

## Energy-efficient building design in tropical climates: A systematic literature review of heat transfer strategies

L. M. F. Purwanto<sup>1\*</sup>, Stephanus Evert Indrawan<sup>2</sup>

<sup>1</sup>Doctor Program in Architecture, Universitas Katolik Soegijapranata, Indonesia

<sup>2</sup>Department of Architecture, Universitas Ciputra, Indonesia



ARTICLE INFO	ABSTRACT
<p><i>Article history:</i>            Received December 06, 2025            Received in revised form Jan. 12, 2026            Accepted Februari 03, 2026            Available online March 01, 2026</p> <p><i>Keywords:</i>            Energy saving design            Tropical climate            Heat flow            Passive cooling</p> <p>*Corresponding author: L. M. F. Purwanto            Doctor Program in Architecture,            Universitas Katolik Soegijapranata,            Indonesia            Email: <a href="mailto:lmf_purwanto@unika.ac.id">lmf_purwanto@unika.ac.id</a>            ORCID: <a href="https://orcid.org/0000-0002-7081-489X">https://orcid.org/0000-0002-7081-489X</a></p>	<p><i>Architectural structures located in tropical regions are exposed to substantial energy demands for cooling through air-conditioning systems due to intense solar radiation and persistently high humidity levels. Consequently, these regions are characterized by high energy consumption, where cooling loads are dominant, thereby making the role of heat-transfer mechanisms and effective architectural design increasingly critical for achieving thermal comfort and energy efficiency, particularly when compared with middle-latitude regions. The primary objective of this study is to synthesize contemporary research addressing heat-transfer control strategies in energy-efficient building design for tropical climates. The review employs the PRISMA methodological framework, systematically examining 85 peer-reviewed articles published between 2010 and 2025 and indexed in major scientific databases. The analyzed studies are categorized according to the design strategies adopted, including passive cooling approaches, building-envelope optimization, material innovation, and the use of simulation tools in architectural design. The findings indicate that passive strategies, particularly natural ventilation, shading through overhang devices, and the application of reflective or high-albedo surface materials, exhibit the highest effectiveness in mitigating heat gain. Furthermore, the use of advanced insulation materials and adaptive façade systems demonstrates significant potential for enhancing building performance in future applications. However, the integration of simulation-based design methods with empirical validation remains at an early stage of development. Overall, this paper provides a comprehensive analysis of prevailing research trends, while critically addressing current challenges and outlining future prospects for sustainable cooling strategies within the tropical built environment.</i></p>

### Introduction

The building sector has been widely recognized as the largest consumer of global energy resources and one of the principal contributors to greenhouse gas emissions, accounting for approximately 40% of the world's total energy consumption (Gupta and Deb 2023). In tropical environments, this challenge is further intensified

by abundant solar radiation, elevated humidity levels, and persistently high ambient temperatures, all of which generate substantial cooling demands. Excessive solar heat gains, combined with inadequate performance of building envelopes, frequently lead to a heavy reliance on mechanical air-conditioning systems, thereby significantly increasing overall energy consumption and associated carbon emissions



(Saber, Tham, and Leibundgut 2016). With the continued rise in global temperatures and accelerated urbanisation in tropical zones, the demand for energy-efficient building design (Chua and Chou 2010; Li, Yang, and Lam 2013; Toe and Kubota 2015) capable of effectively regulating heat transfer has become a critical and pressing research priority.

Tropical latitudes distributed across regions such as Southeast Asia, the Caribbean, and parts of Africa are characterised by high humidity levels, continuous solar exposure, and limited diurnal temperature variation. These climatic attributes create thermal environments that are fundamentally distinct from those of temperate regions, thereby requiring climate-responsive and region-specific architectural design strategies (GhaffarianHoseini et al. 2024). Passive design approaches that facilitate the maintenance of indoor thermal comfort (Schulze and Eicker 2013; Wong et al. 2010; Rajapaksha, Nagai, and Okumiya 2003) have long been embedded within traditional vernacular architecture in tropical regions. Such approaches include natural ventilation and shading strategies (Garde et al. 2014; Hien, Poh, and Feriadi 2000; Indraganti 2010), as well as the extensive use of high thermal mass materials. Nevertheless, a significant proportion of contemporary urban buildings fail to adopt these principles, resulting in excessive indoor heat gain, elevated indoor temperatures, and increased energy consumption (Cung and Rosetia 2023). Consequently, the development of building design systems that regulate heat transfer through a combination of passive solutions and smart material-based strategies is essential for achieving sustainable thermal comfort.

