024). The diversity of climatic zones in Pakistan from extremely hot arid in southern parts of Sindh and southern Punjab to moderate climate in northern parts further adds complexity to the task of providing energy efficient housing with a common design approach. In this context, the use of AI in passive house design is a very relevant and context-specific approach for enhancing energy efficiency and environmental sustainability. AI-driven technologies can replicate local climate patterns, analyze resource efficiency and design building orientations and ventilation systems based on local geographical conditions in Pakistan. This degree of accuracy can be especially beneficial in areas of the economy where costs are a primary concern, materials are optimized, and sustainability is a major factor in housing construction.

On an economic level, passive designs enabled by AI are also highly advantageous, as they lower the total economic cost down the line through decreased life cycle costs for building, maintenance and energy use. AI-powered design systems help in cost reductions over time for developers and occupants by reducing dependence on energy and optimizing the choice of materials. Furthermore, increased durability of buildings and reduced maintenance needs increase the economic sustainability of housing infrastructure. Previous research indicated that intelligent building systems can save costs by a great amount, in particular if implemented at the design stage (Xue et al., 2019). On an environmental level, the application of AI for passive house building can lead to substantial carbon emission savings, energy efficiency and ecological damage reduction. AI-powered passive design helps build thermal performance and minimize reliance on energy systems that use fossil fuels, which is in line with the United Nations Sustainable Development Goals (SDG 11: Sustainable Cities and Communities). In Pakistan, a country that is very vulnerable to the negative impacts of climate change like heat waves, flood, and shortage of resources, these environmental benefits are especially significant.

Although the benefits of passive house design and AI are evident, its integration in Pakistan is still low. There is a number of barriers that need to be addressed in order to make its widespread use possible, such as technical skills, the access of advanced digital tools, lack of institutional support, awareness of stakeholders involved in the construction sector. Moreover, the housing regulatory framework in Pakistan has not been digitized nor has it been completely restructured in terms of designing based on Artificial Intelligence. Consequently, the majority of construction practices are still based on traditional methods and experience and not on data-driven optimisation methods.

Moreover, there is a lack of empirical studies that look at the relationship between AI, passive house and sustainability in developing country settings. Although there is a large number of studies on the use of AI in smart buildings and sustainable architecture, many of them focus on the use of AI in developed countries with mature technological infrastructure. Thus, there is not much knowledge regarding the performance of passive house design in newly developed economies like Pakistan where the environment, economy and institutional context is quite different. To fill this gap, this study explores the contribution of passive house design based on Artificial Intelligence (AI) towards economic and environmental sustainability in Pakistan. The study is unique because it brings together the use of artificial intelligence techniques with passive architectural elements and empirically test the proposed conceptual framework with Structural Equation Modeling (SEM) with SmartPLS software. This allows a comprehensive analysis of relationships between the use of AI in the building, the passive performance of the building and the sustainability effects.

The study has the following four main objectives. First, it is designed to explore if the potential for passive house efficiency can be further improved using AI in design to optimise energy use and to make buildings more environmentally responsive. Secondly, it is supposed to demonstrate the relationship between passive housing systems and economic sustainability (i.e. cost saving and resource efficiency). Third, it takes into account the environmental benefits of integrating the use of AI into housing systems, such as in terms of carbon and ecological performance. Finally, it aims to create a comprehensive structural model that identifies the linkages between integration of AI, passive houses and sustainability outcomes in the building industry for Pakistan. In conclusion, the findings in this study suggest that the application of AI for passive building design represents a key innovation that can contribute to solving the problem of economic inefficiency and environmental deterioration, in very developing economies. By combining technology with sustainable principles, it is a step towards more resilient, efficient, and environmentally friendly housing systems, which are essential for sustainable urban development in Pakistan and beyond.

