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OPTIMIZING PASSIVE DESIGN STRATEGIES IN WARM-HUMID CLIMATES: A HOLISTIC FRAMEWORK FOR GREEN BUILDING RATING SYSTEMS

OPTIMIZACIÓN DE ESTRATEGIAS DE DISEÑO PASIVO EN CLIMAS CÁLIDOS-HÚMEDOS: UN MARCO HOLÍSTICO PARA LOS SISTEMAS DE CERTIFICACIÓN DE EDIFICIOS VERDES

OTIMIZAÇÃO DE ESTRATÉGIAS DE DESIGN PASSIVO EM CLIMAS QUENTES E ÚMIDOS: UMA ABORDAGEM HOLÍSTICA PARA SISTEMAS DE CERTIFICAÇÃO DE EDIFICAÇÕES SUSTENTÁVEIS

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ABSTRACT

Green Building Rating Tools (GBRTs) such as LEED, BREEAM, GRIHA, and WELL assess building sustainability but often overlook a standardized framework for evaluating passive design strategies, which are critical for energy efficiency and thermal comfort in warm-humid climates. This study proposes a holistic framework for optimizing passive strategies by integrating qualitative expert insights with quantitative data across rating systems. Using PCA, MCDA, and regression modelling, a weighted scoring system is developed to compare strategies. Analysis shows that combined passive strategies significantly improve sustainability performance. Home Performance Index (24.72) and ARZ (23.06) score highest in passive design emphasis, while LEED (10.91) and GRIHA (9.96) reveal improvement potential. The proposed AHP framework focuses on envelope optimization, natural ventilation, insulation, and material selection to enhance climate responsiveness. Case studies demonstrate that passive measures such as shading, ventilation, and insulation reduce cooling loads by 59%, lower indoor temperatures by 2.5–3°C, and boost energy savings by up to 29%, reinforcing their value in warm-humid climate contexts.

Keywords
passive design strategies, GBRTs, sustainability performance, warm-humid climate, weighted scoring model

RESUMEN

Las Herramientas de Certificación de Edificios Verdes (GBRT, por sus siglas en inglés), como LEED, BREEAM, GRIHA y WELL, evalúan la sostenibilidad de los edificios, pero a menudo carecen de un marco estandarizado para valorar las estrategias pasivas, esenciales para la eficiencia energética y el confort térmico en climas cálido-húmedos. Este estudio propone un marco holístico para optimizar dichas estrategias, integrando perspectivas cualitativas de expertos con datos cuantitativos de diversos sistemas. Mediante PCA, MCDA y modelos de regresión, se desarrolla un sistema de puntuación ponderado para comparar estrategias. El análisis muestra que las estrategias pasivas combinadas mejoran notablemente el desempeño sostenible. Home Performance Index (24,72) y ARZ (23,06) obtienen puntuaciones más altas, con énfasis en diseños pasivos, mientras que LEED (10,91) y GRIHA (9,96) muestran un margen de mejora. El marco AHP propuesto prioriza la envolvente del edificio, la ventilación natural, la aislación y la selección de materiales. Estudios de caso revelan que las estrategias pasivas pueden reducir la carga térmica en un 59%, bajar la temperatura interior en 2,5–3 °C y ahorrar hasta un 29% de energía, lo que refuerza su valor en contextos de climas cálido-húmedos.

Palabras clave
estrategias de diseño pasivo, GBRTs, desempeño en sostenibilidad, clima cálido-húmedo, modelo de puntuación ponderada

RESUMO

Ferramentas de Avaliação de Edifícios Sustentáveis (GBRTs), como LEED, BREEAM, GRIHA e WELL, avaliam a sustentabilidade, mas frequentemente não incluem um marco padronizado para estratégias de design passivo, essenciais em climas quentes e úmidos. Este estudo propõe um modelo holístico para otimizar essas estratégias, integrando análises qualitativas de especialistas e dados quantitativos entre os sistemas. Utilizando PCA, MCDA e regressão, é criado um sistema de pontuação ponderada para comparação estratégica. A análise mostra que estratégias passivas combinadas aumentam significativamente o desempenho sustentável. Home Performance Index (24,72) e ARZ (23,06) obtêm as maiores pontuações, enquanto LEED (10,91) e GRIHA (9,96) indicam necessidade de aprimoramento. O modelo AHP proposto foca em otimização da envoltória, ventilação natural, isolamento e seleção de materiais. Estudos de caso demonstram que estratégias como sombreamento e ventilação reduzem a carga térmica em 59%, diminuem a temperatura interna em 2,5–3 °C e economizam até 29% de energia, comprovando sua eficácia climática.

Palavras-chave
estratégias de design passivo, GBRTs, desempenho em sustentabilidade, clima quente e úmido, modelo de pontuação ponderada

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INTRODUCTION

Ever since sustainability certification took root in many countries, it has become a widely accepted tool for assessing buildings' environmental performance (Atampugre et al., 2022). Urbanization has increased exponentially, leading buildings to account for nearly 40% of global energy consumption (International Energy Agency [IEA], 2020) and 36% of CO_2 emissions (United Nations Environment Program [UNEP], 2020). The construction sector has thus emerged as a major contributor to climate change (Chen et al., 2021). Consequently, Green Building Rating Tools (GBRTs) such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), and GRIHA (Green Rating for Integrated Habitat Assessment) have become essential for assessing the sector's impact.

However, few studies have explored the comparability and effectiveness of passive design strategies across these rating frameworks, especially in warm-humid climates where such strategies are most crucial. Recent literature supports the notion that passive strategies, such as natural ventilation, shading, and optimized building orientation, can significantly enhance energy efficiency and occupant comfort (Aksamija, 2013; Steemers, 2003; Szokolay, 2012). Specifically, energy use can be reduced by up to 40% in residential buildings and 30% in commercial ones through passive design (Berardi, 2017).