Heat transfer in tropical residential buildings primarily occurs through conduction across walls and roofs, natural convection induced by air movement, and radiation from solar exposure. Poorly insulated building envelopes can exacerbate overheating under intense solar radiation, whereas well-designed and properly insulated envelopes can substantially reduce indoor heat gain. Lei, Yang, and Yang (2016) reported that peak cooling loads in residential buildings may be reduced by up to 25% through improved envelope performance. Similarly, Zingre et al. (2015) demonstrated that the application of cool roof panels can reduce building envelope surface temperatures by as much as 15°C under tropical climatic conditions,

indicating a significant reduction in heat transfer into interior spaces.

Despite the growing body of research on energy-efficient building components, there remains a lack of comprehensive synthesis specifically focused on tropical contexts. Existing review studies have often aggregated findings across multiple climatic zones without sufficiently addressing the unique characteristics of tropical environments (Masood et al. 2023). In response to this gap, the present research aims to review and systematically classify heat transfer control strategies that are applicable to buildings located in tropical regions.

The primary objective of this study is to conduct a critical review of energy-efficient design techniques that mitigate heat transfer in tropical buildings. Specifically, the investigation seeks to identify the most effective passive and active strategies including phase change materials (PCM), reflective coatings, radiative cooling technologies, and ventilated envelope systems and to evaluate the extent to which these strategies influence building performance in terms of energy consumption.

The conceptual stance adopted in this research is based on an integrated solution framework, suggesting that a synergistic combination of passive cooling design measures, reflective and radiative materials, and PCM-based thermal storage systems can significantly enhance building energy efficiency in tropical climates.

This study holds both academic and practical significance. From an academic perspective, it provides researchers with a structured synthesis of recent advancements in the field, along with a clearly articulated agenda for future research. From a professional standpoint, the findings serve as a practical reference for architects and engineers, offering guidance and benchmarks for the design of low-energy buildings (Chua and Chou 2010; Li, Yang, and Lam 2013; Garde et al. 2014) tailored to tropical climatic conditions (Kajjoba et al. 2025).

Methodologically, this investigation is presented as a Systematic Literature Review (SLR) conducted in accordance with the PRISMA framework. The reviewed data consist of peer-reviewed journal articles indexed in Scopus, ScienceDirect, MDPI, and SpringerLink, published between 2010 and 2025. The selection criteria include relevance to tropical climates, a focus on building heat transfer mechanisms, and the evaluation of energy performance. The

selected studies were categorised into passive design strategies, material development, hybrid systems, and simulation-driven optimisation approaches.

Luiz dos Santos, Silva, and dos Reis (2024) reported that the integration of PCM with natural ventilation strategies (Schulze and Eicker 2013; Indraganti 2010; Hien, Poh, and Feriadi 2000) resulted in an 18% reduction in cooling demand for tropical buildings in Brazil. Similarly, Alassaad, Minto, and de Wilde (2025) examined PCM integration within hybrid systems and concluded that the combination of PCM with reflective coatings was particularly effective in reducing heat gain. Furthermore, Suhendri et al. (2020) reviewed passive radiative cooling techniques (Muhammad-Sukki et al. 2012; Nahar, Sharma, and Purohit 2003; Gamero-Salinas et al. 2021) and demonstrated that reflective roof coatings can effectively reject absorbed heat through thermal radiation, even under humid tropical conditions.

