

Advanced Building Envelope Systems for Energy Efficiency: Implications for Architectural Design in Tropical Climates

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DOI: <https://doi.org/10.51584/IJRIAS.2026.110400113>

Received: 14 April 2026; Accepted: 20 April 2026; Published: 12 May 2026

ABSTRACT

Building envelope systems determine energy efficiency, environmental impact, and occupant comfort in modern buildings. This systematic review of 101 Scopus-indexed sources (2020–2025) evaluates advanced envelope technologies for tropical climates, with emphasis on developing regions. Buildings consume 30–40% of global energy, with tropical regions exceeding 50% for cooling. This review evaluates performance advantages, implementation challenges, and current trends for advanced envelope technologies including phase change materials (PCM), adaptive facades, smart glazing, building-integrated photovoltaics (BIPV), and IoT-enabled systems. Results indicate that climate-responsive envelope design, interdisciplinary collaboration, and policy support are essential for sustainable buildings. Tropical office buildings achieve 14.2–31.5% energy savings through PCM and adaptive dynamic facades with IoT monitoring. Developing regions face barriers including high initial costs, limited technical expertise, and inadequate regulatory frameworks.

Keywords: Building envelope, energy efficiency, adaptive facades, sustainable architecture, tropical climate

INTRODUCTION

Tropical climates present unique challenges for building energy performance. High temperatures, intense solar radiation, and elevated humidity levels create substantial cooling demands throughout the year. Unlike temperate climates where seasonal variation allows passive heating and cooling strategies, tropical regions require continuous cooling for thermal comfort. This condition makes building envelope design particularly critical for energy efficiency.

The building envelope comprises walls, roofs, floors, windows, and doors that control heat transfer, air movement, moisture transfer, and daylight entry. Envelope performance establishes indoor temperatures, thereby determining the required size and efficiency of mechanical systems (Zhou et al., 2025). Poor envelope design in tropical climates leads to excessive heat gain, thermal discomfort, and elevated energy demands (Almeida et al., 2024).

Energy-efficient envelopes use materials with high thermal resistance, active control systems that prevent air leakage, and optimal solar shading. Envelope design must balance visual attractiveness with environmental efficiency, enabling buildings to respond to local climate conditions. The envelope controls building thermal performance; therefore, envelope technology development enhances occupant acoustic, visual, and spatial comfort while reducing electrical cooling requirements (Ogunnaike et al., 2025; Almeida et al., 2024).

Recent progress in material science has created better envelope systems, giving architects more options for climate-responsive buildings. High-performance insulation materials such as aerogels and vacuum insulated panels (VIPs) provide superior thermal resistance with minimal thickness, suitable for both new construction and retrofitting (Zhangabay et al., 2024). Phase change materials (PCMs) have emerged as popular thermal stability solutions because they absorb and release latent heat, reducing indoor temperature variations (Zhou et al., 2025; Almeida et al., 2024).

This review addresses three research gaps in tropical building envelope literature: (1) lack of systematic comparison between advanced technologies, (2) inadequate analysis of implementation barriers in developing regions, and (3) insufficient critical evaluation of technology suitability for different tropical climate sub-types. We evaluate material developments, adaptive façade technologies, and design approaches used for tropical building design, focusing on performance advantages, implementation challenges, and current trends.

METHODOLOGY

This study adopted a systematic literature review approach using Scopus, Web of Science, ScienceDirect, and Google Scholar, covering publications from January 2020 to March 2025. The search employed keywords such as “building envelope” combined with “energy efficiency” or “thermal performance,” and “tropical climate” or “hot humid climate,” alongside terms like “advanced materials,” “adaptive facade,” “phase change material,” and “smart glazing.” Only English-language peer-reviewed journal articles, conference proceedings, and technical reports were considered. Inclusion criteria focused on studies conducted in tropical climate zones (Köppen classifications Af, Am, Aw, As, BSh) that reported quantitative energy or thermal performance data, addressed building envelope technologies, were published in reputable indexed outlets, and presented clear, reproducible methodologies. Exclusion criteria eliminated studies centered on temperate or cold climates, purely theoretical works without empirical or simulation validation, publications prior to 2020 (unless highly cited seminal works), and non-peer-reviewed sources such as blogs, magazines, and commercial white papers.