In warm-humid climates, where mechanical space cooling can account for nearly half of a building's electricity use, passive cooling techniques offer promising alternatives to reduce energy demand (Alaidroos & Krarti, 2016; Hu et al., 2023). Current GBRTs vary widely in how they score and weigh passive strategies. For instance, LEED emphasizes energy and water performance but underrepresents passive design elements (USGBC, 2019). BREEAM includes broader sustainability indicators but lacks a clear provision for passive strategies BRE Global (2016). GRIHA aligns better with Indian climate conditions but does not benchmark against global standards (Kochhar et al., 2022). Finally, WELL places heavy emphasis on IEQ parameters such as ventilation and daylighting, while neglecting energy optimization (Kent et al., 2024).

The primary aim of this research is to develop a holistic framework that accounts for passive design strategies across all applicable Green Building Rating Tools (GBRTs) and to evaluate their practical effectiveness in achieving energy savings, thermal comfort, and carbon footprint reductions.

OBJECTIVES OF THE STUDY

- To develop a quantified framework for passive design strategies in warm-humid climates, integrating qualitative insights from experts and performance metrics from case studies with the leading GBRTs: LEED, BREEAM, GRIHA, and WELL.
- To assess these rating tools regarding the weighting and evaluation methodologies of passive design strategies, identifying differences, gaps, and inconsistencies.
- To collect and analyse quantitative performance data from certifying bodies, energy simulation models, and field studies to assess the performance of major passive design features such as natural ventilation, thermal insulation, daylighting, and shading devices.
- To employ advanced statistical techniques such as Principal Component Analysis (PCA), Multi-Criteria Decision Analysis (MCDA), and weighted scoring methods for quantifying the relative impact of different passive design strategies within and across rating frameworks.
- To develop predictive models and conduct sensitivity analysis using regression equations to identify the most influential passive design criteria contributing to energy efficiency, thermal comfort, and reduced carbon footprint.
- To provide policy recommendations for stronger integration and standardization of passive design measures into GBRTs, fostering a holistic and climate-responsive approach to sustainable building design.

This research will benefit various stakeholders, including architects, policymakers, developers, and sustainability consultants, by providing an evidence-based framework to evaluate passive design solutions across certification systems. By combining statistical data with qualitative expert insights, this study supports a performance-based, climate-adaptive certification process. Findings aim to reduce operational energy demand in buildings, a crucial step toward achieving global climate goals. If properly integrated, passive strategies could reduce carbon emissions by 50% by 2030 and help achieve net-zero status by 2050 (Legg, S., 2021). These goals require systematic integration, assessment, and optimization of passive design within formal certification programs to ensure energy efficiency, occupant comfort, and climate-sensitive architectural solutions.

LITERATURE REVIEW

Passive design strategies, including natural ventilation, thermal insulation, daylighting, and shading devices, enhance building performance in warm-humid climates. These strategies improve indoor environmental quality and energy efficiency by leveraging local climatic conditions, thereby reducing dependence on mechanical systems. Green Building Rating Systems (GBRS) generally endorse such approaches for sustainability assessment. Natural ventilation is a key passive strategy that promotes indoor thermal comfort by facilitating heat removal and improving air quality. A systematic review highlights its popularity in hot-humid

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regions for enhancing thermal comfort while lowering mechanical cooling demands (Chen et al., 2021). Thermal insulation, meanwhile, minimizes heat transfer between indoor and outdoor environments. Zahiri & Altan (2016) demonstrated that proper insulation in hot climates significantly reduces cooling energy consumption. Daylighting replaces artificial lighting with natural light, helping conserve energy. However, it must be balanced with solar heat gain to be effective in warm-humid conditions. Altan et al. (2016) showed that appropriate daylighting design improves occupant comfort while reducing lighting loads. Shading devices, such as louvers and overhangs, are essential for blocking direct solar radiation and lowering indoor heat gain. Jega and Muhy Al-Din (2023) reported that shading significantly decreases energy demand in hot-humid buildings.

Beyond shading and insulation, materiality plays a crucial role. Tang et al. (2020) advocate including such systems under the innovation categories in GBRTs. Major GBRS—LEED, BREEAM, GRIHA, and WELL, evaluate sustainability through several indicators. A comparative study revealed that, while all these systems promote energy-efficient designs, the emphasis on passive strategies varies (Chen et al., 2015). LEED assigns points across energy, IEQ, and innovation, with studies suggesting improved occupant satisfaction in LEED-certified buildings (Kent et al., 2024). BREEAM emphasizes resource efficiency and well-being, encouraging passive design to attain higher scores. GRIHA focuses more on India's climate, promoting passive techniques such as daylighting and natural ventilation (Jadhav et al., 2020).

Despite their potential, passive strategies face several barriers in GBRS implementation, particularly in warm-humid zones. Chenvidyakarn (2018) emphasized challenges like inadequate climate data, behavioural variability, and conflicting design goals. Effective implementation requires a holistic approach that considers orientation, climate, and user behaviour. While active systems (HVAC, lighting) improve efficiency, passive strategies reduce energy demand at the design stage.

Indian GBRSs have yet to provide region-specific assessment mechanisms tailored to varying climatic needs (Shan & Hwang, 2018). Moreover, GRIHA and others still undervalue passive design in their credit systems, leaving significant scope for expansion. A shift toward rewarding passive interventions can better support sustainability goals in practice. Recent low-energy interventions and rising energy costs have renewed interest in passive design. GBRTs have become key to standardizing green building assessments globally. However, many remain indifferent to regional climate nuances, creating evaluation gaps. The National Building Code (NBC) of India acknowledges the importance of early-stage passive design assessment and urges integration of region-specific measures into certification programs.