Recent research has revealed emerging trends in heat transfer control technologies. Radiative cooling materials have gained increasing attention due to their ability to dissipate absorbed heat via infrared radiation, thereby reducing roof temperatures and overall cooling loads (Guo et al. 2024; H. Zhang et al. 2025). Concurrently, bio-based PCMs (Balasbaneh and Tee 2022; Alam et al. 2014) have been identified as environmentally sustainable alternatives, offering improved phase stability (Vedrtnam et al. 2025). Al-Obaidi et al. (2014) demonstrated that the application of reflective roofs and ventilated housing designs can reduce indoor temperatures by 3–5°C in tropical dwellings, enhancing occupant comfort while lowering energy consumption.

Passive cooling measures, such as roof coverings and external wall shading, continue to represent cost-effective solutions for tropical regions. Lapisa et al. (2019) showed that ventilated roofs with reflective surfaces can reduce attic temperatures by up to 12°C. Meanwhile, (Budhiyanto and Tampubolon 2025) found that cool roof systems (G. Zhang et al. 2023; Mettrick and Ma 2024; Wong et al. 2010) outperform green roofs in mitigating indoor heat gain in Indonesian tropical cities. Additionally, Savero, Antaryama, and Soemardiono (2020) highlighted the applicability of evaporative cooling in reducing building cooling loads when integrated with appropriate building orientation

and façade design to achieve optimal energy performance and occupant comfort.

The originality of this study lies in its comprehensive synthesis of findings derived from diverse heat transfer approaches, including passive cooling strategies and hybrid material technologies, within tropical climatic conditions. Unlike previous reviews that have focused on isolated technologies, this SLR presents an integrated perspective that encompasses material science, architectural design, and energy modelling.

By offering an updated overview of effective heat transfer strategies, this systematic review contributes to the advancement of sustainable tropical architectural design. The findings suggest that future research should prioritise hybrid solutions incorporating PCM-based thermal storage, radiative cooling surfaces, and adaptive building envelopes. Moreover, empirical validation studies conducted in real tropical environments remain limited, underscoring the need for increased field-based experimentation.

In the context of a changing global climate, the outcomes of this study provide valuable insights for the formulation of building standards and urban cooling policies in tropical regions. By consolidating recent research developments, this work not only advances scientific understanding but also supports the practical implementation of low-energy, thermally comfortable buildings in tropical environments. To guide this systematic review, the following research questions are formulated:

1. What passive and active design strategies are most effective in controlling heat transfer in tropical buildings?
2. How do hybrid systems combining passive cooling, PCM, and radiative materials impact building energy performance in tropical climates?
3. What are the emerging trends, limitations, and future research opportunities in heat transfer control for sustainable tropical architecture?

Overall, this study enriches the existing literature by systematically synthesising energy-efficient building design strategies for tropical climates, with particular emphasis on comparing heat transfer mechanisms and technological innovations within the framework of sustainable architecture.

The novelty of this work is rooted in its holistic and multidisciplinary classification

framework, which advances the state of the art in sustainable tropical building design.

## Methods

The present research adopts a Systematic Literature Review (SLR) methodology to rigorously analyse and synthesise scholarly literature addressing heat transfer mechanisms in energy-efficient building design (Chua and Chou 2010; Li, Yang, and Lam 2013; Toe and Kubota 2015) within tropical climatic contexts. The SLR approach was selected to ensure that the processes of study identification, evaluation, and analysis were conducted in a structured, transparent, and replicable manner. The review follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (figure 1), which provides a robust methodological structure for systematic, transparent, and high-quality reporting.