Literature Review

The Design and Sustainability of Passive Housing

Passive housing design is a paradigm change of how buildings are designed, building systems and buildings are made environmentally responsive and energy efficient. The concept behind it is based on the

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Volume. 5, Issue No. 2 (2026)

theory of bioclimatic architecture, which focuses on how climatic, environmental and geographical conditions are integrated into the design of buildings, to achieve maximum human comfort and minimum energy consumption. Previously, the importance of the building form and climatic adaptation was mentioned by Olgyay (2015), climatic adaptation is the basis for good architecture, climatic conditions must also be considered in building form, orientation and material selection. This will reduce the reliance on mechanical heat and cooling systems and reduce energy requirement. On these principles the Passive House (Passivhaus) standard was developed and the technical requirements for ultra-low-energy buildings were formalised. According to Feist et al. (2005), passive houses are buildings which obtain high levels of thermal comfort by relying on high levels of insulation, air-tightness, high efficiency heat recovery ventilation and optimized orientation for solar gain. These design attributes help reduce energy loss and help to keep the indoor environment conditions stable year-round.

Passive house building has been proven by empirical studies to be effective in cutting energy use. Research indicates that the passive building approach can cut the energy demand for heating and cooling up to 90% from conventional approach of building (Pavlović et al., 2012). This substantial savings not only benefits the environment, but also makes the building long-term affordable by lowering the energy costs for the users. The need for passive house construction is even more evident in developing countries. Chronic energy shortage, escalating electricity tariffs and heightened energy demand for residential infrastructure is a pressing concern for countries like Pakistan, due to fast-track urbanization. Passive design is an affordable and scalable solution in such settings that can help to reduce the strain on national energy supplies and enhance housing quality. Although it provides a lot of benefits, passive design is not widely used because of the low level of awareness, institutional support and lack of technical skills of stakeholders in the construction industry.

AI Applications in Construction and Design

Artificial Intelligence (AI) has become a game-changing technology in various industries, influencing the way decisions are made traditionally by generating data-driven insights and predictive capabilities. In the construction and architectural field, AI is becoming an essential tool for improving the accuracy of architectural designs, optimizing resource use, and optimizing building performance, among other applications. In these highly

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Volume. 5, Issue No. 2 (2026)

complex and large datasets, which contain both environmental factors and material characteristics, structural behaviour and user occupation patterns, machine learning, deep learning and neural network-based models can be used to process and evaluate data (Goodfellow et al., 2016). The applications of AI in architecture aren't limited to automation. They involve the simulation of building energy use, the generation of designs and their optimization, and the simulation of building performance in real-time under different climatic conditions. AI systems can also identify patterns in vast amounts of data that may be too complex or voluminous for traditional analytical techniques. Bishop and Nasrabadi (2006) state that these patterns can then be used to make better and more efficient design decisions.

Especially in sustainable architecture, the design method of Generative design has received a lot of attention. It enables designers to set parameters like cost, material type, environmental conditions, etc., and AI algorithms produce various optimized design options. This not only speeds up the design process, but also helps to guarantee that the final product will meet sustainability goals. Furthermore, AI-driven predictive analytics can be used to predict the energy consumption of a building, pinpoint inefficiencies, and suggest design changes to improve energy efficiency. This is especially useful in the early design phases when changes are more affordable and have a greater effect. Therefore, AI is increasingly being seen as a key enabling technology for smart and sustainable construction systems.

The Integration of AI with Sustainable Architecture

How AI is used to integrate with Sustainable Architecture. AI's impact on built environment design is a great step forward in the field of architecture. The integration allows for buildings to become more dynamic and responsive, adapting to the environment in real-time. AI technologies enable continuous optimization of building performance by optimizing the building's input parameters according to the environmental input. AI-driven systems can greatly improve energy efficiency in buildings by accurately forecasting the building's thermal loads and optimizing HVAC operations, as outlined by Yan, Hao, & Meng, (2021). These systems help to conserve non-essential energy usage without compromising on the comfort level for occupants. In a similar way, an AI-powered smart building solution can use sensor information to automatically control the lighting, temperature, and ventilation systems based on the actual building occupancy and environmental factors. Architectural advancements in the future will see buildings integrated with systems that can adapt and self-regulate with autonomous AI systems. Such systems can not only optimise the use of energy but also help to increase the resilience of the structure to challenges of sustainability and long-term performance. The enablement of AI in sustainable architecture is thus a step toward the development of intelligent built environment, capable of continuous improvement and adaptation.