The built environment is known to modify the climatic variables that influence the human body's energy balance; thermal comfort is one of the factors that influence spatial habitability (Sosa-Castro et al., 2017). To truly embed sustainability, GBRTs must move beyond generic scoring and develop climate-sensitive, research-based frameworks. As the National Building Code of India (Bureau of Indian Standards, 2016) highlights, passive design is cost-effective, locally adaptable, and critical to ensuring occupant comfort while reducing energy use. Regional standards should reflect these priorities to support a resilient, low-carbon built environment.

METHODOLOGY

This study employs a mixed-method research design to systematically evaluate the integration and weighting of passive design strategies within major Green Building Rating Tools (GBRTs), including LEED, GRIHA, BREEAM, and WELL, with a focus on warm-humid climates. The research objective is not to assess the inherent effectiveness of the strategies themselves, but to analyze how they are accounted for and prioritized within these certification frameworks. The methodology is structured into three sequential phases: data collection and criterion mapping, quantitative and qualitative analysis, and framework development and benchmarking.

The first phase involved comprehensive data collection and criterion mapping. Qualitative data were gathered through semi-structured interviews with architects, sustainability consultants, and building performance analysts to capture expert insights on the perceived importance and implementation challenges of passive strategies. Concurrently, quantitative data on building performance metrics—such as energy consumption and daylighting levels—were compiled from case studies and literature focused on warm-humid regions. Crucially, a systematic mapping of the credit criteria from the selected GBRTs was conducted to identify and categorize all prerequisites and credits relevant to passive design, establishing a baseline of their current representation.

In the second phase, this data was subjected to rigorous quantitative and qualitative analysis. The Analytic Hierarchy Process (AHP) was used to assign relative weights to passive design parameters based on expert judgment, creating a benchmark for their ideal importance. Simultaneously, regression models were developed to identify the relationship between passive design variables and key performance indicators. The outcomes of these models—the expert-derived weights and performance-based predictors—were then systematically compared against the actual credit weighting and structure of the GBRTs through sensitivity and ROC (Receiver Operating Characteristic curve) analysis, revealing gaps and misalignments.

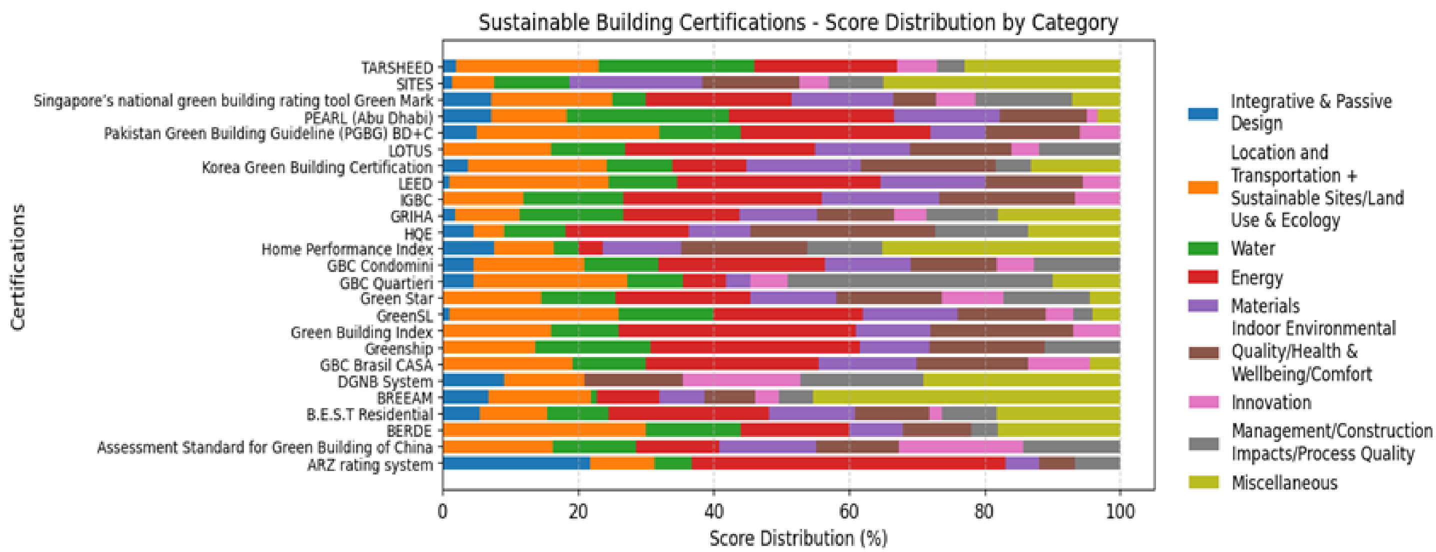

Figure 1. Score distribution of certifications across different categories. Source: Prepared by authors.

The final phase focused on synthesizing these findings into a practical output. A new weighted scoring framework was developed by integrating AHP-based expert weights with performance data from statistical models. This proposed framework was then benchmarked against a selection of certified projects under LEED, BREEAM, GRIHA, and WELL to illustrate its application and to identify, with greater specificity, where and how existing rating systems could be enhanced to better integrate and reward passive design strategies in future green building assessments.