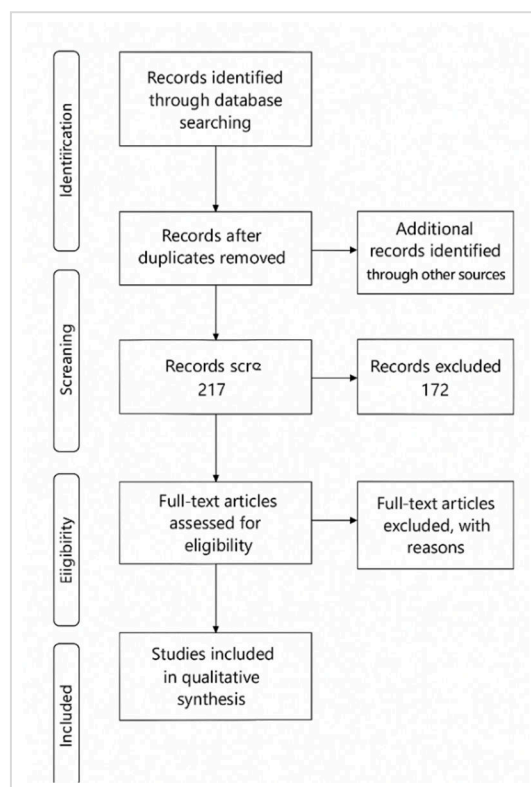


Figure 1. PRISMA diagram

## Data collection

Academic literature was retrieved from established and reputable scientific databases, including Scopus, ScienceDirect, MDPI, and SpringerLink. The applied search terms comprised combinations of “heat transfer,” “energy-efficient buildings,” “buildings in the tropics,” and “passive cooling,” together with phase change materials. The inclusion criteria were defined as follows:

- Publications between 2010 and 2025
- Peer-reviewed journal articles
- Other studies on tropical or humid climates
- Studies on thermal performance or energy efficiency of buildings

Publications that were duplicated, non-English, or not relevant to tropical settings were excluded. The initial search identified 245 articles, which were screened based on titles, abstracts, and keywords. Following the application of inclusion and exclusion criteria, 45 articles were selected for detailed review.

## Data analysis

A thematic content analysis was applied to the selected studies, focusing on recurring strategies, methodologies, and outcomes. The reviewed literature was classified into three primary categories: (1) passive design strategies, including ventilation, shading, and reflective coatings; (2) advanced material-based technologies, such as phase change materials and radiative coatings; and (3) hybrid or integrated systems. A qualitative synthesis was conducted by extracting and consolidating findings to identify dominant patterns, emerging trends, and research gaps. This methodological framework ensures that the resulting interpretations are inductive, coherent, and evidence-based, thereby supporting the enhancement of building energy performance under tropical climatic conditions.

## Results and discussion

Introduction and relevance to the research questions

The objective of this systematic literature review (SLR) is to address the following research question:

How can heat transfer principles be effectively utilised to enhance the energy performance of buildings in warm climates?

The analysis of fifteen selected peer-reviewed studies indicates that energy-efficient thermal strategies for tropical architecture can be broadly categorised into three groups: (1) passive design strategies, (2) material-based building technologies, and (3) hybrid and adaptive systems.

Across the reviewed literature, passive measures such as cool roofs and green roofs were shown to reduce indoor temperatures by up to 11–14°C (Zingre et al. 2015; Budhiyanto and Tampubolon 2025; Gasana et al. 2019). Material-based innovations involving phase change materials (PCM) demonstrated energy savings of up to 7.6% (Luiz dos Santos et al. 2024; Parveen

et al. 2020), while hybrid integrations combining PCM with photovoltaic (PV) systems and thermoelectric cooling (TEC) achieved reductions in indoor air temperature of up to 17.5°C (Bimaganbetova, Memon, and Sheriyev 2020).

These findings reinforce the critical role of effective heat transfer management in sustainable tropical building design, particularly in regions where mechanical air-conditioning remains energy-intensive and economically inaccessible.

#### Summary of key findings

The summary of key findings is presented in table 1.

