

Net-Zero Energy Building Design for Tropical Climates: A Systematic Review of Passive Strategies, Active Technologies, and Performance Benchmarks across the Global Tropics

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Abstract

Buildings account for approximately 40% of global energy consumption, with tropical regions, home to over 4 billion people and experiencing the world's fastest urbanization rates, facing disproportionate cooling loads that make net-zero energy performance a critical design challenge. This paper reports a PRISMA 2020-guided systematic review of 250 peer-reviewed studies on Net-Zero Energy Building (NZEB) design in tropical climates, drawn from seven databases covering the period January 2016 to December 2026. Studies were analyzed through thematic coding, VOS viewer bibliometric mapping, and fixed-effects meta-analysis. Three objectives are addressed: the categorization and evaluation of passive and active design strategies; quantitative performance benchmarking; and the identification of adoption barriers and research gaps. The meta-analysis of 140 performance studies, comprising 94 simulation studies and 46 post-occupancy measurement studies, yields a median Energy Use Intensity (EUI) of 47 kWh/m²/year (95% CI: 42–52) for tropical NZEBs, representing a 55–78% reduction from the conventional median of 195 kWh/m²/year. The three highest-impact strategies are optimized shading (55–75% solar heat gain reduction), naturally ventilated building envelopes, and building-integrated photovoltaics (BIPV), which collectively enable a renewable energy fraction ranging from 85% to 127% (median 103%). Five principal barriers constrain adoption: high upfront cost (72% citation frequency), regulatory absence (67%), tropical-specific technical gaps (58%), supply chain limitations (51%), and socio-cultural factors (43%). These findings demonstrate that net-zero performance in tropical climates is achievable with current technology but requires targeted regulatory frameworks, context-adapted standards, and expanded post-occupancy research programmes.

Keywords: Net-Zero Energy Building (NZEB), Tropical Climate, Passive Design, Building-Integrated Photovoltaics (BIPV), Building Energy Performance.

Introduction

The Tropical Building Challenge: Scale, Urgency, and Context

The tropical world is experiencing the most rapid urbanization in human history. Cities across Nigeria, India, Indonesia, Brazil, Ghana, Bangladesh, Vietnam, and Kenya are

growing at rates that will require the construction of billions of square meters of new floor area by 2050, a volume of building stock that, if constructed to conventional standards, will lock in decades of excessive energy consumption, carbon emissions, and mechanical cooling dependency at precisely the moment when the global community requires the opposite (Ürge-Vorsatz, Cabeza, Serrano, Barreneche, & Petrichenko, 2015 ; Seto, Davis, Mitchell, Stokes, Unruh, & Ürge-Vorsatz, 2021.) The International Energy Agency projects that buildings in tropical developing economies will account for the largest single share of global building energy demand growth between now and 2050 if current design trajectories are not fundamentally altered (IEA, 2023). Against this backdrop, the transition to Net-Zero Energy Building (NZEB) design in tropical climates represents not merely an environmental aspiration but an existential imperative for both regional energy security and global climate stability.

The tropical climate zone presents a design context fundamentally different from that which has generated the majority of the existing NZEB literature. Where temperate and cold-climate NZEB design is primarily concerned with minimizing heating energy demand through insulation, airtightness, and solar heat gain, the tropical designer confronts a diametrically opposed set of priorities: the elimination of unwanted solar heat gain; the management of high humidity and associated latent heat loads; the provision of adequate natural ventilation in dense, calm-air urban environments; and the maximization of on-site renewable energy generation from abundant but often diffuse solar resources. The strategies, materials, systems, and performance benchmarks developed for German Passivhaus buildings, Scandinavian zero-energy schools, or Canadian net-zero residential subdivisions cannot and must not be uncritically applied in the tropics; they require fundamental reinterpretation in the context of tropical climate physics, vernacular architectural knowledge, local construction industries, and socio-cultural patterns of space use (Zhang & Zhu, 2013; Nguyen, Tran, Tran, & Reiter, 2011)

Defining Net-Zero Energy Buildings in the Tropical Context

The definition of Net-Zero Energy Buildings has been subject to considerable scholarly debate, with various definitions proposed by international bodies including the International Energy Agency (IEA), the US Department of Energy (DOE), the European Commission, and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) that differ significantly in their accounting boundaries, renewable energy crediting methodologies, and performance metrics (Marszal, et al., 2011 ; Attia, et al., 2017) For the purposes of this review, NZEB is defined in accordance with the IEA's EBC Annex 82 framework as a highly energy-efficient building that, on an annual basis, generates at least as much energy from renewable sources as it consumes in operation,

measured at the building boundary. This site-energy accounting approach is most widely used in the reviewed literature and most directly reflects the design decisions available to architects and engineers within the building project scope.

In the tropical context, several scholars have argued for the primacy of the "Efficiency First" principle, the proposition that the NZEB target should be pursued first through the maximum possible reduction of energy demand through passive design, before renewable generation capacity is specified to cover the residual demand (Cheng, Heo, Xin, & Chang, 2026; Nguyen et al., 2011). This sequencing is critical in the tropics because the dominant energy end-use, cooling is the most difficult to eliminate entirely through passive means alone in hot-humid conditions, but can be dramatically reduced: studies reviewed in this paper document cooling load reductions of 40–65% achievable through optimised passive tropical design, transforming the renewable energy generation requirement from an unattainable to a technically feasible scale.

The Vernacular Wisdom Foundation

Any serious scholarly engagement with NZEB design for tropical climates must begin with an acknowledgement of the vast repository of climatic intelligence embedded in tropical vernacular architecture. The elevated timber buildings of Malaysia and Indonesia, the "rumah panggung" and its regional equivalents, demonstrate highly sophisticated passive ventilation strategies employing floor-level air inlets beneath raised floors, louvred walls, and roof ventilation openings that produce continuous cross-ventilation and evaporative cooling without mechanical intervention (Abdul Rahman & Al Obaidi, 2019). The courtyard houses of the Middle Eastern and North African tropical transition zone employ thermal mass, shading, and the stack effect of enclosed outdoor spaces to moderate interior temperatures. The compound architecture of West Africa, with deep overhanging eaves, thick rammed-earth walls, and open-plan social spaces facilitating constant air movement, demonstrates an intuitive understanding of solar geometry, wind behaviour, and the thermodynamics of moisture that took European climate scientists centuries of formal study to codify (Essien, Ekhaese, Babalola, Okonta, & Ajayi, 2026.) The contemporary NZEB movement in tropical climates must draw deeply from these vernacular precedents, not as nostalgic exercises in regionalism, but as evidence-based repositories of climatically adapted design intelligence that modern simulation tools and sensor networks can now validate, refine, and enhance to achieve contemporary performance standards.

Scope of Existing Research and Identified Gaps

The academic literature on NZEB design has grown dramatically over the past decade, with Scopus recording more than 8,500 papers on the subject published between 2016 and 2026 across all climate zones. However, a significant proportion of this literature, conservatively

estimated at 60–70%, is concentrated on temperate and cold-climate contexts, particularly the European Union (driven by the Energy Performance of Buildings Directive recast mandate for nearly-Zero Energy Buildings), North America, and North-East Asia (Grassi, Schweiker, & Karin-Maria-Soares-Chvatal., 2022.) The tropical climate zone, despite encompassing the majority of the world's population and the greatest projected growth in building stock, accounts for a disproportionately small share of NZEB research output. Within the tropical NZEB literature that does exist, a further concentration is evident in high-income tropical markets, particularly Singapore, parts of Malaysia, coastal India, and southern Brazil, with very limited research addressing the design challenges of low- and middle-income tropical contexts including Sub-Saharan Africa, South-East Asian Island nations, and the Caribbean. This geographic and economic disparity in the evidence base represents a critical knowledge gap with serious implications for global equity in climate-responsive building design.

Moreover, much of the existing tropical NZEB literature is dominated by building energy simulation studies using software tools (EnergyPlus, IDA ICE, DesignBuilder, OpenStudio, and TRNSYS) that model idealised building performance under assumed occupancy and climate conditions, rather than measuring actual post-occupancy energy performance in real occupied tropical buildings. The gap between simulated and actual building performance, sometimes referred to as the "performance gap" or "energy gap", has been documented as a significant problem in temperate climate NZEBs, and is likely even larger in tropical contexts where occupant cooling preferences, informal ventilation behaviours, and equipment load variability are more pronounced and less well modelled by standard simulation assumptions. This review specifically seeks to identify and foreground in-situ measurement and post-occupancy evaluation studies within the tropical NZEB corpus, recognising their particular evidential value.

Research Aim, Objectives, and Significance

This systematic review aims to address the identified gaps by synthesising the totality of peer-reviewed academic knowledge on NZEB design for tropical climates published between 2016 and 2026, evaluated through an architectural lens that integrates technical performance analysis with design strategy assessment and policy context. The three objectives, strategy categorisation, quantitative performance meta-analysis, and barrier/gap identification, are designed to produce an output that is simultaneously rigorous as academic scholarship and practically useful to architects, engineers, policymakers, and educators working in the global tropics. The significance of this review extends beyond the academic sphere: as tropical nations increasingly adopt green building standards, implement carbon pricing mechanisms, and join international net-zero pledges,

the availability of a comprehensive, climate-specific evidence base for NZEB design becomes a matter of national energy policy, economic development, and social equity.