RESULTS AND DISCUSSION

This study employed a mixed-method approach incorporating PCA, AHP, regression analysis, and expert interviews to evaluate how passive design strategies are represented and prioritized across global Green Building Rating Tools (GBRTs) in warm-humid climates. Results revealed significant inconsistencies in the weighting and depth given to passive strategies in prevailing tools, necessitating a more climate-responsive assessment framework.

VARIATIONS IN SUSTAINABILITY EMPHASIS ACROSS CERTIFICATION SYSTEMS

An in-depth analysis of the score distributions across 25 global green building certification systems (Figure 1) highlights the diverse ways in which sustainability is interpreted and prioritized across geographic and climatic regions. Internationally prominent systems such as LEED (U.S.) and BREEAM (UK) demonstrate a relatively balanced scoring methodology, distributing emphasis evenly among key categories including energy efficiency, material usage, water conservation, and indoor environmental quality (IEQ). This balanced structure reflects their intent to provide universally applicable sustainability benchmarks.

Table 1. PCA Breakdown for each Certification based on passive design strategies. Source: Prepared by authors.

Certification	PCA Score
ARZ rating system	3.84
Assessment Standard for Green Building of China	-0.81
BERDE	-0.81
B.E.S.T Residential	0.35
BREEAM	0.63
DGNB System	1.13
GBC Brasil CASA	-0.81
Greenship	-0.81
Green Building Index	-0.81
GreenSL	-0.59
Green Star	-0.81
GBC Quartieri	0.16
GBC Condomini	0.16
Home Performance Index	0.81
HQE	0.16
GRIHA	-0.40
IGBC	-0.81
LEED	-0.61
Korea Green Building Certification	-0.02
LOTUS	-0.81
Pakistan Green Building Guideline (PGBG) BD+C	0.26
PEARL (Abu Dhabi)	0.73
Singapore Green Mark	0.72
SITES	-0.50
TARSHEED	-0.38

In contrast, region-specific tools such as Singapore's Green Mark and Abu Dhabi's PEARL certification system assign

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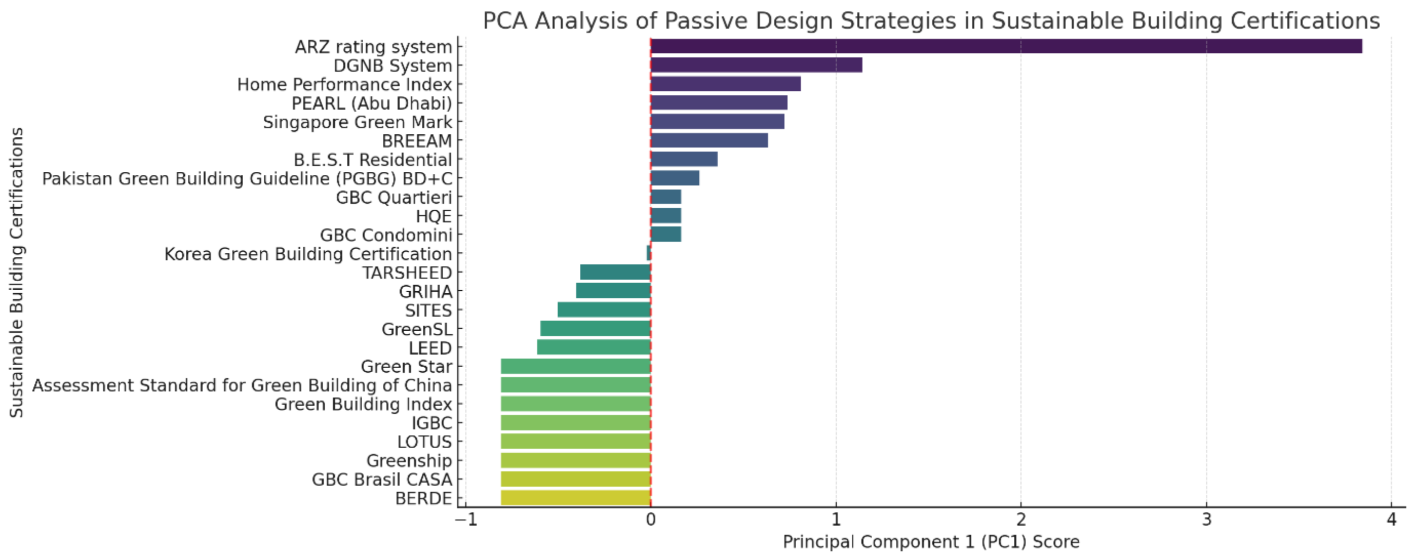

Figure 2. PCA analysis of passive design strategies in sustainable building certification. Source: Prepared by authors.

greater weight to categories such as sustainable land use, water efficiency, and urban ecological integration. These priorities reflect the dense urban character and tropical climate of Singapore, and the arid, resource-scarce environment of the Middle East. Meanwhile, European systems such as DGNB (Germany) and HQE (France) place greater importance on indoor environmental quality and occupant well-being, aligning with stringent health, comfort, and safety regulations prevalent within the EU.

On the other hand, systems like Greenship (Indonesia) and TARSHEED (Qatar) prioritize water conservation and energy reduction, given the pressing environmental issues faced in those regions. Collectively, these distinctions underscore that GBRTs are not one-size-fits-all models but are deeply shaped by contextual climatic, cultural, and policy factors, emphasizing the need for adaptive and region-sensitive sustainability frameworks.