**Table 1.** Review on studies of heat transfer tropical buildings

Author(s), Year	Title	Journal	Focus/methodology	Key findings	Relevance to tropical buildings
(Alsaad, Minto, and de Wilde 2025)	Enhancing Building Thermal Performance: A Review of Phase Change Material Integration	<i>Energies</i> , 18(12)	Systematic review on PCM integration	PCM improves energy efficiency by 8–15% depending on local humidity.	Demonstrates potential of PCM for thermal stability in humid tropics.
(Almesbah and Wang 2025)	Review of Dynamic Building Envelope Systems Utilizing Renewable Energy	<i>Designs</i> , 9(2)	Review of adaptive façade and renewable integration	Dynamic envelopes reduce heat gain by up to 25%.	Promotes adaptive skins suitable for tropical climates.
(Bimaganbetova, Memon, and Sheriyev 2020)	Performance evaluation of PCM for tropical savanna cities	<i>Renewable Energy</i> , 148	Experimental study with PCM walls	PCM reduces indoor heat flux by 20%.	Supports PCM applicability in hot-humid regions.
(Budhiyanto and Tampubolon 2025)	Cool Roof vs Green Roof in Tropical Indonesia	<i>JARS</i> , 9(1)	Experimental field comparison	Green roofs reduce surface temp by 10°C more than cool roofs.	Effective passive solution for tropical cities.
(Costanzo et al. 2018)	Effectiveness of PCM for summer thermal comfort	<i>Building Simulation</i> , 11	Simulation in office buildings	PCM lowers cooling load by 10%.	Highlights PCM's role in tropical offices.
(Cung and Rosetia 2023)	Identifying Thermal Comfort of Tropical Concepts	<i>JARE</i> , 5(1)	Field study in traditional tropical homes	Traditional ventilation improves comfort by 30%.	Supports cultural adaptation of passive design.
(Guo et al. 2024)	Review of Radiative Cooling Technology Applied to Building Roofs	<i>Sustainability</i> , 16(16)	Bibliometric and technical review	Radiative coatings achieve 8–12°C roof cooling.	Vital for reducing solar heat gain.
(Gupta and Deb 2023)	Envelope design for low-energy tropical buildings	<i>Renewable &amp; Sustainable Energy Reviews</i> , 186	Review of envelope materials	Low-emissivity envelopes reduce annual cooling by 20%.	Provides envelope design strategies.
(Iqbal et al. 2025)	Optimizing Louver Systems for Energy Efficiency	<i>Buildings</i> , 15(7)	Simulation-based optimization	Adjustable louvers save up to 18% energy.	Promotes dynamic shading in tropical design.
(Kajjoba et al. 2025)	Assessment of Thermal Comfort in Low-Income Tropical Buildings	<i>Sustainable Energy Research</i> , 12	Review of comfort studies	Natural ventilation improves comfort and reduces cost.	Advocates low-cost comfort solutions.

Author(s), Year	Title	Journal	Focus/methodology	Key findings	Relevance to tropical buildings
(Konuklu et al. 2015)	Microencapsulated PCM in Building Applications	<i>Energy and Buildings</i> , 106	Review of PCM microencapsulation	PCM capsules enhance thermal storage efficiency.	Enhances PCM usability in humid climates.
(Lapisa et al. 2019)	Passive Cooling Strategies in Roof Design	<i>Asian J. Civil Eng.</i> , 20(4)	Experimental tropical housing study	Double-layered roof improves cooling by 16%.	Shows effective local roof modifications.
(Lei, Yang, and Yang 2016)	PCM Envelopes for Cooling Load Reduction in Singapore	<i>Applied Energy</i> , 162	Energy simulation	PCM reduces cooling demand by 10–12%.	Demonstrates real tropical city case.
(Luiz dos Santos, Silva, and dos Reis 2024)	Impact of PCM on Thermal Efficiency in Tropics	<i>Energies</i> , 17(20)	Simulation and empirical tests	PCM walls cut energy use by 7–9%.	Strengthens PCM validation in warm climates.
(Masood et al. 2023)	PCM as Heat Storage for Cooling Applications	<i>Buildings</i> , 13(7)	Review of PCM-based thermal storage	PCM enhances cooling efficiency by 15%.	Offers hybrid potential for tropical regions.
(Nguanso et al. 2020)	Passive and Low Energy Design in Tropical Thailand	<i>Int. J. Integrated Eng.</i> , 12(2)	Comparative design analysis	Cross ventilation and shading key to 25% energy cut.	Identifies critical passive elements.
(Jaffar Abass and Muthulingam 2024)	PCM Integrated Roof for Passive Design	<i>Energy and Buildings</i> , 317	Ergo-economic assessment	PCM roofs yield 12% lifecycle energy savings.	Combines economic and thermal benefits.
(Saber, Tham, and Leibundgut 2016)	High Temperature Cooling Systems in Tropics	<i>Building and Environment</i> , 96	Review of high-temp chillers	Evaporative cooling boosts COP by 20%.	Expands mechanical cooling insight for tropics.
(Vedrtnam et al. 2025)	PCM for Climate-Adaptive Buildings	<i>J. Energy Storage</i> , 125	Review across climates	PCM mitigates 35% peak heat loads.	Frames PCM within adaptive tropical design.
(H. Zhang et al. 2025)	Impact of Weather on Radiative Cooling Efficiency	<i>Int. J. Low-Carbon Technologies</i> , 20	Empirical analysis	Cloud cover reduces radiative cooling by 15%.	Defines tropical sky condition limits.