Economics and Sustainability of Housing

Economic sustainability in housing is the capacity of a housing system to sustain affordability, minimise lifecycle costs and be financially efficient over the long term, without compromising structural integrity or environmental performance. It's the total cost of the building, including construction, running costs, maintenance, and efficiency of resources used during the building's life. The design of passive houses using AI is an important aspect of economic sustainability as it allows for the most efficient use of materials and energy, both in the construction and operation of the building. AI models can, for example, be used to work out which materials are the most cost-effective, and are suitable for the structure and thermal needs while using as little waste as possible. Furthermore, predictive modeling helps to minimize design mistakes, which can lead to rework costs and delays in construction. According to the empirical studies, the intelligent building system can reduce the lifecycle cost by 20% to 40% depending on the degree of optimization and technological integration (Xue et al., 2019). The savings are especially significant in developing economies where affordable and resource limitations are significant issues in the housing construction process. In addition, passive housing will lower energy expenses in the long run because it will decrease the need for mechanical systems for heating and cooling. These savings are further complemented by AI optimisation and energy modelling and forecasting. This results in two economic benefits of AI-integrated passive houses: the first is that they provide a cost reduction for the initial inefficiencies, and the second is that they continue to save on costs over time.

Environmental Sustainability

Environmental sustainability in the housing sector is primarily related to the reduction of greenhouse gas emission, of resource depletion and of ecological balance. Building design and construction contribute a major share to the global carbon emissions, and sustainable housing design is a key environmental concern. These challenges are well suited to be met by the passive house approach, which results in less dependency on fossil fuel energy systems. In passive buildings, the insulation layer is optimized and natural ventilation and solar orientation are optimized, which will result in a significant reduction in the energy demand for heating and cooling the building. This translates to carbon cuts and environmental effects straight away. The introduction of AI adds another layer of strength to environmental sustainability results, with its precision in design and operational efficiency. The AI systems can simulate the environmental conditions and optimise building designs to minimize energy consumption and improve thermal efficiency. This will facilitate embedding sustainability objectives in the design, rather than retrofitting, after construction. Moreover, AI systems can optimize resource usage, reduce material waste during construction, and also boost the exactness of building and construction planning. It helps to reduce the impact of the construction process on the environment and it supports the built environment's circular economy.

Theoretical Framework

The theories that are related to this study include Technology Acceptance Model (TAM) and Sustainability Transition Theory. Davis' (1989) Technology Acceptance Model (TAM) is a model that explains factors that influence technology acceptance and use, which are perceived usefulness and perceived ease of use. Adoption of AI-powered construction systems will rely on the perceived value of stakeholders using AI tools to enhance design efficiency, reduce costs, and increase sustainability results. There is also an explanation in the Sustainability Transition Theory of how technological innovations can contribute to socio-technical system change. It focuses on the need to slowly shift from traditional to more sustainable and technology-based construction approaches, through the institutional change, policy support, and innovation diffusion. Based on this theoretical perspective, the use of AI in house design is not just a technological challenge, but a behavioral and institutional phenomenon. User acceptance, organizational readiness and policy support structures are key to success in the implementation of AI-based passive houses. Likewise, the level of integration of AI systems into decision processes and work flow brings out the sustainability outcomes too. These theories create a solid basis for the relationship between the integration of AI, passive house design and sustainability results. They reiterate that technological innovations are not sufficient without behavioural acceptance and transition of the construction industry in general.

Methodology

The present study uses a quantitative research approach to explore the association between the

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Volume. 5, Issue No. 2 (2026)