EMPHASIS ON PASSIVE DESIGN STRATEGIES: PCA INSIGHTS

Principal Component Analysis (PCA) outcomes (Figure 2, Table 1) reveal disparities in how certification systems incorporate passive design strategies. PCA is data-driven, reducing all variables into principal components. It highlights the systems that statistically emphasize certain passive strategies (ventilation, shading, insulation). The ARZ rating system scored highest (PC1 = 3.84), followed by DGNB, Home Performance Index, PEARL, and Green Mark, indicating strong integration of ventilation, insulation, and shading. In contrast, systems such as LEED, GRIHA, IGBC, Green Building Index, and Greenship scored negatively, reflecting weaker incorporation of passive design. Because PCA relies on the statistical variance of input variables, it tends to highlight systems with strong quantitative integration of multiple passive features (e.g., ARZ, DGNB). However, PCA does not capture subjective prioritization or expert-assigned weightings, which explains why some systems that score well in PCA rank differently in AHP.

PASSIVE STRATEGY RANKINGS: AHP AND REGRESSION RESULTS

The Analytic Hierarchy Process (AHP) yielded weighted rankings (Table 2, Figure 3), identifying the Home Performance Index (24.72) and ARZ (23.06) as the top-performing rating systems, given their strong emphasis on passive design strategies. In contrast, LEED (10.91) and GRIHA (9.96) received moderate scores, indicating limitations in their responsiveness to climate-adaptive design principles. AHP is expert-driven and prioritizes based on human judgment of importance. That is why Home Performance Index and ARZ both appear strong, but systems like LEED move up in AHP (despite weaker PCA scores) because experts recognize their broader frameworks.

The AHP scores were derived from expert judgments ($n = 15$) who conducted pairwise comparisons of passive design criteria across 25 rating systems. The experts—architects, consultants, and policy advisors from India, Singapore, and the Middle East—were selected for their direct experience in warm-humid climate projects. The final weights were synthesized using the standard AHP eigenvalue method to ensure consensus-based prioritization.

Complementing this, regression analysis (Table 4) demonstrated the statistical significance of specific passive design elements in reducing cooling energy consumption: shading devices led to a reduction of 18.2 kWh/m²/year ($p < 0.001$), wall insulation achieved a savings of 12.3 kWh/m²/year, roof albedo contributed 10.5 kWh/m²/year, and natural ventilation improved air change

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rates by 7.8 ACH. The regression model accounted for 82% of the variance in cooling energy use ($R^2 = 0.82$), underscoring the critical role of passive strategies. These coefficients were extracted and standardized from multiple peer-reviewed studies in warm-humid climates. To ensure comparability, values were normalized against baseline buildings reported in the literature (typically minimum-compliance or conventional designs without passive features). The "savings" therefore represent relative improvements over these baselines, rather than absolute universal figures.

Additionally, ROC curve analysis (Figure 4) supported these findings, with an AUC (Area Under Curve) of 0.80, indicating strong predictive accuracy of passive design variables in assessing sustainability performance. The ROC was based on a logistic classification where buildings were categorized as "high-performing" if cooling load reduction was ≥20% compared to baseline values reported in literature, and "low-performing" otherwise. Using passive variables (shading, insulation, roof albedo, natural ventilation) as predictors, the model achieved an AUC of 0.80, demonstrating that these strategies reliably distinguish between high- and low-performance cases.

The divergence between PCA and AHP highlights a key insight: PCA reflects the structural embedding of passive criteria in certification frameworks, whereas AHP reflects perceived importance assigned by experts. For example, LEED's relatively poor PCA score (-0.61) shows limited statistical emphasis on passive features, yet its moderate AHP score (10.91) reflects experts' recognition of its global adaptability and indirect contributions to passive performance. This overlap and divergence illustrate how statistical and expert-based assessments can complement each other. Regression outcomes reinforce both PCA and AHP findings by quantifying the impact of individual passive measures. For instance, shading (-18.2 kWh/m²/yr) and wall insulation (-12.3 kWh/m²/yr) emerge as statistically significant predictors of energy savings, aligning with expert-weighted AHP rankings that placed envelope and shading strategies at the top. Thus, while PCA/AHP differ in overall rankings, both converge on the importance of envelope optimization and ventilation.

EXPERT INSIGHTS ON PASSIVE DESIGN IMPLEMENTATION

Insights from expert interviews were gathered through semi-structured interviews with 15 professionals, including architects, sustainability consultants, and policy advisors, primarily from India, Singapore, and the Middle East. Selection criteria included direct experience in warm-humid climate projects or involvement with GBRTs. Interviews included 8 participants from India, 4 from Singapore, and 3 from the Middle East. A purposive sampling strategy was adopted to ensure direct involvement with warm-humid climate projects or GBRT development. Responses were coded and categorized

Table 2. Weighted scores based on sustainability for each certification. Source: Prepared by authors.

Rank	Certification	Weighed Score
1	Home Performance Index	24.72
2	ARZ rating system	23.06
3	SITES	19.28
4	PEARL (Abu Dhabi)	19.14
5	Singapore Green Mark	15.06
6	Korea Green Building Certification	14.26
7	BREEAM	14.14
8	DGNB System	12.09
9	GBC Quartieri	11.58
10	B.E.S.T Residential	11.44
11	Pakistan Green Building Guideline	11.27
12	TARSHEED	11.19
13	BERDE	11.04
14	GBC Condomini	10.97
15	LEED	10.91
16	Greenship	10.66
17	HQE	10.40
18	GBC Brasil CASA	10.29
19	GreenSL	10.19
20	GRIHA	9.96
21	Green Star	9.66
22	Green Building Index	9.16
23	LOTUS	8.98
24	IGBC	6.52
25	Assessment Standard for Green Building of China	4.12

Figure 3. Ranking based on weighted scores. Source: Prepared by authors.