Advanced Building Envelope Technologies

Phase Change Materials (PCM)

PCMs provide an effective method to control temperature in tropical environments. Research across Brazilian cities demonstrates that PCMs with melting temperatures around 27–28°C perform optimally in tropical conditions, reducing cooling loads by up to 48% during summer conditions (Almeida et al., 2024; Saffari et al., 2017). PCM wall systems achieve 10–30% heat load reduction compared to standard wall systems, creating indoor temperatures 2–4°C cooler (Zhou et al., 2025).

PCM integration requires specific climate data to determine melting point, layer thickness, and optimal installation zone (Almeida et al., 2024). Performance is highly sensitive to melting point selection; a 2°C deviation from optimal can reduce effectiveness by 40% (Almeida et al., 2024). This sensitivity makes PCM design particularly challenging for tropical regions with variable microclimates.

Properly designed PCM-integrated envelopes enable buildings in tropical Singapore to achieve cooling energy savings between 21% and 32% (Lei et al., 2016). However, long-term performance data (>10 years) in tropical humidity remains limited, and degradation mechanisms are not fully understood.

Advanced Glazing Systems

Glazing technologies have progressed significantly since their initial development. Low-emissivity coatings, double and triple glazing, and gas-filled cavities decrease both conductive and radiative heat transfer. Smart glazing systems containing electrochromic and thermochromic technologies control solar heat gain and daylight transmission, reducing tropical cooling requirements (Zhangabay et al., 2024).

Semi-transparent photovoltaic (STPV) glazing can deliver 90% energy savings for lighting purposes, though glare remains a concern (Ismail et al., 2022). Smart glazing systems achieve 15–25% energy savings and 20–35% cooling load reduction but require very high initial investment and high technical complexity.

Adaptive Facades

Adaptive systems differ from traditional static envelopes because they use sensors, actuators, and control algorithms to respond to changing environmental conditions. These systems control shading, ventilation, and thermal performance for maximum energy efficiency during different operational situations (Zhangabay et al.,

2024; Zhang et al., 2022). Design elements include kinetic facades, automated louvers, and responsive shading devices that follow the sun's daily movement pattern.

Zhang et al. (2022) demonstrated that adaptive façade systems using computational optimization achieve energy savings between 14.2% and 29.0% compared to static systems. Ventilated facades with open joints function as effective energy-saving solutions for hot summer climates because they improve natural ventilation and heat removal (Zhangabay et al., 2024). Optimized ventilated facades (OVFs) with adaptive dynamic insulation systems remove heat at 2.1–2.6 times greater efficiency than regular systems (Zhangabay et al., 2024).

Adaptive facades present significant limitations for developing tropical regions. High capital and maintenance costs, mechanical failure risk in tropical humidity and salt air, and limited post-occupancy evaluation data reduce their suitability for low-cost housing. Most studies are simulation-based, and occupant acceptance studies are lacking.

IOT-Enabled Building Energy Management

IoT-enabled building energy management systems have transformed envelope performance optimization. Munadi et al. (2025) designed an IoT and EDGE hybrid framework connecting ongoing monitoring with simulation methods, achieving 31.49% energy reduction and 24.7% water efficiency enhancement. Data-driven systems allow buildings to adapt operations based on occupancy, temperature changes, and environmental conditions, marking a major advancement in intelligent building design.

However, IoT-enabled systems require high initial investment, very high technical complexity, and skilled operators for maintenance. Data privacy concerns and dependency on existing digital infrastructure limit their applicability in developing tropical regions.

Vegetated Envelope Systems

Green roofs provide extra insulation and shading benefits while enabling plants to cool through evaporation, serving as a tool against urban heat islands (Wang et al., 2025; Chung-Camargo et al., 2023). Building envelope vegetation can decrease heat gain by about 80% while reducing energy consumption between 2.2% and 16.7% (Chung-Camargo et al., 2023).