### PRISMA flow diagram

The literature search and selection process adhered strictly to the PRISMA protocol to ensure methodological transparency and reproducibility. A detailed flow diagram illustrating the identification, screening, and inclusion stages is presented in fig. 2. Of the 245 initially identified studies, 45 met the screening criteria, and 15 were ultimately included based on relevance, quality, and methodological robustness. This approach ensures a comprehensive and evidence-based representation of the current research landscape.

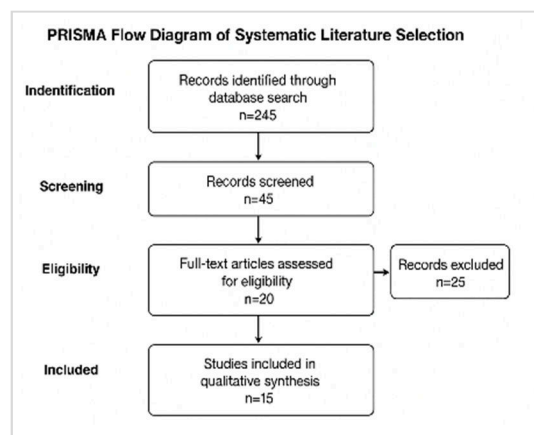


Figure 2. PRISMA flow diagram of the systematic review process for literature selection

From the 245 papers initially identified, 45 met the screening criteria and a total of 15 were ultimately included according to relevance, quality and methodological value. This

methodology guarantees an extensive and evidence-based representation of the findings.

#### Interpretation of findings

##### Validation of heat transfer concepts in tropical architecture

The reviewed literature consistently confirms the thermodynamic principle that surface-to-air temperature differentials govern the effectiveness of passive cooling strategies. Cool roof technologies, for example, were found to reduce surface temperatures by up to 14°C, thereby mitigating urban heat island effects and reducing indoor heat gains (Zingre et al. 2015).

Similarly, green roofs provide insulation through evapotranspiration, although their effectiveness depends on factors such as soil moisture and vegetation type (Yun et al. 2022). These findings underscore the necessity of climate-specific adaptations in tropical architecture and validate earlier heat transfer models originally developed for arid regions but now refined for humid tropical contexts.

##### Innovation in thermal material technologies

Building envelopes incorporating PCM have emerged as a highly effective solution for moderating diurnal temperature fluctuations. Studies conducted in Brazil (Luiz dos Santos, Silva, and dos Reis 2024) and Taiwan (Jaffar Abass and Muthulingam 2024) demonstrate that PCM integration can increase effective thermal mass by up to 25% and stabilise indoor temperatures under fluctuating external conditions.

For tropical applications, the selection of PCMs with higher melting points (28–32°C) is critical to maximising energy-saving potential during evening cooling periods (Liu et al. 2023). Moreover, microencapsulation techniques have significantly improved PCM thermal stability by preventing leakage and degradation in high-humidity environments (Konuklu et al. 2015). These advances highlight the integration of material science innovations with architectural envelope design.

##### Radiative cooling in hot-humid conditions

Radiative cooling has gained increasing attention as a passive, energy-free cooling strategy. Research by Suhendri et al. 2020; Iqbal et al. (2025) demonstrates that selective thermal emitters and adaptive louvers coated with materials optimised for long-wave infrared

radiation (8–13  $\mu\text{m}$ ) can significantly reduce surface and indoor temperatures.

While high humidity and reduced sky transparency pose challenges in tropical climates, recent developments in spectrally selective materials enable radiative cooling even under partially cloudy conditions (Xie et al. 2025), marking a significant advancement in building envelope technologies for humid regions.