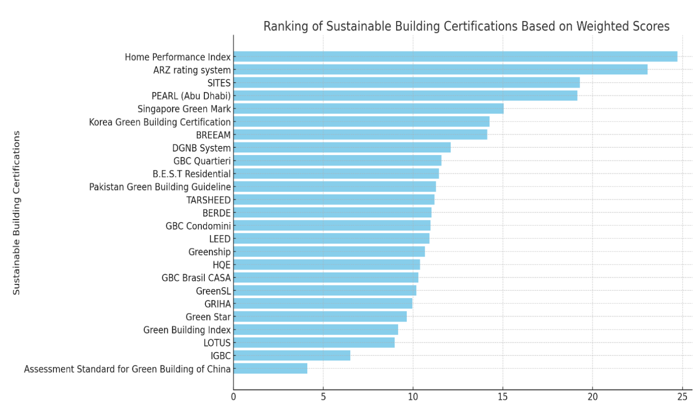

Figure 4. ROC curve. Source: Prepared by authors.

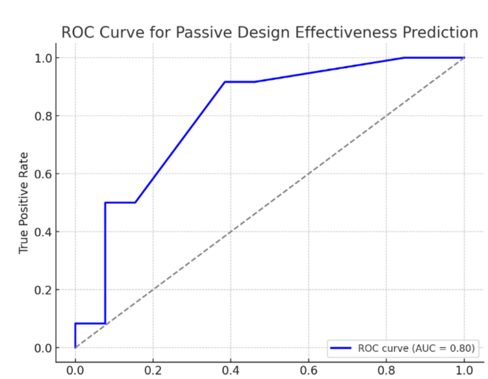

Table 3. Mean Scores of Passive Design Variables based on experts. Source: Prepared by authors.

Variable	Mean	Standard Deviation (SD)	Minimum	Maximum
Cooling Energy Consumption (kWh/m²/yr)	134.5	18.7	110.0	180.0
Shading Devices (Binary: 1 = Yes, 0 = No)	0.65	0.48	0.00	1.00
Natural Ventilation (ACH)	4.5	1.2	1.5	6.0
Roof Albedo (Reflectance %)	0.52	0.15	0.20	0.80
Wall Insulation (U-Value, W/m²K)	1.2	0.6	0.4	2.5

thematically, and key variables such as shading, insulation, and ventilation were quantified using expert rating scales. The qualitative insights were then translated into quantitative ratings through expert scoring exercises, where participants assigned relative importance values to each strategy on a standardized scale. These scores informed Table 3.

Most experts emphasized cross-ventilation, shading devices, and insulation as critical for warm-humid climates. Many referenced vernacular precedents, such as thick lime walls and courtyards in Amaravati, which improve both comfort and daylight access.

One architect stated:

"In warm-humid regions, the most effective passive design strategy is cross-ventilation. Placement of openings should encourage wind movement to reduce humidity naturally."

Others emphasized roof insulation and reflectivity. Experts also highlighted disparities in insulation design practices, noting that U-values ranged from 0.4 to 2.5 W/m²K across buildings studied (Table 3). A material scientist added:

"PCMs, bamboo composites, and high-albedo roofing materials can significantly enhance thermal performance."

However, several challenges continue to hinder the widespread implementation of passive design strategies. Experts highlighted key barriers, including cost-related reluctance among developers, the constraints posed by high urban density, which limit effective ventilation and daylight penetration, and the absence of robust performance-based metrics in current Green Building Rating Tools (GBRTs). Despite these obstacles, technology was widely regarded as a catalyst for improvement. Many experts emphasized the potential of AI-driven tools to optimize passive strategies, the use of Building Information Modelling (BIM) for simulating airflow, shading, and daylighting, and the importance of integrating locally sourced materials with climate-appropriate thermal properties. There was broad consensus on the necessity of policy-driven incentives and on the mandatory incorporation of passive design components into rating systems. As one sustainability analyst noted:

"Governments should mandate passive elements and incentivize developers through tax rebates and expedited permits."

Experts further recommended that architectural curricula include training in passive design to ensure that future professionals are well-equipped.

FRAMEWORK DEVELOPMENT FROM EXPERT INPUTS

The framework was derived by combining quantitative weightings from AHP (Table 2), statistical validation from regression analysis (Table 4), and expert perception data (Table 3). This triangulation ensured that the inclusion of each strategy was not only based on theoretical relevance but also supported by expert consensus and quantified energy performance impacts. It highlights strategies such as envelope optimization, insulation, ventilation, and material selection—tailored for warm-humid climates. These results validate the need for integrating contextual passive strategies into GBRTs to ensure true climate responsiveness.

The core theme of the framework involves Building Envelope Optimization, Natural Ventilation, Roof & Wall Insulation, and Material Selection as components to significantly lower energy demand. Among these, strategies such as shading devices, insulation thickness (U-values, R-values), and roof albedo were directly quantified through regression analysis, demonstrating measurable reductions in cooling loads (Table 4). Others, such as adaptive facades and bamboo composites, were included based on expert judgment and qualitative evidence, indicating strong potential but requiring further empirical validation. Thus, the framework integrates both measured impacts and emerging strategies, reflecting both current practice and innovation trajectories. Qualitative themes from interviews (e.g., the role of courtyards, vernacular openings, adaptive facades) were triangulated with quantitative AHP weights and regression outcomes to refine the framework categories.