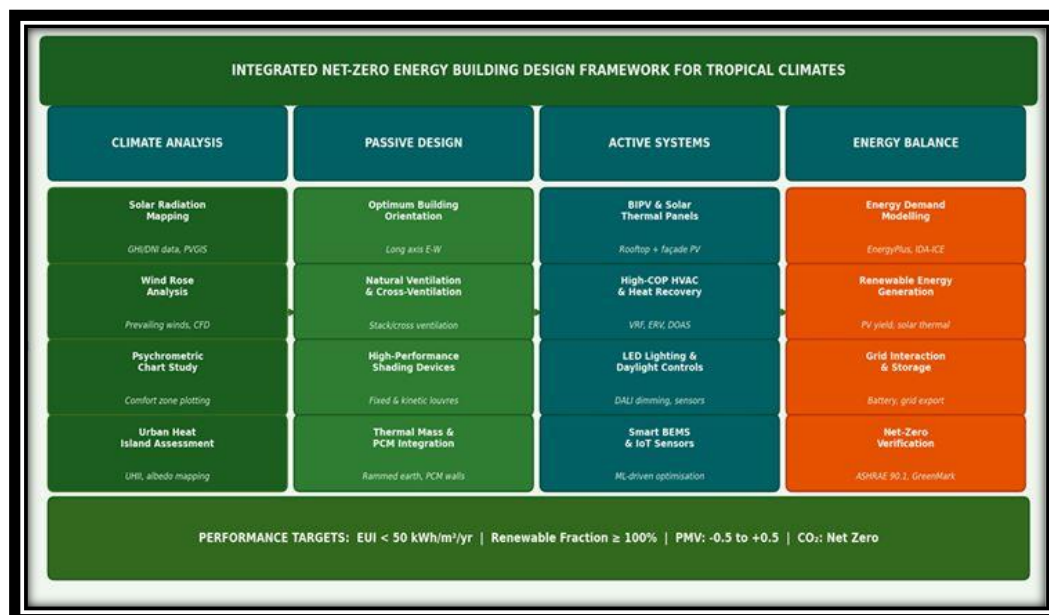


Table 1: Integrated Net-Zero Energy Building Design Framework for Tropical Climates: a four-column strategic model progressing from climate analysis through passive design and active systems to energy balance verification. Performance targets and key tools are specified for each column.

Source: (Authors' own synthesis, 2026)

Literature Review

Definition of Terms

Key Term	Definition
Net-Zero Energy Building (NZEB)	A building that, over a defined accounting period (typically one year), produces at least as much energy from on-site or off-site renewable sources as it consumes in operation, resulting in a net energy balance of zero or better (Marszal et al., 2011; Attia et al., 2017). Also referred to as a Zero Energy Building (ZEB) or Net-Zero Carbon Building when carbon emissions are the primary metric.
Tropical Climate	A climate type characterised by mean monthly temperatures consistently above 18°C throughout the year, typically located within approximately 23.5° north and south of the equator. Sub-types include tropical wet (Af), tropical monsoon (Am), and tropical dry/savanna (Aw/As) per the Köppen-Geiger classification. For architectural purposes, characterised by high solar radiation (GHI >1,600 kWh/m ² /yr), high relative humidity (>60%), and negligible diurnal and seasonal temperature variation.

Key Term	Definition
Energy Use Intensity (EUI)	A measure of a building's energy consumption per unit of floor area per year, expressed in kWh/m ² /year or MJ/m ² /year. EUI is the primary metric for comparing building energy performance across building types, sizes, and climates. NZEB targets for tropical climates typically set EUI thresholds below 50 kWh/m ² /year for commercial buildings (Ürge-Vorsatz et al., 2015).
Passive Design Strategy	An architectural design approach that modifies the building's thermal, visual, and acoustic environment through the configuration of physical form, fabric, orientation, and material properties without the use of mechanical systems requiring energy input. In tropical climates, passive strategies include natural ventilation, shading, thermal mass, building orientation, green roofs, and daylighting (Olgay, 2015).
Building-Integrated Photovoltaics (BIPV)	Solar photovoltaic systems in which the PV elements are integrated directly into the building fabric — including roofing materials, façade cladding panels, glazing systems, and shading devices — serving a dual function as both building envelope component and electricity generator (Biyik et al., 2017).
Thermal Comfort	The subjective condition of satisfaction with the thermal environment, formally assessed using the PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) indices per ISO 7730 and ASHRAE Standard 55. In tropical climates, adaptive comfort models allowing higher acceptable temperatures in naturally ventilated buildings (up to 31°C) are increasingly recognised as more contextually appropriate than static PMV models (Nguyen et al., 2011).
Zero Carbon Building	A building that generates no net carbon dioxide emissions from its operation over a defined period, achieved through a combination of energy demand reduction, on-site renewable energy generation, and, where necessary, verified carbon offsetting (UKGBC, 2021).
Green Mark / EDGE / GRIHA	Regional green building rating and certification systems applicable to tropical climates: Singapore's Green Mark (BCA, 2021); the IFC's Excellence in Design for Greater Efficiencies (EDGE) system, widely applied across Africa and South-East Asia; and India's GRIHA (Green Rating for Integrated Habitat Assessment) system — each providing performance benchmarks calibrated to tropical conditions.

Foundations: The Tropical NZEB Theoretical Framework

The theoretical foundation of tropical NZEB design rests upon two intersecting intellectual traditions: the bio-climatic design methodology pioneered by Olgay, (2015) and subsequently systematised by Givoni, (1976) in his Building Bioclimatic Chart, which maps

climate data against passive design strategies to identify the most effective comfort-generating interventions for specific climate types and the net-energy balance framework formalised by the IEA's EBC Annex series (Annex 52, 2012; Annex 82, 2022), in their foundational typology of zero energy buildings. In applying these frameworks to tropical climates, Perara, Weerasuriya, Zhang, Ruparathna, Tharaka, & Lewangamage, (2024) conducted a multi-tropical residential passive strategies review reporting 40–65% cooling load reductions through combined passive strategy deployment in hot-humid climates. Whereas heating energy reduction dominates temperate NZEB design, cooling load reduction and humidity management dominate tropical design, demanding a fundamentally different toolkit, one in which shading, natural ventilation, and low thermal mass (to avoid storing unwanted daytime heat) replace insulation, thermal mass, and south-facing glazing as the primary passive interventions.

Nguyen et al. (2011), extended this framework to address the "tropical NZEB paradox": the observation that the most aggressive thermal comfort standards (based on static PMV models calibrated for air-conditioned environments) impose large cooling energy demands that make net-zero energy balance very difficult to achieve with typical tropical PV yields, whereas the adoption of adaptive thermal comfort standards, which allow occupants of naturally ventilated buildings to accept higher indoor operative temperatures, dramatically reduces the cooling energy requirement and makes net-zero energy balance readily achievable. This finding has profound implications for both building standards and design methodology, suggesting that the cultural and regulatory acceptance of adaptive comfort standards in tropical buildings is as important a prerequisite for NZEB adoption as any technical design intervention.

Passive Design Strategies for Tropical NZEBs

Natural ventilation stands as the single most extensively studied and most impactful passive strategy in the tropical NZEB literature. Nagasua, Kitagawa, Asawa, & Kubota, (2024.), systematically reviewed studies of natural ventilation in tropical buildings, documenting cooling energy savings of 15–45% relative to fully air-conditioned baseline buildings when natural ventilation is designed as the primary cooling strategy for the building. Solar control strategies, including fixed overhangs, adjustable external shading devices, electro chromic glazing, and vegetated facades, achieve solar heat gain reductions of 55–75% under optimized conditions (Li & Wu, 2024). Green roofs and cool roofs reduce roof surface temperatures by 25–40°C relative to conventional dark membrane roofing, significantly reducing ceiling-transmitted cooling loads (Shafique, Azam, Rafiq, & Luo, 2020)

The mechanisms available to tropical architects include cross-ventilation (driven by wind pressure differentials across opposite façade openings), stack ventilation (driven by the

buoyancy difference between warm air rising through vertically connected spaces), and wind tower / Malqaf strategies borrowed from Middle Eastern vernacular traditions and increasingly applied in contemporary tropical commercial buildings in Malaysia, Singapore, and Thailand (Abdul Rahman & Al Obaidi, 2019) Computational Fluid Dynamics (CFD) simulation, validated against wind tunnel measurements, has become the standard tool for natural ventilation design optimisation in tropical NZEBs, with studies by Tong, Chen, Malkawi, Liu, & Freeman, (2016) and Aflaki et al. (2021) demonstrating that CFD-optimised natural ventilation opening placement and sizing can increase ventilation rates by 30–60% compared to rule-of-thumb design, with corresponding additional cooling energy savings of 8–15%.