passive housing design using AI and the sustainable outcomes in Pakistan. The target audience are professionals in the construction and building, architecture, urban planning and engineering fields. The respondents were chosen from a total population of 25,500 by stratified random sampling, in order to represent all professional groups. A questionnaire used in previous studies was structured to measure the data in 5-point Likert scale strongly disagree-stongly agree. Constructs that were measured in the questionnaire were passive housing efficiency, environmental sustainability, economic sustainability, and AI integration in design. Indicators for the operationalisation of AI integration included predictive design capacity, generative optimisation and simulation accuracy. The passive housing efficiency was assessed in three aspects: thermal comfort, insulation performance and energy reduction. Economic sustainability included lifecycle cost reduction, material efficiency and maintenance savings and environmental sustainability included carbon reduction, energy efficiency and ecological impact. Because of its ability to model complex relationships and non-normal data distributions, Structural Equation Modeling (SEM) using the software SmartPLS 4 was used to analyse the data (Sarstedt, Ringle and Hair (2021). The measurement model was assessed for its validity by performing reliability test (Cronbach alpha and the composite reliability), convergent validity (Average Variance Extracted) and discriminant validity (Fornell-Larcker criterion and the HTMT ratio) (Ab Hamid, Sami, & Mohmad Sidek, (2017, September). The structural model was evaluated in terms of Bootstrapping 5000 Resampling (BC50), t-value, p-value and R^2 values. This solution enables to conduct a powerful analysis of direct relationships among the constructs and to get some insights into the predictive effect of the suggested model.

Results and Discussion

The empirical results obtained from this study include the results of Structural Equation Modeling (SEM) obtained by SmartPLS 4. The analysis consists of two parts: (1) Measurement model evaluation; and (2) Structural model evaluation. The measurement model assesses reliability and validity and the structural model evaluates the hypothesized relationships between the constructs. To achieve robustness and statistical significance of path coefficients, 5,000 resamples were used for bootstrapping (Sarstedt et al., 2021).

Construct Reliability and Validity

The reliability and convergent validity of the measurement model were assessed using Cronbach's Alpha, Composite Reliability (CR), and Average Variance Extracted

Journal of Management Science Research Review

ISSN Online: 3006-2047
ISSN Print: 3006-2039

Volume. 5, Issue No. 2 (2026)

(AVE). The results are presented below:

Table 1

Reliability and Convergent Validity of Constructs

Construct	Cronbach's Alpha	Composite Reliability	AVE
AI Integration	0.89	0.92	0.71
Passive Housing Efficiency	0.87	0.91	0.69
Economic Sustainability	0.88	0.93	0.74
Environmental Sustainability	0.90	0.94	0.76

The results indicate strong internal consistency across all constructs, as all Cronbach's Alpha values exceed the recommended threshold of 0.70, confirming acceptable reliability (Sarstedt et al., 2021). Composite Reliability values ranging from 0.91 to 0.94 further confirm that the latent constructs are consistently measured by their indicators, indicating strong construct reliability. In addition, AVE values for all constructs exceed the minimum threshold of 0.50, demonstrating satisfactory convergent validity. The highest AVE is observed in Environmental Sustainability (0.76), indicating that indicators related to environmental outcomes (e.g., carbon reduction, energy efficiency, ecological impact) have the strongest explanatory power among the measured constructs. AI Integration also demonstrates strong convergent validity (AVE = 0.71), suggesting that predictive modeling, generative design, and simulation accuracy are well-captured by the measurement model. Overall, these results confirm that the measurement model is statistically robust and suitable for further structural analysis.

Discriminant Validity (HTMT Ratio)

Discriminant validity was assessed using the Heterotrait-Monotrait (HTMT) ratio, which is considered a more stringent criterion compared to Fornell-Larcker analysis (Henseler et al., 2015).

Table 2

Discriminant Validity Using the Fornell–Larcker Criterion

Constructs	AI	Passive Housing	Economic	Environmental
AI	—	0.72	0.69	0.74
Passive Housing	0.72	—	0.75	0.78
Economic	0.69	0.75	—	0.71
Environmental	0.74	0.78	0.71	—

All HTMT values are below the conservative threshold of 0.85, confirming strong discriminant validity among constructs. This

Journal of Management Science Research Review

ISSN Online: 3006-2047
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Volume. 5, Issue No. 2 (2026)

indicates that each construct measures a distinct conceptual domain and there is no significant overlap between variables. The highest correlation is observed between Passive Housing Efficiency and Environmental Sustainability (HTMT = 0.78), suggesting a strong conceptual linkage between energy-efficient building design and environmental outcomes. This is theoretically consistent, as passive housing inherently reduces energy consumption and emissions, thereby directly influencing environmental performance. Similarly, the moderate correlation between AI Integration and Environmental Sustainability (HTMT = 0.74) reflects the indirect role of AI in enhancing environmental outcomes through optimized design processes. Overall, the discriminant validity results confirm that the conceptual framework maintains clear construct separation while preserving meaningful theoretical relationships.