The framework adopts an all-encompassing, multi-layered approach, integrating passive strategies to create energy-efficient, climate-responsive buildings in India's warm and humid zones. Importantly, the

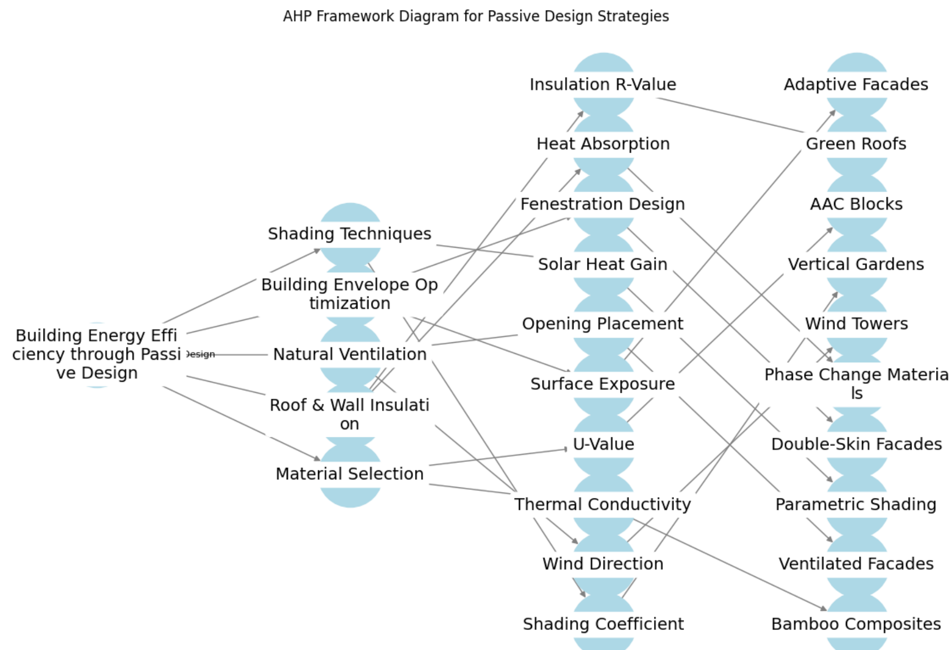

Figure 5. Framework web of passive strategies for warm and humid climates through expert opinions. Source: Prepared by authors.

framework is not a static checklist but a weighted decision-support tool. The AHP-based scoring allows each measure to be ranked by relative importance, while regression coefficients provide a means to translate design decisions into expected energy savings. For example, designers can prioritize high-impact strategies like shading and wall insulation, while policymakers can use the weightings to adjust GBRT credits toward climate-specific relevance.

EVIDENCE FROM CASE STUDIES

Case studies from various climatic regions strongly reinforce the effectiveness of passive design strategies in improving thermal comfort and reducing energy demand (Tables 4 and 5). A total of five representative case studies and one meta-analysis were included. Selection criteria were (i) location in warm-humid or hot-climate regions, (ii) availability of quantifiable performance data on passive strategies, and (iii) diversity in building types (residential and non-residential). In Tangerang, Indonesia, a hot-humid region, the integration of insulation, ventilation, and solar shading resulted in a 35% reduction in cooling loads, a 2.5°C drop in indoor temperatures, and a 29% decrease in energy use, demonstrating the combined impact of multiple passive techniques.

A broader meta-analysis of hot-climate buildings revealed consistent benefits, with passive strategies leading to a 31% average reduction in cooling loads and a 23% increase in thermal comfort hours. In the Gaza Strip, known for its harsh climate and limited access to energy, passive interventions—such as improved envelope design and shading—achieved a 59% reduction in cooling demand and a 3°C reduction in indoor temperatures. In Washington, USA, the use of advanced glazing and shading reduced discomfort hours by up to 60%, while Egyptian case studies reported increases in comfort hours ranging from 22.6% to 46%, depending on the city and specific intervention.

Although the present case studies are drawn from Asia, the Middle East, and North America, similar climatic and urban challenges exist in Latin America. For example, studies in Brazil and Colombia have documented the role of shading and cross-ventilation in reducing cooling demand in tropical regions (e.g., GBC Brasil CASA framework). Linking these regional findings demonstrates the transferability of our proposed framework to Latin American contexts, where warm-humid zones such as the Amazon basin face parallel challenges. Figures reported represent either averages from simulation studies (Hu et al., 2023) or measured post-occupancy evaluations (Chen et al., 2021). When sources reported a range, we used the mean. Energy savings are compared against conventional baseline buildings in the same climate and use type. While these findings demonstrate strong technical performance, their adoption is shaped by local cultural practices (e.g., vernacular courtyards in Gaza), economic feasibility (e.g., the high cost of triple glazing in the U.S. context), and regulatory incentives (e.g., Egypt's evolving energy codes). This indicates that passive design effectiveness is not only climatic but also socio-economic and policy-dependent. Which means, collectively, though these findings highlight the versatility, resilience, and effectiveness of passive design when tailored to local climatic and cultural contexts, they also emphasize the need for climate-specific guidelines and performance-based benchmarks in green building frameworks to mainstream these strategies globally.

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Table 4. Impact of Passive Strategies on Cooling Energy Consumption. Source: Prepared by authors.

Variable	Coefficient (β)	Standard Error	t-Statistic	p-Value
Intercept (β_0)	185.4	5.2	35.65	<0.001
Shading Devices	-18.2	3.4	-5.35	<0.001
Natural Ventilation	-7.8	2.1	-3.71	0.002
Roof Albedo	-10.5	2.8	-3.75	0.001
Wall Insulation	-12.3	3.0	-4.10	<0.001

Table 5. Performance metrics- case studies. Source: Prepared by authors.