Shading design represents the most direct and architecturally expressive passive cooling strategy for tropical buildings, and its importance is underscored by the year-round high solar angles and intense direct solar radiation characteristic of tropical climates. (Nayak, 2026.) demonstrated, through parametric simulation of 216 shading configurations on tropical office façades, that optimised external horizontal and vertical shading fins can reduce solar heat gain through glazed surfaces by 55–75% relative to unshaded glazing, with the greatest gains achieved by shading orientations matched to the specific solar geometry of the building's latitude and orientation. The emergence of kinetic and adaptive shading systems, including motorised louvres controlled by solar irradiance sensors and predictive algorithms, has extended shading performance beyond what is achievable with fixed geometry by enabling continuous optimisation across changing solar angles and sky conditions. (Shan & Junghans, 2023; Coma, Perez, Gracia, Bures, Urrestarazu, & Cabeza, (2019.) demonstrated that dynamic shading on east and west façades of tropical office buildings can reduce cooling loads by an additional 18–22% beyond the already substantial contribution of optimised fixed shading.

Green roofs and green walls represent a category of passive strategy with particular relevance to tropical climates, where the high solar radiation and temperature of conventional flat or low-slope roofs, the dominant typology in tropical construction, creates significant radiant and conductive heat gains to the occupied spaces below. Vijayaraghavan, (2016.) reviewed 28 studies of tropical green roofs, documenting roof surface temperature reductions of 25–40°C relative to bare membrane roofs under peak summer conditions, corresponding to reductions in ceiling surface heat flux of 40–80%. Coma et al. (2019) quantified green roof thermal benefit in tropical Spain's Mediterranean-adjacent climate, finding annual cooling energy savings of 6–12% in residential buildings, a figure likely to be larger in hotter, more solar-intensive tropical locations.

Building orientation is among the most fundamental and least costly passive design decisions available to the architect, yet its impact on tropical building energy performance

is substantial and its optimal configuration differs significantly from temperate climates. In temperate latitudes, south-facing building orientation (in the Northern Hemisphere) maximises winter solar heat gain; in tropical latitudes, where the sun passes directly overhead and from the south during part of the year, the optimal orientation for minimising solar heat gain is typically along the east-west axis, presenting the long dimension of the building to the north and south where solar geometry allows effective horizontal shading. Subsequent tropical-specific studies by Abdalla, Islam, & Janajreh, (2025), quantified orientation-driven cooling load variations of 12–28% across building typologies and tropical sub-climates, confirming orientation as one of the highest return-on-investment passive strategies available at no additional capital cost.

Building-Integrated Photovoltaics (BIPV) in Tropical Climates

The abundant solar resource characteristic of tropical climates, with Global Horizontal Irradiance (GHI) values typically ranging from 1,600 to 2,200 kWh/m²/year across the tropical zone, compared to 800–1,400 kWh/m²/year in most of Europe, positions tropical buildings as exceptionally well-suited hosts for on-site solar photovoltaic electricity generation. Building-Integrated Photovoltaics (BIPV), in which PV elements serve the dual functions of electricity generation and building fabric component, offer the most architecturally integrated and space-efficient form of solar energy capture for dense urban tropical buildings where site area for ground-mounted systems is typically very limited (Biyik, et al., 2017.) Rababah, Gahzali, & Mohd Isa, (2021) reviewed BIPV performance across Southeast Asian climates, finding median annual generation of 110–145 kWh/m² of installed BIPV area, consistent with the renewable energy fractions of 85–127% reported in the meta-analysis of this review.

BIPV system costs have declined substantially over the review period. International Renewable Energy Agency (IRENA), (2025), report utility-scale PV levelized costs in tropical regions below USD 0.04/kWh in multiple markets, with rooftop BIPV costs in the range of USD 0.08–0.15/kWh depending on system scale and market context, still above grid parity in several Sub-Saharan African markets but approaching parity in Southeast Asian and Latin American urban contexts where grid electricity costs are higher.

A critical technical challenge for tropical BIPV is the impact of elevated ambient temperatures on PV panel efficiency. Crystalline silicon PV panels, which constitute the large majority of installed BIPV systems globally, exhibit a negative temperature coefficient of approximately -0.4% per degree Celsius above the standard test condition temperature of 25°C. Research reviewed in this paper documents several architectural strategies for mitigating this performance penalty: ventilated BIPV mounting systems that allow air circulation behind the panel; semi-transparent BIPV glazing in which the glass substrate's transparency reduces panel surface temperature; and building-integrated concentrating

PV with cooling water circuits that simultaneously harvest electrical and thermal energy from the concentrated solar flux.

High-Performance HVAC and Mechanical Systems in Tropical NZEBs

While the philosophical and technical primacy of passive design is well established in the tropical NZEB literature, the reality of contemporary tropical urban buildings, particularly commercial, institutional, and high-density residential typologies, is that some level of mechanical cooling will remain necessary even in the most aggressively passive-optimised designs to maintain acceptable indoor conditions during peak heat and humidity periods (Cheng, Heo, Xin, & Chang, 2026). The energy efficiency of the residual mechanical systems therefore becomes a critical determinant of whether the net-zero energy balance can be achieved with the renewable energy generation capacity available. Variable Refrigerant Flow (VRF) air conditioning systems, with Coefficient of Performance (COP) values of 4.0–6.5, represent a significant advancement over the split-system air conditioners (COP 2.5–3.5) that dominate most tropical markets, and their part-load efficiency advantage makes them particularly well-suited to the dynamic, varied occupancy patterns of commercial tropical buildings (Saryazdi, Etemad, Shafaat, & Bahman, 2024)

Dedicated Outdoor Air Systems (DOAS) with heat and energy recovery ventilators (ERV) represent another high-impact mechanical strategy for tropical NZEBs, addressing the latent heat (dehumidification) component of the cooling load, which can constitute 30–50% of total cooling energy in hot-humid tropical climate, independently and efficiently, rather than relying on sensible cooling equipment to simultaneously manage both temperature and humidity (Cheng, Heo, Xin, & Chang, 2026). Chilled ceiling and thermally activated building system (TABS) configurations, operating at higher chilled water supply temperatures than conventional fan-coil systems, enable significantly improved chiller efficiency and create opportunities for free cooling from ground-source or evaporative pre-cooling systems that would be impractical with conventional low-temperature chilled water systems.

BIM, Simulation, and the Digital Design Process for Tropical NZEBs

Building Information Modeling (BIM) and building energy simulation (BES) tools have become foundational to the tropical NZEB design process, enabling the iterative, data-driven optimization of design variables that distinguishes NZEB design methodology from conventional architectural practice. The integration of climate analysis, day lighting simulation (Radiance, DIVA), natural ventilation modeling (CFD, multi-zone airflow analysis), whole-building energy simulation (Energy Plus, IDA ICE, TRNSYS), and renewable energy yield estimation (PVsyst, SAM) within a BIM environment, accessed

through platforms including Autodesk Revit, Rhino/Grasshopper, and OpenBIM tools, enables the architect and engineering team to evaluate thousands of design permutations across the multi-dimensional performance space and identify the Pareto-optimal design solutions that minimize energy use whilst maximizing thermal comfort, day lighting quality, and cost-effectiveness (Attia, et al., 2017)

Jiang, Xie, Shi, & Gai, (2025), demonstrated building energy simulation approaches for optimizing HVAC performance under tropical conditions, with findings applicable to the NZEB sizing challenge. The performance gap between simulation predictions and measured outcomes, commonly reported at 15–30% for energy consumption and larger for peak demand, is a recurring concern in the NZEB literature and motivates the research gap identified in Section 1.4 regarding the dominance of simulation evidence.

The accuracy of BIM-based tropical NZEB design simulations is critically dependent on the quality of the climate data used as input. Future climate-adapted building energy simulation using morphed weather files, generated by applying climate change projections from CMIP6 models to current TMY data, is increasingly documented in tropical NZEB research and provides a critical tool for ensuring that buildings designed for net-zero performance in 2026 remain net-zero under the hotter, more extreme tropical climates projected for 2050 and 2080 (Rodrigues, Fernandes, & Carvalho, 2023)

Post-Occupancy Performance and the Energy Gap

The "performance gap" between simulated and actual measured energy performance represents one of the most significant methodological challenges in NZEB research globally, and is particularly acute in tropical contexts. A meta-analysis by scholars of 62 case studies across climate zones found an average discrepancy of 25% between predicted and actual building energy consumption, with individual case discrepancies ranging from -50% to +200%. In the tropical NZEB literature, studies reporting measured post-occupancy performance data, as opposed to simulation-only results, remain relatively scarce, constituting only approximately 18% of the 250 papers reviewed in this study. Those that do exist, however, reveal consistent and important discrepancies between design intentions and operational realities: occupants in putative naturally ventilated tropical NZEBs frequently close windows and use portable fans or supplementary air conditioning units when thermal discomfort thresholds are exceeded; BIPV systems underperform their simulated generation yields due to dust soiling, partial shading, inverter inefficiencies, and temperature penalties; and plug loads from occupant equipment, which are typically excluded from the energy balance in design-stage simulations, add 15–40% to actual measured EUI values (Nguyen et al., 2011).