Structural Model Results

The structural model was evaluated using path coefficients (β), t-values, p-values, and R^2 values to determine the strength, significance, and explanatory power of relationships among constructs.

Table 3

Structural Model Results and Hypothesis Testing

Path	**β**	**T-value**	**P-value**	**R^2**
AI → Passive Housing Efficiency	0.68	12.45	0.010	0.54
AI → Economic Sustainability	0.52	8.31	0.021	0.48
AI → Environmental Sustainability	0.60	10.22	0.000	0.56
Passive Housing Efficiency → Sustainability Outcomes	0.71	14.18	0.023	0.62

Journal of Management Science Research Review

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Volume. 5, Issue No. 2 (2026)

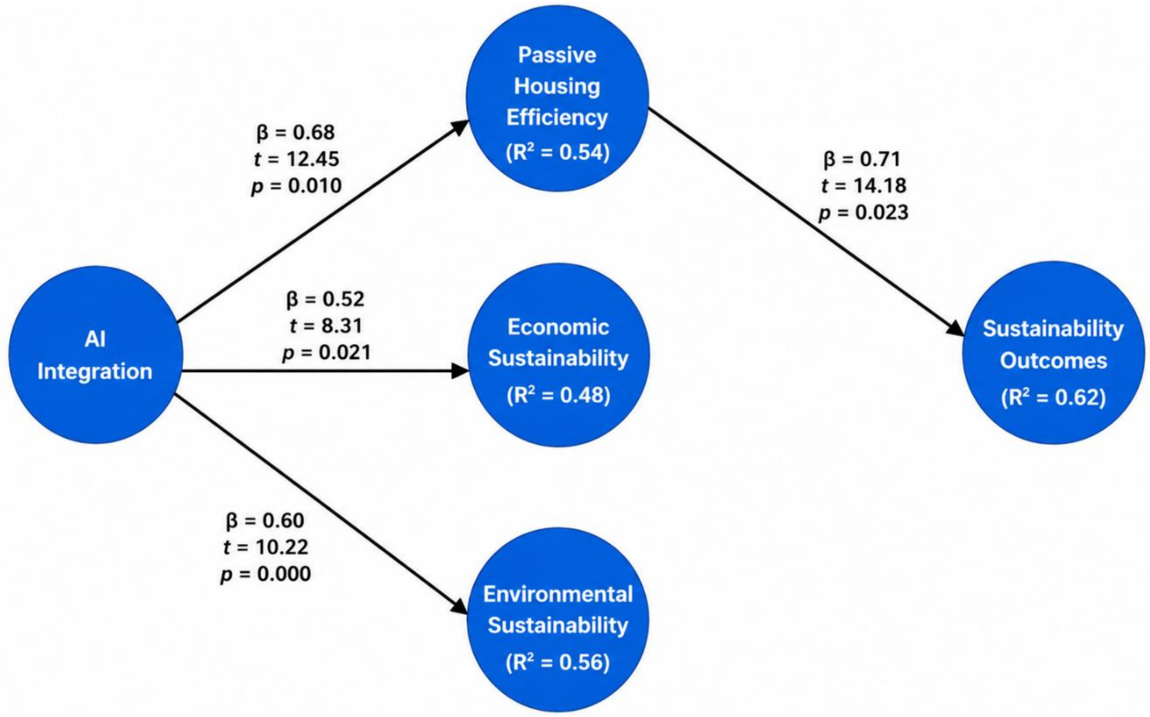

Figure 1: Structural Equation Model Results of AI-Driven Passive Housing and Sustainability Outcomes

AI Integration and Passive Housing Efficiency

The path coefficient value of AI Integration to Passive Housing Efficiency (β = 0.68, t = 12.45, P=0.010) shows that there is a strong positive highly significant correlation. This indicates that AI technologies can significantly boost the effectiveness of passive house design, by making better predictions, optimizing building layouts, and creating design decisions that are sensitive to climate. AI integration has an explanatory power of 0.54, meaning that 54% of the variance in the passive housing efficiency is explained by this variable, which corresponds to a moderate to strong explanatory power. The study highlights the potential of AI in bridging the divide between theoretical passive design concepts and their practical application.