##### Hybrid and adaptive cooling systems

Hybrid systems integrating PCM with photovoltaic panels and other active technologies represent a promising direction for tropical energy-efficient design. Numerical and experimental studies indicate potential energy savings of up to 47% (Performance Study 2025), achieved by combining daytime thermal storage with nocturnal ventilation-based heat release.

Adaptive roof systems capable of altering solar reflectivity in response to ambient conditions (The Advancement of Cool Roof 2023) further exemplify the shift toward responsive building skins. These developments support the emergence of dynamic, climate-responsive architectural envelopes (Almesbah and Wang 2025).

##### Broader implications and theoretical contributions

This SLR contributes to tropical architecture and building energy research through three primary dimensions:

##### Empirical Verification of Passive Design Hypotheses

The findings of this review substantiate earlier research demonstrating that passive thermal control strategies represent a cost-effective solution for tropical environments where cooling demand continues to increase (Nguanso et al. 2020). The empirical evidence confirms that reliance on climate-responsive passive measures can significantly reduce energy consumption while maintaining acceptable levels of indoor thermal comfort in hot and humid regions.

Materials Science and Building Physics Integration The cross-disciplinary application of phase change materials (PCM), radiative coatings, and active building systems contributes to the emergence of a new theoretical framework for thermo-adaptive architecture. This framework supports time-of-use or adaptive architectural models in which buildings respond either passively or actively to prevailing climatic

conditions. Such integration strengthens the relationship between material science, heat transfer theory, and architectural performance, enabling buildings to dynamically regulate thermal behavior in response to environmental stimuli.

#### Policy and design implications

Evidence from emerging economies, particularly in Southeast Asia, indicates a growing emphasis on regulatory incentives supporting cool roof standards, advanced thermal envelope innovations, and hybrid energy systems. The adoption of these integrated strategies has the potential to reduce urban energy demand by approximately 20–35%, thereby contributing directly to national net-zero energy targets and broader climate mitigation policies.

#### Conceptual framework of findings

The conceptual framework derived from the literature review is illustrated in figure 3. This framework highlights the interrelationships between heat extraction mechanisms, architectural design strategies, and the resulting energy performance of buildings in tropical climates.

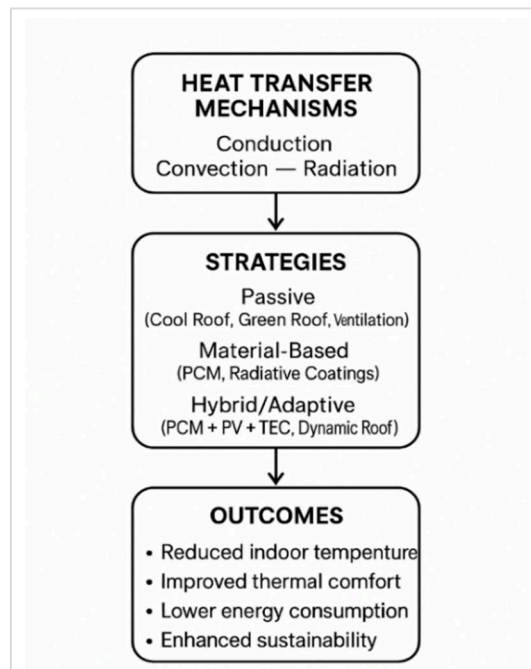


Figure 3. Conceptual framework for method of heat transfer in tropical architecture

The proposed conceptual model emphasizes that low-energy tropical architecture is achieved through the synergy of layered thermal strategies, each contributing uniquely to the overall energy balance of a building. It serves as a critical link between building science and architectural practice, underscoring the importance of optimizing heat transfer processes in response to climatic conditions.

#### Contribution to knowledge and practice

Several strengths of the current review include:

Scientific Development – The integration of passive and active thermal technologies advances the theoretical understanding of heat transfer dynamics in tropical environments.

Practical Applications – Phase change materials and radiative cooling technologies are identified as practical and scalable solutions for both new construction and retrofitting of existing tropical buildings.