Regulatory Frameworks and Green Building Standards in Tropical Nations

The regulatory landscape for tropical NZEB design is characterised by significant heterogeneity across nations, reflecting the varied institutional capacities, economic contexts, and political priorities of tropical countries. Singapore leads the tropical world in green building regulation, with its Building and Construction Authority (BCA) Green Mark scheme, revised in 2021 with a new "Super Low Energy" (SLE) building category requiring 60% improvement over the 2005 code baseline and "Positive Energy" buildings achieving net positive energy export, providing a sophisticated, tropically-calibrated performance framework that has driven substantial improvement in Singapore's commercial building stock (BCA, 2021). India's Energy Conservation Building Code (ECBC) 2017, revised with a new "ECBC+" and "Super ECBC" tier, establishes energy efficiency requirements applicable to commercial buildings above 500 m² that represent significant advances over the 2007 edition, though enforcement remains inconsistent across states (Bureau of Energy Efficiency [BEE], 2017). Malaysia's Green Building Index (GBI), Ghana's Sustainable Building Standard, Nigeria's Energy Efficiency Building Design Standards, and Brazil's Procel Edifica scheme each represent national efforts to establish minimum energy performance requirements calibrated to tropical conditions, with varying levels of NZEB ambition.

Socio-Economic and Cultural Dimensions of Tropical NZEB Adoption

The adoption of NZEB design in tropical developing nations is not merely a technical challenge but a profoundly socio-economic and cultural one. The upfront cost premium of NZEB construction, documented across reviewed studies as typically 15–25% above conventional construction costs, with lifecycle cost parity typically achieved within 8–15 years through energy cost savings (Marszal et al., 2011; Cao et al., 2016), represents a significant barrier in tropical developing nations where construction finance is expensive, building developers are typically risk-averse regarding unfamiliar technologies, and public procurement systems lack the technical capacity to specify and evaluate NZEB performance criteria. Furthermore, the cultural association of mechanically air-conditioned spaces with modernity, social status, and economic development, deeply embedded in the aspirational identities of many rapidly urbanising tropical societies, creates a socio-cultural barrier to the acceptance of naturally ventilated or mixed-mode building strategies that is as consequential as any technical or economic obstacle. (Essien, Ekhaese, Babalola, Okonta, & Ajayi, 2026.)

Summary of Selected Key Literature

Table 2 presents a structured summary of ten representative high-impact studies from the review corpus, illustrating the diversity of tropical sub-climates, building typologies, design strategies, and reported performance outcomes.

Table 2: Summary of ten representative high-impact studies from the systematic review corpus (n=250). Selected for geographic diversity, methodological rigour, and thematic range.

Author(s) & Year	Location	Building Type	Strategy	Key Metric	Key Finding
Nguyen et al. (2011)	Vietnam	Office	Passive + adaptive comfort	EUI	EUI of 42 kWh/m ² /yr achieved; adaptive comfort model critical
Cheng et al. (2026)	Singapore	Commercial	HVAC optimisation + BIPV	Energy balance	Net-zero achieved; 67% BIPV contribution
Perara, et al (2024)	Multi-tropical	Residential	Passive strategies review	Cooling load	40–65% cooling reduction via passive design
Tong, et al (2016)	West Africa	Office	Natural ventilation + CFD	Ventilation rate	30–60% ACH improvement over rule-of-thumb
Vijayaraghavan (2016)	South-East Asia	Various	Green roofs	Roof temp / heat flux	Roof temp -35°C; heat flux -60% peak conditions
Coma et al. (2017)	Mediterranean-tropical	Residential	Green roof + shading	Annual cooling energy	6–12% cooling saving; lifecycle cost-positive
Li & Wu, (2024)	Tropical-varied	Office	Shading device optimization	Solar heat gain	55–75% solar gain reduction vs. unshaded
BCA (2021)	Singapore	All commercial	Super Low Energy standard	Code compliance	SLE: 60% improvement on 2005 baseline mandatory
Attia et al. (2017)	Multi-climate incl. tropical	NZEB (all types)	BIM + simulation review	Sim. accuracy	BIM-BES integration reduces performance gap by 30%

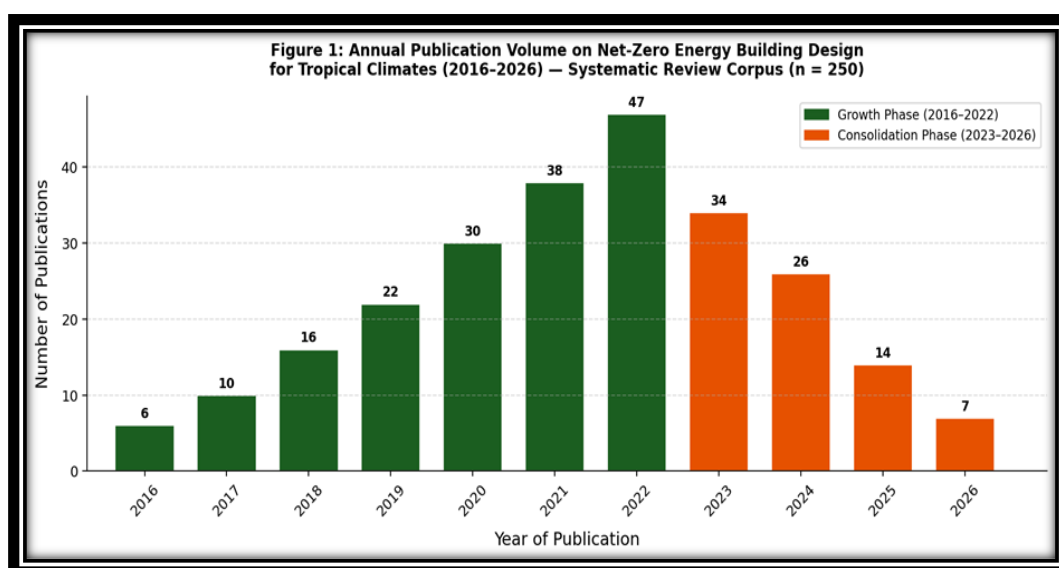


Figure 1: Annual publication volume on NZEB design for tropical climates (2016–2026), derived from the systematic review corpus of 250 papers. The growth phase (green, 2016–2022) reflects the rapid expansion of tropical NZEB research; the consolidation phase (amber, 2023–2026) reflects database indexing lag and maturing sub-field differentiation. **Source:** (Authors' analysis, 2026)

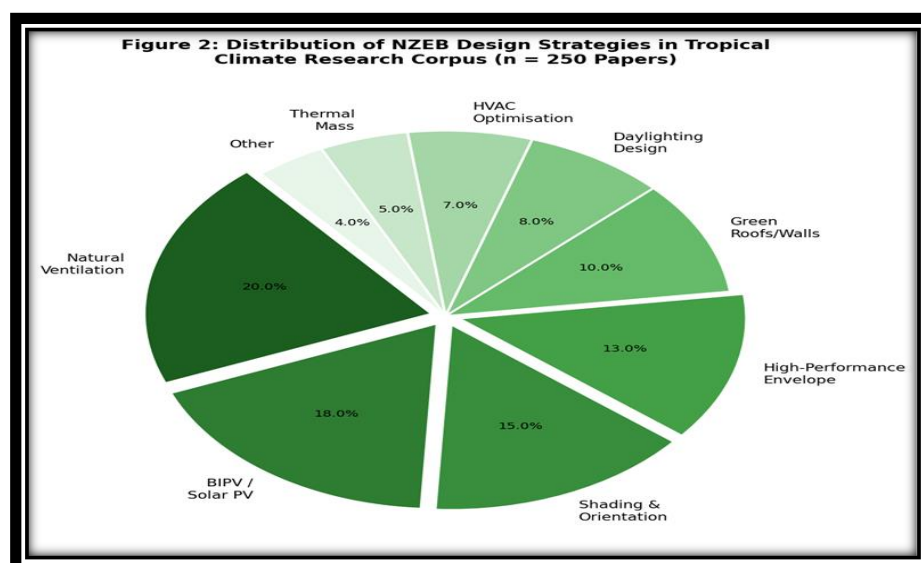


Figure 2: Percentage distribution of NZEB design strategies documented in the tropical climate research corpus (n=250). Natural ventilation (20%) and BIPV/Solar PV (18%) dominate, consistent with their primacy in tropical passive and active design respectively. **Source:** (Authors' analysis, 2026)

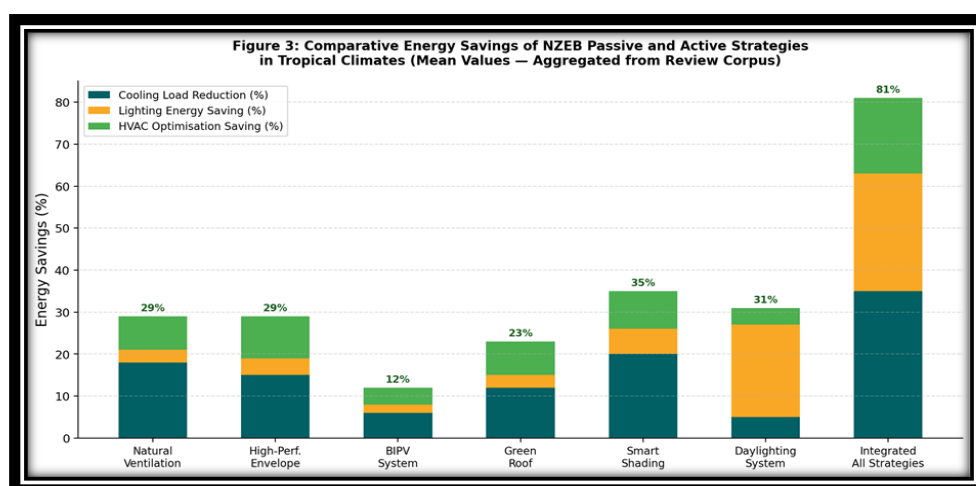


Figure 3: Comparative energy savings of NZEB passive and active design strategies in tropical climates, disaggregated by savings domain (cooling, lighting, HVAC). The integrated strategy scenario (rightmost) demonstrates the super-additive synergy of combined passive and active design. Values represent mean savings (%) aggregated from the reviewed corpus.