Vertical greenery systems enhance thermal insulation properties while lowering surface temperatures and reducing urban heat island effects (Wang et al., 2025; Zhao et al., 2025). Living envelopes provide stormwater management, CO₂ sequestration, and visual/mental health advantages that boost occupant happiness (Zhao et al., 2025).

BIGP results in energy consumption reductions of about 18% while decreasing summer heat flux density substantially (Wang et al., 2025). Green envelopes establish thermal transfer value (ETTV) reductions through decreased envelope thermal transfer value, evaporative cooling, and solar protection (Zhao et al., 2025).

Vegetated envelopes present critical limitations for tropical climates: energy savings are modest (2.2–16.7%), maintenance requirements are high, and structural implications must be carefully evaluated. Plant species selection for specific tropical microclimates is under-researched, and the irrigation water use versus energy savings trade-off is rarely quantified. These systems are best suited for urban heat island mitigation rather than as primary energy efficiency strategies.

Trombe Walls and Multi-Alveolar Structures

Trombe walls show exceptional efficiency when combined with multi-alveolar structures (MAS) and PCMs in Mediterranean and tropical climates. Research indicates that such integrated systems can achieve phase shifts up to 6 hours and damping factors of 40–50%, significantly reducing indoor temperature fluctuations compared to conventional walls (Zhou et al., 2025). However, space requirements and limitation to new construction reduce their applicability for retrofit projects.

Building-Integrated Photovoltaics (BIPV)

BIPV systems allow envelope components to generate renewable energy while providing shading and weather protection. BIPV systems installed on facades and rooftops help meet net-zero energy requirements when combined with PCMs, which decrease air conditioning usage by about 30% (Saffari et al., 2017).

BIPV systems face critical limitations in tropical climates: very high upfront cost, efficiency degradation in high temperatures, and tropical soiling that reduces output. Integration with PCM cooling is not yet optimized, and cleaning/maintenance protocols for tropical environments remain undeveloped.

Comparative Analysis of Envelope Technologies

TABLE 1: Comparative Analysis of Advanced Building Envelope Technologies for Tropical Climates

Technology	Energy Savings	Cooling Load Reduction	Initial Cost	Technical Complexity	Maintenance	Best Application	Key Limitations
Phase Change Materials (PCM)	10–30%	Up to 48%	High	Medium	Low	Hot-humid climates with stable diurnal cycles	Requires precise melting point; limited lifespan
Smart Glazing	15–25%	20–35%	Very high	High	Medium	High-rise commercial buildings	High capital cost; potential glare issues
Green Roofs/Vertical Greenery	2.2–18%	Up to 80% heat gain reduction	Medium	Medium	High	Urban areas with urban heat island concerns	Structural load; irrigation needs; plant selection critical
Adaptive/Kinetic Facades	14.2–29.0%	25–40%	Very high	Very high	High	Large commercial/institutional buildings	Mechanical complexity; sensor maintenance; system dependency
Ventilated Facades (OVF)	15–20%	30–45%	Medium-high	Medium	Low-medium	Hot climates with predictable wind patterns	Requires careful design to prevent moisture issues
BIPV + PCM Integration	30%+	40–50%	Very high	High	Medium	Net-zero energy buildings	High upfront cost; grid integration challenges
Trombe Walls + MAS + PCM	15–25%	35–45%	High	High	Low	Buildings requiring high thermal mass	Space requirements; mainly suitable for new construction
IoT-Enabled Adaptive Systems	31.5%	40–50%	High	Very high	High	Smart buildings with digital infrastructure	Data privacy concerns; requires skilled operators

Note. MAS = Massive (high thermal mass) materials; BIPV = Building-Integrated Photovoltaics; OVF = Open Ventilated Facades. Percentages represent ranges reported across reviewed studies.

Multi-Criteria Assessment Model

This section proposes a weighted multi-criteria assessment model for evaluating envelope technologies in tropical developing regions:

Table 2: Weighted Evaluation Criteria for Building Envelope Technologies

Criterion	Weight	Rationale
Energy performance	30%	Primary objective of envelope optimization
Economic viability	25%	Critical barrier in developing regions
Technical feasibility	20%	Local capacity constraints
Maintenance requirements	15%	Long-term sustainability
Scalability potential	10%	Regional applicability

Note. Weights reflect the relative importance of each criterion in evaluating building envelope technologies within tropical and resource-constrained contexts.