Case Study Location	Passive Strategies Implemented	Cooling Load Reduction (%)	Indoor Temperature Reduction (°C)	Energy Savings (%)	Thermal Comfort Improvement (%)
Tangerang, Indonesia (Chen et al., 2021)	Improved insulation, natural ventilation, solar shading	35%	2.5°C	29%	N/A
Hot Climates (Hu et al., 2023)	Roof and wall insulation, window shading, ventilation optimization	31% (avg.)	2.2°C (avg.)	29%	23% increase in thermal comfort hours
Gaza Strip (Mushtaha et al., 2021)	Shading devices, natural ventilation, thermal insulation	59%	3.0°C	N/A	N/A
Washington, USA (Rana, 2021)	Low-E triple-glazed windows, overhangs, blinds, enhanced insulation, natural ventilation	N/A	N/A	N/A	44% - 60% reduction in discomfort hours
Egypt (El Gindi, S. 2023)	Passive cooling interventions	N/A	N/A	N/A	Increase in comfort hours: Aswan (22.6% → 33.1%), Cairo (31.1% → 38.6%), Alexandria (36.9% → 46%)

SYNTHESIS: TOWARD A HOLISTIC PASSIVE DESIGN FRAMEWORK

The study culminates in proposing a climate-sensitive passive design framework (Figure 6) integrating key strategies identified across analytical methods. The framework is structured to guide both design and assessment, categorizing passive strategies under five clusters: Envelope (insulation, shading, glazing), Ventilation (cross-ventilation, stack effect), Daylighting (glare control, window placement), Spatial Planning (zoning, orientation), and Materiality (thermal mass, surface reflectance).

The combination of PCA, AHP, and regression thus offers a triangulated understanding. PCA reveals structural representation of passive strategies, AHP contextualizes expert perceptions of importance, and regression validates their real-world performance impacts. Together, these methods reveal both gaps (underrepresentation of LEED/GRIHA despite strong expert recognition) and synergies (high alignment between PCA and AHP in ARZ and HPI) in

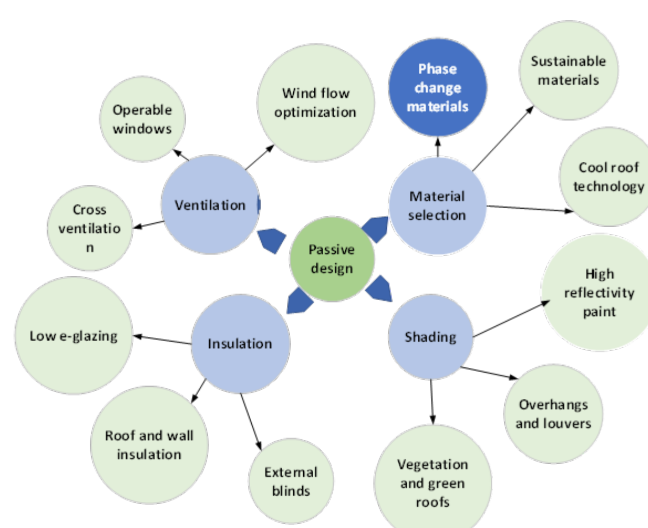

Figure 6. Framework based on findings from case studies and expert interviews. Source: Prepared by authors.

current rating systems. This framework not only bridges the gap between strategy and rating but also addresses contextual adaptability, which is currently absent in GBRTs. The cumulative insights suggest that existing rating systems, though expansive, do not sufficiently promote passive design excellence, especially in warm-humid regions.

CONCLUSION

The study achieved its objectives by (i) systematically comparing GBRTs to passive strategy weightings using PCA, AHP, and regression analysis, (ii) integrating expert interviews to capture context-specific knowledge, and (iii) developing a weighted decision-support framework that quantifies both measured and perceived contributions of passive strategies. This study developed a data-driven framework that integrates passive design strategies tailored to India's warm-humid climates. The framework emphasizes a systems-based approach over isolated interventions and addresses the need for regional adaptability. Its significance lies in bridging theoretical strategies with real-world application, offering scalable guidance for both urban and rural contexts. A key contribution of this research is the integration of multiple analytical methods (PCA, AHP, regression) with expert-coded insights, which together move beyond descriptive lists of strategies toward a quantified, climate-specific prioritization model. The comparative findings—such as the underrepresentation of passive strategies in LEED and GRIHA, in contrast to stronger performance in ARZ and HPI—offer evidence-based benchmarks not previously consolidated in the literature. However, limitations include the need for broader geographic validation, adaptability in dense urban areas, and financial feasibility for some interventions.

For professional practice, the framework provides actionable guidance: shading and wall insulation should be prioritized as high-impact, low-cost interventions, while innovative materials like PCMs and adaptive facades should be pursued where budgets allow. For policy, governments can accelerate adoption by embedding passive measures as mandatory prerequisites in GBRTs and linking them with financial incentives such as tax rebates or expedited approvals. Certifying bodies should also recalibrate their scoring to reflect climate-responsive priorities, ensuring that strategies critical for warm-humid regions receive adequate weight.

Future research should focus on long-term performance studies, integration of AI-based design tools, and performance-based assessment models. Policy support, financial incentives, and education are critical for widespread adoption. This study contributes a foundational step toward climate-responsive, occupant-centered architecture in green certification systems.

AUTHOR CONTRIBUTION CRediT

Conceptualization, K.C.; Data Curation, K.C.; Formal Analysis, K.C.; Funding Acquisition; Research, K.C.; Methodology, K.C. and K.K.M.; Project Management, K.K.M and S.D.; Resources, K.C.; Software. K.C.; Supervision, K.K.M and S.D.; Validation, K.C.; Visualization, K.C.; Writing - original draft, K.C.; Writing - review and editing, K.K.M and S.D.; Writing - revision and editing, K.C., K.K.M. and S.D.

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