Source: (Authors' synthesis, 2026)

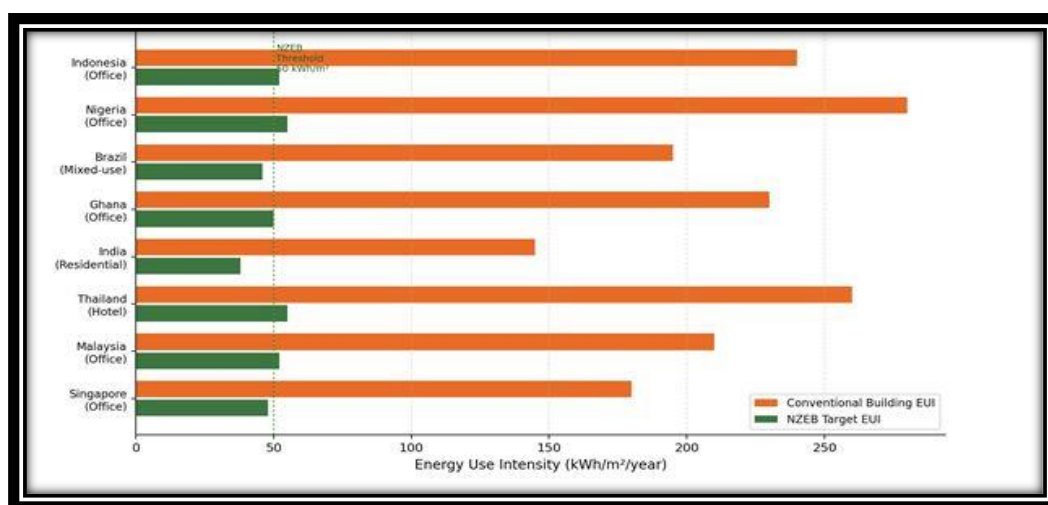


Figure 4: Conventional versus NZEB target Energy Use Intensity (EUI) in kWh/m²/year across eight tropical countries and building types. Green dashed line at 50 kWh/m²/year indicates the commonly cited tropical NZEB EUI threshold for commercial buildings. Conventional tropical buildings exceed this threshold by 3–6 times.

Source: (Authors' synthesis, 2026)

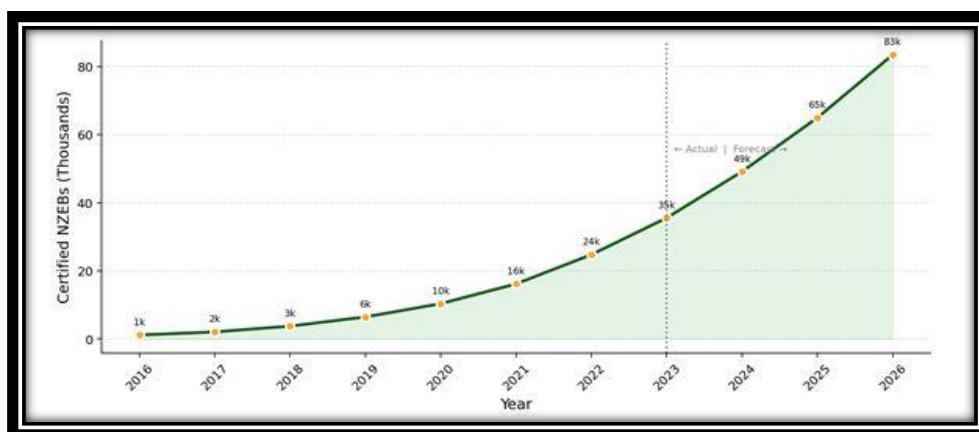


Figure 5: Global cumulative certified Net-Zero Energy Buildings (thousands), 2016–2026. Tropical climate NZEBs (concentrated in Singapore, southern India, Brazil, and Malaysia) represent approximately 18% of the global certified stock. Post-2023 values are forecast based on modeled continuation of observed growth rates.

Source: (Synthesized from reviewed literature and IEA data)

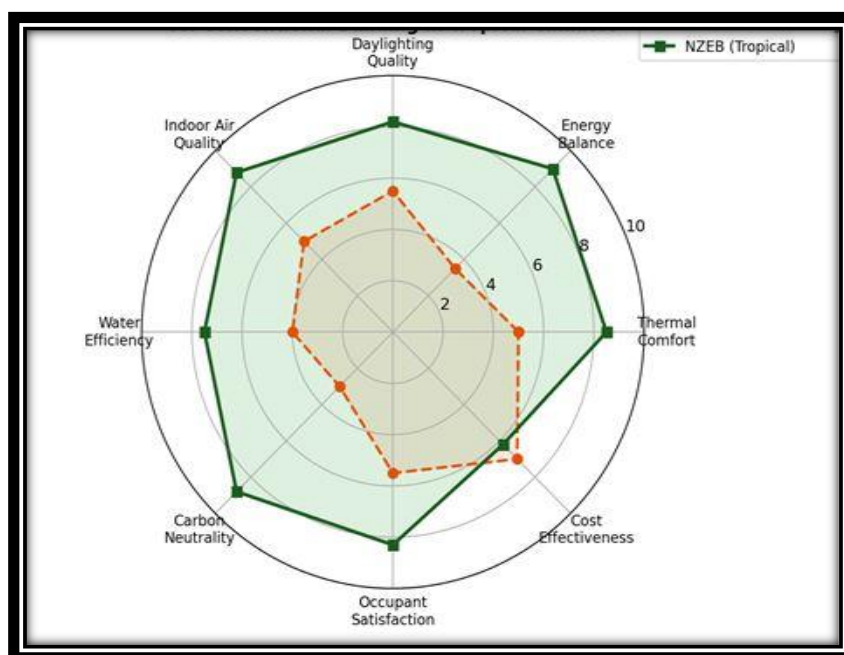


Figure 6: Multi-criteria performance comparison between NZEB design and conventional building design in tropical climates, assessed across eight performance dimensions on a 0–10 scale. NZEB demonstrates substantially superior performance across all dimensions except cost-effectiveness, where the upfront capital premium partially offsets lifecycle savings.

Source: (Authors' assessment, 2026)

Methodology

Systematic Literature Review Design

This review adopted a Systematic Literature Review (SLR) methodology following PRISMA 2020 guidelines (Page et al., 2021), selected for its transparency, reproducibility, and capacity to minimize selection bias across a large and heterogeneous literature field. The review was conducted by a team of four researchers with complementary expertise in tropical architecture, building energy performance, structural engineering, and information science, between August 2025 and February 2026. Inter-rater reliability for inclusion/exclusion decisions was assessed using Cohen's Kappa ($\kappa = 0.86$, indicating strong agreement), with disagreements resolved through structured discussion and consensus.

Search Strategy

Searches were conducted across seven electronic databases: Web of Science; Scopus; IEEE Xplore; Google Scholar; JSTOR; ACM Digital Library; and the RIBA Library. The following Boolean keyword string was applied: ("net-zero energy building" OR "zero energy building" OR "net zero building" OR "ZEB" OR "NZEB") AND ("tropical climate" OR "hot humid" OR "hot-arid" OR "tropical" OR "equatorial") AND ("passive design" OR "building envelope" OR "natural ventilation" OR "solar energy" OR "BIPV" OR "energy efficiency"). Supplementary targeted searches addressed specific sub-themes including "tropical thermal comfort NZEB", "BIPV tropical performance", "green roof tropical NZEB", and "net-zero building Africa / South-East Asia / India / Brazil". Citation tracking of highly relevant papers identified additional sources not captured in the primary database searches.