Critical Discussion and Research GAPS

The critical analysis reveals that while phase change materials (PCM) demonstrate strong cooling load reductions (up to 48%), their performance is highly sensitive to melting point selection, with small deviations significantly reducing efficiency, and there is limited understanding of long-term degradation under tropical humidity, making them more suitable for new construction than retrofits. Adaptive facades offer dynamic environmental responsiveness and optimization potential but are constrained by high costs, mechanical complexity, and durability concerns in humid or coastal conditions, with a notable lack of post-occupancy and user-acceptance data, limiting their practicality to high-end commercial applications.

Green envelope systems provide multiple co-benefits such as improved air quality and urban heat island mitigation, yet their direct energy savings remain modest and are offset by maintenance demands and structural considerations, while key gaps persist in plant selection for tropical microclimates and water–energy trade-offs. Building-integrated photovoltaics (BIPV) combine energy generation with envelope functionality but face challenges including high initial investment, reduced efficiency in high temperatures, and soiling effects, with insufficient research on integration with cooling technologies like PCM and maintenance protocols in tropical settings. However, major research gaps include the lack of long-term empirical performance data in tropical climates, insufficient integration of occupant behavior into system design, limited quantification of maintenance costs in life-cycle assessments, inadequate climate-specific material optimization, and a weak understanding of policy and financing mechanisms needed to drive adoption in developing regions.

Implementation of advanced building envelope technologies in developing tropical regions is constrained primarily by financial and capacity limitations, but targeted strategies can address these barriers. High initial costs, identified as critical, can be mitigated through mechanisms such as green bonds, access to international climate finance (Green Climate Fund), phased project execution, and bundling multiple technologies to improve cost-effectiveness, while capital shortages may be addressed via microfinance schemes for retrofits, public–private partnerships, and performance-based incentives; additionally, limited awareness of life-cycle costs can be improved through educational initiatives, demonstration projects, and tools that illustrate long-term utility savings.

Strengthening capacity requires university–industry partnerships for technology transfer, vocational training programs to upskill local construction workers, South–South collaboration among tropical countries, and the establishment of regional centers of excellence focused on envelope technologies. From a regulatory perspective, effective adoption depends on enforcing mandatory energy codes for new buildings, prioritizing performance-based standards over rigid prescriptive rules, requiring post-occupancy evaluation for public projects to ensure accountability, and introducing incentive structures that reward performance beyond minimum compliance levels.

Integrated Design Approach

Interdisciplinary Collaboration

Integrated design promotes early-stage collaboration between architects, engineers, and energy specialists. This approach develops envelope strategies that work in harmony with mechanical systems rather than competing with them (Munadi et al., 2025; Truong et al., 2024). Architects use Building Information Modelling (BIM) and energy simulation software to create precise performance estimates.

BIM to Building Energy Modelling (BEM)

Building Energy Modelling uses data exchange, geometric simplification, and parameter validation to maintain simulation accuracy when transitioning from BIM (Truong et al., 2024; Nwodo & Akinola, 2022). Energy-efficient building design requires two phases: conceptual design using BIM for energy analysis to determine building orientation and configuration, and detailed analysis in later phases for hourly load calculations and economic assessment (Truong et al., 2024; Benge & McAlpine, 2021).

LCA combined with energy simulation creates a complete system to assess different facade and fenestration choices. Enhanced glazing reduces operational energy demands by 8.3%, though this advantage requires assessment of increased embodied impacts that rise by 10% (Röck et al., 2020). Integrated assessments empower designers to select options that balance short-term performance goals with long-term environmental sustainability.

Design Principles for Tropical Climates

The performance of building envelope systems in tropical conditions depends on window-to-wall ratio (WWR) and material characteristics. Research advises hot and humid areas to maintain a WWR between 15% and 20% because windows serve as the main source of heat absorption (Chung-Camargo et al., 2023). Orientation, shading devices, and surface reflectance materials require precise coordination to reduce solar heat gain while enhancing daylight usage. Envelope design must adopt an integrated approach combining passive techniques with active system design for maximum operational efficiency.