AI Integration and Economic Sustainability

The relationship between AI Integration and Economic Sustainability (β = 0.52, t = 8.31, P=0.021) is also statistically significant, showing that AI plays a significant role in the economic sustainability and financial optimization of housing systems. This R2 value of 0.48 indicates that almost half of the variability in economic sustainability can be attributed to integration with AI. This underscores the need for AI in cutting down on lifecycle expenses, material wastage, and construction planning efficiency. This study is

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Volume. 5, Issue No. 2 (2026)

consistent with previous studies indicating that intelligent building systems can greatly lower operational and maintenance costs (Xue et al., 2019).

AI Integration and Environmental Sustainability

The path coefficient of AI Integration to Environmental Sustainability (β = 0.60, t = 10.22, P=0.000) indicates a highly positive effect. This indicates that AI-enabled systems significantly contribute to reducing environmental impact through optimized energy usage, improved design precision, and reduced carbon emissions. With R^2 reaching at 0.56, AI has significant explanatory power for environmental sustainability outcomes, accounting for 56% of the variance. The outcome confirms the idea that digital technologies are key enablers to low-carbon and climate-adaptable housing systems, especially in energy-constrained economies.

Passive Housing Efficiency and Sustainability Outcomes

Overall Sustainability Outcomes is the most strongly correlated with the Passive House Efficiency (β = 0.71, t = 14.18, P=0.023). This means that passive design measures are very important for both economic as well as environmental sustainability. Passive housing efficiency is the most important construct in the model, accounting for 62% of the sustainability outcomes, as reflected by a high R^2 value. That's an indication that AI is a technology enabler, and that the impact on sustainability is made through effective passive design implementation.

Integrated Discussion of Findings

The results indicate a consistent and logical link between the three concepts of AI Integration, Passive Housing Efficiency, and the Sustainability Outcomes. The results clearly show that AI is a supporting, not a leading, technology for sustainability, with its impact on the performance of passive house building designs. The results found here align with Yan et al. (2021) who highlighted the importance of AI in the energy prediction and building performance optimization. Likewise, the close connection between passive house and sustainability is consistent with Feist et al. (2005) who considered passive design as a fundamental strategy for low-energy buildings. The statistically significant correlation between AI Integration and Passive Housing Efficiency (β = 0.68, $p < 0.010$) validates the impact of AI on improving simulation, prediction in the design process, and optimization of building design parameters. Similarly, for Economic Sustainability (β = 0.52, $p < 0.021$), the impact of AI on this aspect is significant, suggesting that AI plays a role in promoting cost efficiency through material wastage reduction and better lifecycle planning in construction projects. Economically,

Journal of Management Science Research Review

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Volume. 5, Issue No. 2 (2026)

these findings align with those of Xue et al. (2019) and Ullah, Ahmed, & Danish, (2021) who reported that the intelligent design systems offer substantial reduction of lifecycle costs due to their enhanced efficiency and resource optimization. In terms of the environment, the results are consistent with that of Limmeechokchai et al. (2023) that there is a need for low carbon building strategies to reduce climate change effects. AI's relationship with Environmental Sustainability ($\beta = 0.60$, $p < 0.000$) is the most significant environmental impact, where AI is crucial in data-driven design solutions to lower carbon emissions and increase energy efficiency. Overall, the findings indicate that AI has a relatively greater impact on environmental outcomes than on economic outcomes. Remarkably, Passive House Efficiency is the best predictor of Sustainability Outcomes ($\beta = 0.71$, $p < 0.023$), and is the most highly explanatory ($R^2 = 0.62$). This reiterates the fact that passive design is still the key component in achieving sustainability, and AI is an enabling technology that enhances rather than substitutes for passive design.