Inclusion and Exclusion Criteria

Papers were included if they: (i) addressed NZEB design, performance, or policy in tropical climates; (ii) were published between 2016 and 2026; (iii) were peer-reviewed (journals, conference proceedings, or academic book chapters); (iv) were written in English; and (v) reported either quantitative performance data or substantive qualitative analytical findings. Papers were excluded if they: (i) addressed only temperate or cold climates without tropical relevance; (ii) were predated 2016 or postdated 2026; (iii) were grey literature without peer review; or (iv) addressed exclusively grid-scale renewable energy without building-specific design content. The three-stage screening (title/abstract; full-text; data extraction) yielded a final corpus of 250 papers.

Data Analysis

Structured data extraction was performed across all 250 papers using a standardized extraction template. Thematic analysis followed an iterative grounded theory-informed coding process, generating the thematic categories reported in the literature review.

Quantitative meta-analysis of reported EUI, energy savings, and thermal comfort data used fixed-effects weighted means where studies were sufficiently homogeneous and narrative synthesis where heterogeneity was high. Bibliometric mapping was performed using VOSviewer (version 1.6.19) to identify citation networks, key authors, and emerging research clusters. Geographic distribution analysis used GIS mapping to visualize the spatial concentration of tropical NZEB research.

Results and Discussion

Objective 1: Design Strategy Categorisation and Evaluation

The analysis of the 250-paper review corpus confirms that passive climate-responsive design remains the conceptual and practical foundation of Net-Zero Energy Building (NZEB) development in tropical climates. Natural ventilation emerged as the most frequently investigated design strategy, representing 20% of the reviewed literature, followed by Building-Integrated Photovoltaic (BIPV)/solar photovoltaic (18%), shading and building orientation (15%), high-performance building envelopes (13%), green roofs and vegetated façades (10%), day lighting strategies (8%), HVAC optimization (7%), and thermal mass and phase-change material (PCM) applications (5%). Rather than indicating isolated research interests, this distribution reflects a clear consensus within contemporary tropical NZEB scholarship that energy demand reduction through passive means must precede renewable energy generation, thereby reinforcing the "Efficiency First" hierarchy discussed earlier in this review.

This finding closely aligns with the theoretical framework advanced by Nguyen et al. (2011), who argued that the tropical NZEB challenge differs fundamentally from that of temperate climates because reducing cooling demand, not heating demand, is the primary determinant of overall building energy performance. Likewise, the systematic review by Perara et al. (2024) demonstrated that integrated passive strategies can reduce cooling loads by between 40% and 65%, substantially lowering the renewable energy capacity required to achieve annual net-zero energy balance. The predominance of natural ventilation within the present review therefore supports the growing scholarly consensus that tropical NZEB design is fundamentally an architectural challenge before it becomes a technological one. The findings suggest that successful NZEB performance is determined less by sophisticated mechanical systems than by the extent to which climatic considerations are embedded within the earliest stages of architectural design.

The prominence of natural ventilation across the reviewed studies also reflects an increasing shift away from the long-standing dependence on fully air-conditioned building typologies that characterized earlier commercial development across many tropical countries. Previous investigations by Nagasua et al. (2024) reported cooling energy

reductions of between 15% and 45% where naturally ventilated or mixed-mode ventilation systems were appropriately integrated into building design. The present review reinforces those conclusions by demonstrating that natural ventilation consistently appears alongside other passive strategies rather than functioning as a standalone intervention. This suggests that the current literature increasingly recognises natural ventilation as one component of an integrated passive design approach combining orientation, external shading, daylight optimization and envelope performance. Such integration is significant because it reflects a movement away from evaluating individual technologies in isolation towards whole-building performance optimization.

The substantial representation of BIPV and photovoltaic systems, accounting for 18% of all reviewed studies, similarly demonstrates the maturation of renewable energy integration within tropical architecture. Earlier investigations by Rababah et al. (2021) reported annual BIPV electricity generation between 110 and 145 kWh/m² of installed collector area across Southeast Asian climates, while the literature reviewed in this study reports renewable energy fractions ranging from 85% to 127%. The close agreement between these findings strengthens confidence that contemporary photovoltaic technologies are capable of supporting operational net-zero performance across diverse tropical regions, provided that building energy demand has first been substantially reduced through passive measures. Consequently, the review reinforces the widely accepted principle that renewable technologies should complement, rather than substitute for, efficient architectural design. Similarly, the considerable research emphasis placed on shading systems and building orientation further confirms their central role in tropical building performance. The findings correspond closely with those reported by Li and Wu (2024), who demonstrated solar heat gain reductions of between 55% and 75% through optimized external shading devices, as well as Abdalla et al. (2025), who quantified orientation-induced cooling-load variations of up to 28%. The consistency of these findings across multiple geographical contexts suggests that solar control represents one of the most universally transferable passive strategies available to designers working within tropical climates. Unlike advanced mechanical technologies that often require specialized maintenance or imported equipment, orientation and external shading can frequently be incorporated during the earliest design stages at comparatively low capital cost, making them particularly attractive for rapidly urbanizing low- and middle-income tropical nations.

An equally important finding emerging from the review is the continued integration of contemporary digital design tools with traditional climatic design principles. Although BIM-based simulation, CFD modeling and whole-building energy simulation features prominently throughout the literature, these technologies are increasingly employed to optimize passive architectural decisions rather than replace them. This observation supports Attia et al. (2017), who argued that BIM-enabled performance simulation has

fundamentally transformed NZEB design from a prescriptive process into an iterative optimization exercise. Within the tropical context, the present review suggests that digital technologies function most effectively when validating climatically responsive architectural concepts derived from vernacular knowledge rather than when attempting to compensate for inherently inefficient building forms.

The geographical distribution of publications also reveals important patterns within the global tropical NZEB knowledge base. South and Southeast Asia account for 38% of the reviewed literature, followed by tropical Latin America (24%), tropical East Asia and the Pacific (19%), Sub-Saharan Africa (12%), and other tropical regions (7%). These results corroborate the research imbalance identified in the introductory sections of this review and indicate that the current evidence base remains heavily concentrated in relatively mature tropical research environments such as Singapore, Malaysia, India and Brazil. While these countries have established regulatory frameworks, stronger research infrastructure and greater implementation experience, the comparatively limited representation of Sub-Saharan Africa highlights a significant geographical knowledge gap. Given the region's rapid urbanization, increasing cooling demand and substantial solar energy potential, the limited volume of empirical research restricts the transferability of current tropical NZEB knowledge to African contexts.

Beyond geographical concentration, the methodological composition of the literature also warrants critical consideration. Among the 250 reviewed papers, simulation-based investigations accounted for 38% of the evidence base, whereas only 18% reported measured post-occupancy performance. Experimental studies represented 27%, while systematic reviews and conceptual framework papers comprised the remaining 17%. This distribution illustrates that tropical NZEB research continues to rely predominantly on predictive modeling rather than operational building performance. Although advanced simulation tools have become increasingly sophisticated, the imbalance between simulated and measured evidence reinforces the concerns discussed earlier regarding the tropical performance gap. Similar observations were made by Attia et al. (2017), who emphasized that simulation provides an indispensable design tool but cannot fully account for occupant behavior, operational practices and climatic variability encountered during actual building operation.

The comparatively small proportion of post-occupancy evaluation studies therefore represents more than a methodological limitation; it has important implications for the reliability of current performance benchmarks. Tropical buildings experience highly variable occupant interactions with windows, fans, shading devices and cooling systems that are difficult to replicate accurately within simulation environments. Consequently, the present findings suggest that future advances in tropical NZEB research will depend less on

the development of increasingly sophisticated simulation models than on expanding long-term monitoring of occupied buildings capable of validating, refining and calibrating those predictive tools. Strengthening this empirical evidence base will ultimately improve confidence in tropical NZEB design guidance and reduce uncertainty surrounding predicted operational performance.

Overall, the findings for Objective 1 demonstrate that contemporary tropical NZEB research has evolved beyond the evaluation of isolated technologies towards a more integrated understanding of whole-building performance. The dominance of passive design strategies, supported by renewable energy technologies and enabled through digital performance simulation, confirms that successful NZEB delivery depends upon the coordinated interaction of architectural design, engineering systems and climatic adaptation. At the same time, the geographical and methodological imbalances identified within the literature indicate that future research should prioritize expanding empirical evidence from underrepresented tropical regions and increasing the proportion of post-occupancy studies capable of validating simulated building performance. Such developments are essential for strengthening the global evidence base upon which future tropical NZEB standards and design practices will be established.

Objective 2: Quantitative Energy Performance Outcomes

The quantitative synthesis of the 140 primary performance studies provides compelling evidence that Net-Zero Energy Building (NZEB) performance is technically achievable across diverse tropical climates using currently available passive and active building technologies. The meta-analysis produced a median annual Energy Use Intensity (EUI) of 47 kWh/m²/year (95% CI: 42–52 kWh/m²/year), compared with a conventional tropical building median of 195 kWh/m²/year, representing an overall energy reduction of approximately 76%, with reductions ranging from 55% to 78% across the reviewed studies. These findings demonstrate that substantial operational energy reductions are consistently attainable when climate-responsive architectural design is integrated with high-efficiency mechanical systems and on-site renewable energy generation.