Air Tightness and Moisture Management

Air tightness combined with moisture management are essential for advanced envelope systems in tropical regions. High humidity and temperature differences elevate moisture threats. Uncontrolled air infiltration increases cooling energy demand because warm humid outdoor air enters conditioned spaces, creating higher operational demands for mechanical systems (Zhou et al., 2025). Moisture entry creates condensation inside envelope structures, producing mold growth, material damage, and indoor environmental quality problems.

Advanced envelope systems use continuous air barriers, sealed construction joints, and carefully detailed interfaces between envelope components. Vapor-permeable water-resistant membranes enable controlled moisture diffusion while blocking liquid water entry. Air-tightness is a design responsibility that architects must resolve during the initial design phase, not merely a technical problem.

Effective moisture control requires drying potential and ventilation systems. Advanced envelopes use a combination of ventilation control and material layering for moisture management instead of depending on isolated waterproof assemblies. The combination of air-tightness with moisture control reduces energy usage while maintaining building durability and creating better occupant conditions. Facade opening shape and occupant perception play a vital role in achieving effective moisture control that maintains comfort levels (Zhangabay et al., 2024).

Roof Systems and Daylight Optimization

Roof Systems

Roofs are vital components for energy efficiency in tropical climates because they withstand constant strong sunlight exposure throughout the year. Indoor temperatures and cooling needs increase when heat enters through poorly designed roof structures. Advanced roof systems reduce solar heat absorption and improve thermal resistance.

High-reflectance roofing materials, enhanced insulation layers, and ventilated roof cavities minimize heat transfer into interior spaces. Green roofs provide extra insulation and shading while enabling plants to cool through evaporation, serving as a tool against urban heat islands (Wang et al., 2025; Chung-Camargo et al., 2023). Architects must create roof designs that combine structural needs with environmental adaptability and aesthetic design.

Daylight Optimization

Roof design enables daylight optimization to reduce artificial lighting needs. Roof-based daylighting solutions such as skylights, clerestory windows, and light-guiding systems deliver uniform natural illumination deep into interior spaces. Tropical climates require daylighting solutions that maintain low heat gain while preventing excessive sunlight entry.

Parametrically controlled light shelves have demonstrated superior performance by redirecting sunlight to create optimal visual comfort conditions inside Malaysian office buildings (Ismail et al., 2022). Light duct mechanisms operating in deep spaces have proven to enhance natural light usage throughout Bangkok's expansive buildings that lack accessible interior windows (Ismail et al., 2022).

Advanced envelope design uses shading devices, selective glazing, and daylight control systems to create visual comfort alongside optimal thermal performance. Integration of these strategies requires architects to coordinate architectural form, envelope composition, and building orientation to maximize benefits while reducing potential negative effects.

Case Studies

Table 3: Case Studies of Building Envelope Technologies in Tropical Regions

Building	Location	Technologies Used	Measured Savings	Key Lessons
Building and Construction Authority Academy	Singapore	Advanced envelope renovation	Zero-energy status achieved	Integrated envelope strategies enable full energy optimization
Enerpos Building	La Réunion Island	Natural ventilation during class hours	Reduced energy consumption	Natural ventilation can substitute mechanical cooling in suitable contexts
Ilet du Center	Saint-Pierre, La Réunion	Double envelope layer and green areas	Improved passive cooling	Vegetated double envelopes enhance thermal performance
NUS SDE4	Singapore	Combination of passive and active design strategies	Energy neutrality achieved	Effective use of natural resources supports net-zero outcomes

Zero Carbon Building	Hong Kong, China	Integrated sustainable systems	Net-zero carbon	High-density tropical cities can achieve carbon neutrality
LLDIKTI Region XIII Office	Banda Aceh, Indonesia	Envelope enhancement, optimized lighting, adaptive HVAC, and IoT integration	31.49% energy reduction	Smart systems combined with envelope design yield significant efficiency gains

Note. Case studies highlight real-world applications of envelope technologies demonstrating energy efficiency and sustainability outcomes across tropical regions.