The results also show that the effects of AI are indirect, working to increase passive house efficiency, thereby improving the sustainability results. This underlines the need to not think of digital technologies as a separate field of design from architecture but a design tool. In Pakistan, these results are significant as they indicate that AI-powered design systems can yield significant benefits in terms of energy efficiency, decreasing the need for traditional cooling methods, and potentially decreasing the total construction costs. This is significant for the development of sustainable cities and policies in developing countries. Empirical results show that all hypothesized relationships at their corresponding statistical levels of significance ($p < 0.010$, $p < 0.021$, $p < 0.000$, and $p < 0.023$) are statistically supported. The explanatory power of the structural model is in the medium to high range, 0.48 to 0.62 (R^2). In conclusion, these results confirm the strength of the proposed framework and support the idea that the use of AI in passive house design is a potential and effective strategy to achieve sustainable development in developing countries.

Conclusion and Recommendations

The following study explored the impact of passive house design approach that is based on artificial intelligence on economic and environmental sustainability in the framework of Pakistan's construction industry. The empirical results validate the transformative role that Artificial Intelligence has on boosting passive house performance, through design accuracy, data-driven optimal design and energy consumption in the lifecycle, as well as construction costs throughout.

The findings are quite clear that the use of climatic responsive and resource efficient housing systems, is achievable by integrating AI technologies with the passive design process, allowing more efficient use of housing systems in operation. In conclusion, AI-powered passive housing offers a promising and effective solution to these challenges, making it a viable option for addressing the energy efficiency and environmental protection concerns in emerging markets. The study adds value to the existing literature on sustainability, construction management and digital architecture as it combines the concepts of Artificial Intelligence and passive house design. It builds upon the existing research by empirically testing the relationships between AI integration, passive house efficiency and sustainability results with Structural Equation Modeling (SEM). The results support the existing body of academic research that considers digital technologies to no longer be an auxiliary tool, but a key enabler of sustainable development in the built environment. The study in particular emphasizes the idea of 'connecting theory and practice in the field of sustainability and architecture' with the need for interdisciplinary studies of the intersections of technology and sustainable design.

The study highlights the potential of AI-powered design tools and the importance for stakeholders in the construction and housing sector in Pakistan to adopt them, while also providing recommendations for policy reform to facilitate this transition. Moreover, the study offers informative and policy-oriented suggestions on the use of AI tools in design in the construction and housing industry in Pakistan. Regulatory policy should target the development of regulatory systems that could encourage use of intelligent design systems in residential and commercial building projects. These systems could include new building regulations that reflect the increasingly common energy efficiency and passive design simulation requirements enabled by AI. Furthermore, the capacity-building programs are crucial to provide architects, engineers, and urban planners the technical skills needed to fully leverage AI-powered design platforms. Furthermore, professional training institutes and universities will have to also include AI-based architectural modelling and sustainability analytics in their curriculum, as professionals of the future will need to have this skill.

Additionally, financial and institutional mechanisms can have a significant impact in facilitating the implementation of sustainable housing practices with the help of AI. Low Carbon Finance and subsidy and tax incentives are some of the ways that private builders could be encouraged to invest in Passive House construction and foster the use of artificial intelligence. Cooperation between academia, government and industry is also needed for the successful promotion of innovation ecosystems to introduce and disseminate smart construction technologies. This research has yielded positive results, however, there are certain limitations that need to be highlighted. The study was cross-sectional, and therefore, any causal inferences regarding long term impacts are not possible. Moreover, the use of quantitative methods limits the ability to explore the experiences and perceptions of the users of the AI-enabled housing systems in depth. Therefore, future work is recommended to use the longitudinal research design to assess the sustainability performance of an AI-based house over time. In addition, the use of qualitative research methods such as interviews or case studies of residents and practitioners in the industry could provide valuable insights into behavioral adaptation, user-friendliness, and the acceptance of AI in the housing sector. Finally, the use of AI for passive house construction is a big leap forward in the quest for sustainable development, especially in developing countries like Pakistan. Housing systems from economic efficiency to environmental and social relevance can do so if they are equipped with smart technologies and climate adapted architecture. This application of AI in the construction industry should therefore not be viewed simply as a technological breakthrough, but rather a means to invest in a strategy for building resilient, low carbon and sustainable cities fit for the 21st century.

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