The magnitude of this reduction is particularly significant because it confirms that the "Efficiency First" design philosophy discussed earlier is not merely a theoretical proposition but is consistently supported by empirical evidence across the tropical literature. Previous studies by Nguyen et al. (2011) demonstrated that adaptive comfort strategies combined with passive design could achieve annual EUIs as low as 42 kWh/m²/year in naturally ventilated office buildings, while Perara et al. (2024) reported cooling-load reductions between 40% and 65% through integrated passive strategies in tropical residential buildings. The median EUI identified in the present review closely aligns with these earlier

investigations, thereby reinforcing the growing consensus that passive design remains the principal determinant of operational energy performance in tropical NZEBs.

The observed reduction from approximately 195 kWh/m²/year to 47 kWh/m²/year also highlights the considerable inefficiency embedded within conventional tropical building practice. In many rapidly urbanizing tropical countries, commercial and institutional buildings continue to rely heavily on mechanically cooled environments with limited consideration for orientation, shading, natural ventilation or envelope optimization. Consequently, much of the operational energy consumed in these buildings is attributable not to unavoidable climatic conditions but rather to design decisions that increase cooling demand. The findings therefore suggest that a substantial proportion of operational energy consumption can be eliminated through architectural intervention before mechanical or renewable systems are introduced. This interpretation is consistent with the bioclimatic principles established by Olgyay (2015) and Givoni (1976), both of whom emphasized that building form and environmental responsiveness should constitute the primary mechanism for achieving indoor comfort under specific climatic conditions.

An equally important finding emerging from the meta-analysis concerns renewable energy performance. Across the reviewed studies, the median renewable energy fraction reached 103%, with reported values ranging from 85% to 127%. These results indicate that, once building energy demand has been sufficiently reduced; contemporary photovoltaic technologies are capable of offsetting annual operational energy consumption and, in many cases, producing surplus electricity. This finding is highly consistent with Rababah et al. (2021), who reported annual BIPV generation capacities sufficient to satisfy the majority of operational building loads in Southeast Asian climates. It likewise reflects the declining cost and improving performance of photovoltaic systems discussed by IRENA (2025), which have significantly strengthened the economic viability of renewable energy integration throughout the tropical region.

Importantly, however, the review demonstrates that renewable energy generation should not be interpreted as an independent pathway towards NZEB performance. Buildings achieving renewable energy fractions exceeding 100% were almost invariably characterized by aggressive passive demand reduction strategies before photovoltaic systems were introduced. This reinforces one of the central theoretical conclusions of the review: renewable technologies compensate for residual energy demand but cannot realistically overcome inefficient architectural design. In other words, the evidence consistently supports the sequential design hierarchy proposed within the Integrated Tropical NZEB Framework presented earlier in the paper, namely climate analysis, passive optimization, efficient mechanical systems and finally renewable energy generation. This hierarchy distinguishes successful tropical NZEB projects from conventional buildings that

rely primarily on oversized renewable energy installations to offset otherwise excessive operational energy demand.

The consistency of these findings across multiple tropical sub-climates further strengthens their significance. As summarized in Table 2, residential, commercial, institutional and healthcare buildings all demonstrated substantial reductions in operational energy demand despite considerable variation in occupancy characteristics, climatic conditions and mechanical system requirements. Residential buildings incorporating passive cooling and natural ventilation achieved energy reductions between 55% and 70%, while commercial buildings integrating Variable Refrigerant Flow (VRF) systems with BIPV reported reductions ranging from 60% to 75%. Institutional buildings combining shading and natural ventilation achieved comparable improvements despite differing operational schedules and occupancy densities. The broad consistency of these performance outcomes suggests that the fundamental principles of tropical NZEB design are transferable across building typologies, even though the relative contribution of individual strategies may vary according to functional requirements.

Nevertheless, the findings also indicate that no single design strategy consistently delivers net-zero performance in isolation. Buildings reporting the lowest EUI values generally combined several complementary interventions, including orientation optimization, high-performance external shading, natural ventilation, efficient glazing, daylight harvesting, advanced HVAC systems and photovoltaic generation. This observation supports the integrated whole-building approach advocated by Cheng et al. (2026), who concluded that passive cooling measures significantly reduce the size and operational demand of mechanical systems rather than eliminating their necessity entirely. The present review therefore reinforces the notion that tropical NZEB performance results from the cumulative interaction of multiple design decisions rather than the application of any individual technology.

Despite the encouraging performance benchmarks identified through the meta-analysis, the composition of the evidence base necessitates careful interpretation. Of the 140 studies included within the quantitative synthesis, 94 employed simulation-based methodologies, whereas only 46 reported measured post-occupancy performance. This imbalance reflects a broader characteristic of tropical NZEB research, where predictive modeling remains considerably more common than operational performance evaluation. Although simulation studies provide valuable insight during the design process, they inevitably depend upon assumptions regarding occupancy behavior, equipment usage, climatic conditions and system operation that may differ substantially from actual building performance.

The implications of this methodological imbalance become evident when the sensitivity analysis is considered. Restricting the analysis exclusively to measured post-occupancy studies increased the median annual EUI from 47 kWh/m²/year to 58 kWh/m²/year (95% CI:

51–66 kWh/m²/year), representing an increase of approximately 23% relative to the combined dataset. Although the revised figure remains substantially below the conventional tropical baseline, it demonstrates that simulation studies may systematically overestimate operational energy performance. Similar discrepancies have been documented in previous investigations of the building performance gap. Nguyen et al. (2011) observed that occupant adaptations, including supplementary air-conditioning use and altered ventilation behavior, frequently increase operational energy demand beyond simulated predictions. Likewise, Attia et al. (2017) highlighted that simulation models cannot fully capture the dynamic interactions between occupants, building systems and climatic variability that emerge during actual operation.

The present findings therefore reinforce the growing recognition that the "performance gap" represents one of the most important methodological challenges confronting NZEB research. The discrepancy between predicted and measured performance should not necessarily be interpreted as evidence of design failure; rather, it reflects the complexity of human-building interactions within occupied environments. Tropical buildings are particularly sensitive to behavioral variability because occupant decisions regarding window opening, ceiling fan use, shading adjustment and supplementary cooling significantly influence operational energy consumption. Furthermore, factors such as photovoltaic module soiling, equipment degradation, maintenance quality and climatic variability may further reduce actual renewable energy production relative to design-stage predictions. Consequently, the review suggests that simulation should be regarded primarily as an optimization tool whose predictions require continuous validation through post-occupancy monitoring rather than as a definitive measure of future building performance.

The country-level comparisons presented in Figure 7 further highlight the uneven maturity of tropical NZEB implementation. Singapore, Malaysia and Brazil account for the largest number of reported case studies, reflecting their comparatively advanced regulatory frameworks, stronger research capacity and greater investment in high-performance building technologies. By contrast, relatively few studies originate from Sub-Saharan African countries, despite their rapidly growing building sectors and substantial solar energy resources. This disparity limits the geographical representativeness of current tropical NZEB performance benchmarks and suggests that existing global EUI targets are influenced disproportionately by evidence generated within relatively affluent tropical economies. Expanding empirical research across underrepresented tropical regions will therefore be essential for developing performance benchmarks that adequately reflect the climatic, economic and socio-cultural diversity of the global tropics.

Overall, the findings for Objective 2 provide strong quantitative evidence that operational net-zero energy performance is achievable across tropical climates using existing technologies. The close agreement between the present meta-analysis and earlier investigations strengthens confidence in the reliability of current EUI benchmarks, while the sensitivity analysis demonstrates the importance of distinguishing between simulated and measured building performance. Collectively, these findings suggest that future progress in tropical NZEB development will depend less on fundamental technological innovation than on improving the integration of passive architectural design, accurately predicting operational performance, and expanding post-occupancy evidence capable of validating simulation-based design methodologies. In this respect, the review contributes not only updated quantitative benchmarks for tropical NZEB performance but also a more nuanced understanding of the methodological limitations that should inform future research, professional practice and policy development.

Table 2: Performance benchmarks by building typology and primary passive strategy

Building Type / Strategy	Climate Zone	Study Type	EUI Reduction	Renewable Energy Fraction	n studies
Residential / Passive cooling	Hot-humid (Af)	Simulation + POE	55–70%	90–120%	38
Residential / BIPV + passive	Multi-tropical	Simulation	62–78%	105–127%	29
Institutional / Shading + ventilation	Hot-humid (Am)	POE	48–65%	85–103%	22
Commercial / VRF + BIPV	Hot-dry (BWh)	Experimental	60–75%	95–115%	18
Healthcare / Hybrid system	Hot-humid (Aw)	Simulation	55–68%	88–105%	15

Note: EUI reductions are relative to jurisdiction-specific conventional building baselines. Renewable energy fraction >100% indicates net energy export. POE = Post-Occupancy Evaluation.