Testing and Validation

Energy Modelling and Simulation

Energy modelling and simulation tools enable design teams to forecast thermal and energy performance through static simulations that evaluate hourly system loads and system connections (Zhou et al., 2025; Almeida et al., 2024). Thermal imaging and air-tightness testing methods enable teams to discover construction problems and performance deficiencies during commissioning.

Post-Occupancy Evaluation (POE)

POE delivers essential insights showing how energy consumption and occupant comfort compare to theoretical performance standards. Research in Malaysia shows that buildings certified through sustainable rating tools sometimes have worse indoor environmental quality than expected, highlighting the need for ongoing research to ensure proper implementation of energy-efficient designs (Ng & Akasah, 2013). Occupants of energy-efficient buildings sometimes show dissatisfaction with thermal comfort and lighting conditions, demonstrating that design intent does not always deliver operational results (Ng & Akasah, 2013).

Performance Gap Analysis

The energy performance gap between expected results and actual outcomes arises from occupant behaviors and social practices, making it crucial to study these factors for precise performance forecasting (Sanya et al., 2023). When residents bear responsibility for energy bills, it affects their consumption patterns, indicating that technical solutions need to be paired with educational programs and financial incentives to achieve optimal results (Sanya et al., 2023).

Barriers to Implementation

Advanced building envelope systems encounter multiple obstacles affecting their implementation in tropical developing regions. The three main obstacles are high initial costs, limited technical expertise, and existing regulatory system deficiencies (Chung-Camargo et al., 2023; Sanya et al., 2023).

The International Energy Agency reported that over 90% of more than 300 net-zero energy building projects documented exist in developed regions of Europe and the United States, while only 11 projects take place in humid tropical climate zones (Chung-Camargo et al., 2023; Sanya et al., 2023).

High humidity and heavy rainfall create additional challenges for building materials because both conditions shorten their lifespan and increase maintenance needs. The implementation process reaches critical limits because climate-specific technological needs combined with local capacity development and public awareness programs have not been fulfilled (Chung-Camargo et al., 2023). Existing building orientation limits retrofit options because orientation is a crucial factor determining heat gains in tropical climates (Chung-Camargo et al., 2023).

FUTURE TRENDS AND CONCLUSIONS

Future Developments

Future developments in building envelope systems will focus on artificial intelligence-driven control systems, bio-based and recyclable materials, and modular prefabricated components. Research increasingly emphasizes life-cycle performance, resilience, and circular economy principles (Röck et al., 2020). Integration of IoT and edge computing with building envelopes enables real-time optimization based on occupancy patterns and environmental conditions, representing a significant trend toward intelligent, responsive buildings (Munadi et al., 2025).

For architectural practice, these trends suggest a shift toward more responsive, data-driven, and environmentally integrated building designs. Climate-specific technological solutions focused on moisture control and cooling load reduction remain a priority for tropical applications (Chung-Camargo et al., 2023). Incorporating occupant behaviour models and comfort preferences into envelope design represents an emerging research frontier.

Conclusion

The modern building sector depends on advanced building envelope systems which enable architects to design energy-efficient and sustainable structures that meet tropical climate requirements for cooling. Using phase change materials and vacuum insulated panels, architects can implement adaptive technologies through kinetic facades and smart glazing together with climate-responsive design systems to achieve energy efficiency goals while creating better living conditions for building users. Building envelope optimization in tropical climates can lead to energy savings between 14% and 31% (Zhang et al., 2022; Munadi et al., 2025). However, developing regions must first resolve financial, technical, and regulatory challenges before they can enjoy these advantages. The envelope functions as both a protective barrier and an active environmental control system that balances architectural design with environmental sustainability requirements. Architecture needs ongoing research, professional training programs, and supportive policies to enable these systems as standard practices. The building industry adopts advanced envelope systems to create sustainable and climate-resilient spaces that provide comfort to tropical regions worldwide as they tackle both climate change and resource scarcity challenges.

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