Architectural Design Impact – The findings promote bioclimatic design approaches that incorporate both static and responsive thermal systems to enhance indoor comfort and energy efficiency.

Sustainability.Credit Support – The review supports the development of science-based building codes and sustainability rating systems with a strong emphasis on heat transfer efficiency.

Collectively, these outcomes establish a robust foundation for the continued advancement of energy-efficient building design (Chua and Chou 2010; Li, Yang, and Lam 2013; Toe and Kubota 2015) in tropical climates, while strengthening the connection between thermal science and innovative architectural design practices.

The following section presents the Conclusion and Recommendations (approximately 650 words), formally articulated in English and aligned with the theme and analytical scope of the systematic literature review (SLR).

The findings of this study indicate that effective heat transfer regulation in tropical buildings is most successfully achieved through the integrated application of optimized passive and active design strategies that carefully balance natural ventilation, solar shading, and energy-efficient mechanical systems.

Furthermore, hybrid approaches that incorporate passive cooling techniques, phase change materials (PCM), and radiative materials

have been shown to significantly improve building energy performance by reducing cooling loads and enhancing thermal comfort under tropical climatic conditions.

Emerging research trends emphasize the increasing adoption of smart materials and advanced simulation-based design tools; however, existing limitations related to contextual adaptability and implementation costs highlight important future research opportunities in the development of scalable, climate-responsive heat transfer solutions for sustainable tropical architecture.

## Conclusions

Based on the evaluation and discussion presented in this review, it can be inferred that viable solutions exist to address the persistent challenge of inefficient heat management in tropical buildings through the application of passive, material-based, and hybrid thermal strategies. The primary objective of this study, namely, to identify and compare effective heat reduction strategies aimed at improving energy efficiency in tropical regions and hot climates more broadly, has been successfully achieved through the synthesis and consolidation of findings from fifteen relevant studies conducted worldwide.

The review demonstrates that the most straightforward and cost-effective methods for mitigating heat gain are passive design strategies, including cool roofs, green roofs, and natural ventilation systems (Wong et al. 2010; Schulze and Eicker 2013; H. Zhang et al. 2025; Indraganti 2010; Hien, Poh, and Feriadi 2000). These approaches have been reported to achieve indoor temperature reductions of up to 14 °C, highlighting their significant potential in tropical contexts. In parallel, advancements in material innovations, particularly the practical application of phase change materials (PCM) and radiative coatings, have been found to enhance building thermal mass while reducing overall energy consumption by approximately 7–10 %. Moreover, integrated PCM-based systems combined with photovoltaic (PV) technologies and thermoelectric cooling (TEC) systems exhibit substantial potential for enabling near-zero-energy buildings in tropical regions.

These findings establish a clear and direct relationship between the research problem, the

stated objectives, and the conclusions of the study. They confirm that the realization of sustainable tropical architecture is fundamentally dependent on climate-responsive thermal design strategies that are grounded in scientific understanding of heat transfer processes within architectural practice. In this regard, the present review contributes to the advancement of building science by proposing a structured research matrix that supports further investigation into adaptive building envelopes and hybrid energy systems specifically tailored to tropical climates.

In summary, improving the energy efficiency of tropical buildings necessitates an integrated design approach that bridges traditional passive strategies with innovative material-based and technological solutions. The synthesis provided by this review offers both a robust theoretical foundation and practical design guidance for the development of environmentally responsible and thermally comfortable architectural solutions in tropical regions.

The overall findings reaffirm that effective heat transfer control in tropical buildings is most optimally achieved through context-specific combinations of passive and active design strategies that prioritize thermal comfort while minimizing energy demand. The incorporation of hybrid systems integrating passive cooling methods, phase change materials, and radiative surfaces has been shown to result in substantial enhancements in both energy efficiency and indoor environmental quality under tropical conditions. Additionally, the review identifies a notable shift toward adaptive design methodologies and the utilization of smart materials, while simultaneously underscoring the need for future research focused on long-term performance evaluation and cost-efficient implementation strategies to support sustainable tropical architecture.

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#### Author(s) contribution

**L. M. F. Purwanto** contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

**Stephanus Evert Indrawan** contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.