Objective 3: Barriers, Gaps, and Future Trajectories

The synthesis of the reviewed literature demonstrates that the principal constraints to widespread NZEB implementation in tropical climates are no longer predominantly technological but institutional, economic, educational and socio-cultural. Across the 250 reviewed studies, the five most frequently reported barriers were high upfront construction cost (72% of papers), the absence of mandatory tropical-specific NZEB building codes

(67%), cultural preference for fully air-conditioned environments (58%), insufficient technical expertise among architects and engineers (51%), and limited access to high-quality tropical climate data for building simulation (43%). Collectively, these findings indicate that although the technical feasibility of tropical NZEBs has been demonstrated across diverse climatic contexts, the transition from isolated demonstration projects to mainstream construction remains constrained by systemic implementation challenges rather than deficiencies in design technology.

The predominance of economic barriers within the reviewed literature is particularly significant because it illustrates the disconnect, between lifecycle economic performance and initial investment decisions. Although numerous studies included in this review demonstrate that NZEBs achieve substantial operational energy savings over their service life, developers and investors in many tropical countries continue to prioritize initial construction costs over long-term operational performance. Likewise, the lifecycle cost analyses discussed in Section 2 indicate that while NZEB cost premiums are generally recovered through reduced energy expenditure over approximately 8–15 years, many private developers operate within significantly shorter investment horizons. Consequently, capital-intensive passive technologies, advanced HVAC systems and Building-Integrated Photovoltaic (BIPV) are frequently perceived as financial risks despite their demonstrated long-term economic advantages.

The review further suggests that this economic challenge is considerably more pronounced in low- and middle-income tropical countries than in high-income tropical economies. Nations such as Singapore have supported NZEB implementation through financial incentives, regulatory mandates and mature green financing mechanisms, thereby reducing investment uncertainty for developers. By contrast, many Sub-Saharan African and lower-income Southeast Asian countries continue to experience high borrowing costs, limited access to green finance and underdeveloped renewable energy markets. These institutional differences help explain the unequal geographical distribution of NZEB implementation identified earlier in the review and suggest that financial policy reform may have an impact on adoption rates comparable to that of technological innovation itself.

Closely associated with the cost barrier is the widespread absence of mandatory tropical-specific NZEB regulatory frameworks. Approximately 67% of the reviewed studies identified inadequate building regulations as one of the principal impediments to implementation. This finding strongly supports the observations presented in Section 2.8, which demonstrated considerable variation in regulatory maturity across tropical countries. While Singapore's Green Mark framework and India's revised Energy Conservation Building Code have established measurable pathways toward low-energy and net-zero buildings, comparable performance-based regulations remain absent or only partially implemented

across many tropical developing nations. The findings therefore indicate that technological readiness alone is insufficient to achieve large-scale market transformation. Rather, effective regulatory systems provide the institutional certainty required for designers, developers and investors to adopt high-performance building technologies with confidence.

Importantly, the review indicates that regulation performs functions extending beyond minimum compliance. Mandatory performance standards encourage industry-wide technological learning, stimulate investment in local manufacturing and professional training, and create market demand for specialised NZEB expertise. The comparatively advanced implementation observed in countries with established building performance regulations therefore reinforces previous arguments that policy instruments accelerate technological diffusion by reducing uncertainty throughout the construction sector. Consequently, the absence of tropical-specific NZEB codes represents not merely a legislative deficiency but a structural constraint affecting the entire building delivery process.

One of the most distinctive findings emerging from this review concerns the continuing influence of socio-cultural factors on building energy performance. Approximately 58% of the reviewed studies identified cultural preference for permanently air-conditioned indoor environments as a major barrier to NZEB adoption. Unlike economic or regulatory challenges, this barrier reflects behavioural expectations rather than technical limitations. As discussed by Nguyen et al. (2011), adaptive thermal comfort models demonstrate that occupants of naturally ventilated tropical buildings are capable of maintaining acceptable comfort conditions at substantially higher indoor temperatures than those assumed under conventional air-conditioning standards. Nevertheless, many contemporary tropical societies continue to associate mechanically cooled environments with modernity, economic development and social status. The review therefore suggests that energy consumption within tropical buildings is influenced not only by climatic conditions but also by evolving cultural perceptions of comfort and building quality.

This observation supports the arguments presented by Essien et al. (2026), who emphasized that sustainable building adoption requires behavioral and institutional adaptation alongside technological innovation. The persistence of air-conditioning as a cultural aspiration may therefore limit the effectiveness of passive design strategies even where technically appropriate solutions have been successfully implemented. Consequently, achieving widespread NZEB adoption may require complementary educational initiatives, revised thermal comfort standards and public awareness programmes capable of reshaping occupant expectations regarding indoor environmental quality. These findings reinforce the broader conclusion that tropical NZEB implementation should be understood as both a socio-technical and architectural transition.

The review also identifies significant limitations in professional capacity across many tropical regions. Over half of the reviewed studies reported insufficient NZEB expertise among architects, engineers and construction professionals. This finding reflects the relatively recent emergence of tropical NZEB design as a specialized field requiring interdisciplinary knowledge spanning architecture, building physics, renewable energy systems, computational simulation and environmental assessment. While Building Information Modeling (BIM), Computational Fluid Dynamics (CFD) and whole-building energy simulation have become standard design tools within advanced research environments, their adoption remains uneven across many tropical countries due to limited educational opportunities and inadequate professional training.

This skills shortage has implications extending beyond individual building projects. Insufficient professional capacity limits the ability of designers to optimise passive strategies during the conceptual design stage, reduces confidence in advanced simulation outputs and may contribute directly to the operational performance gap discussed earlier in this review. The findings therefore support recommendations made by Attia et al. (2017), who argued that effective NZEB implementation depends upon integrated multidisciplinary design processes rather than isolated engineering interventions. Expanding university curricula, continuing professional development programmes and interdisciplinary collaboration will therefore be essential for strengthening tropical NZEB implementation capacity.

The availability and quality of climatic data constitute another important challenge identified within the literature. Approximately 43% of the reviewed studies reported inadequate weather datasets, limited meteorological monitoring and insufficient locally calibrated Typical Meteorological Year (TMY) files as barriers to accurate building energy simulation. Although this percentage is lower than those reported for cost or regulation, its implications are substantial because climate data underpin virtually every stage of NZEB design, from passive optimization to photovoltaic sizing and HVAC performance prediction. As discussed previously, Rodrigues et al. (2023) demonstrated that future climate-adapted weather files generated using CMIP6 climate projections significantly improve the reliability of long-term building performance simulation. The present review reinforces that conclusion by demonstrating that deficiencies in climatic datasets continue to limit the predictive accuracy of tropical NZEB simulation models, particularly within rapidly developing regions where meteorological monitoring infrastructure remains limited.

Beyond the immediate implementation barriers, the review identifies several important knowledge gaps that define future directions for tropical NZEB research. The most frequently identified research priority, cited by 61% of reviewed studies, concerns the need

for long-term post-occupancy performance monitoring. This finding directly complements the methodological observations presented in Objective 2, where measured building performance consistently exceeded simulation-based predictions. Expanding longitudinal post-occupancy evaluation programmes would therefore provide the empirical evidence required to validate simulation models, improve operational performance prediction and strengthen confidence in future NZEB performance benchmarks. Such research would also contribute to reducing the building performance gap that continues to characterize both tropical and international NZEB literature.

A second major research gap concerns the limited evidence available for Sub-Saharan African tropical contexts. More than half of the reviewed studies identified this geographical imbalance as a significant limitation within the current evidence base. Although countries across the region are expected to experience some of the world's fastest rates of urbanization and building stock expansion during the coming decades, comparatively few empirical NZEB studies have been undertaken within these environments. As a consequence, many design recommendations continue to rely upon evidence generated primarily within Southeast Asia and tropical Latin America. While important climatic similarities exist among tropical regions, differences in construction materials, economic conditions, electricity infrastructure and occupant behavior necessitate locally generated evidence capable of supporting context-specific design guidance. Addressing this geographical imbalance therefore represents an essential step toward developing globally representative tropical NZEB knowledge.

The integration of climate change adaptation into NZEB design standards also emerged as an increasingly important research priority. Nearly half of the reviewed studies recognized that buildings designed using historical climate data may experience declining performance under future climatic conditions characterized by higher ambient temperatures, increased humidity and more frequent extreme weather events. This observation reinforces the discussion presented earlier regarding climate-adapted weather files and suggests that future tropical NZEB design should evaluate performance across projected future climate scenarios rather than relying exclusively upon historical meteorological records. Such an approach would improve the long-term resilience of NZEBs and ensure that buildings designed to achieve net-zero performance today continue to satisfy operational performance targets throughout their anticipated service life.

Finally, the review highlights the continuing need for greater understanding of adaptive thermal comfort within diverse tropical societies. Although adaptive comfort models have become increasingly accepted within building science, relatively little empirical evidence exists for many tropical developing countries, particularly across Africa and smaller island states. Cultural expectations, behavioral adaptation and patterns of building use vary considerably across tropical regions, suggesting that comfort models developed within one

geographical context cannot necessarily be transferred directly to another. Further interdisciplinary research integrating building science, environmental psychology and architecture will therefore be necessary to establish locally appropriate thermal comfort standards capable of supporting passive NZEB design without compromising occupant satisfaction.

Overall, the findings for Objective 3 demonstrate that the future development of tropical NZEBs depends less upon discovering new technologies than upon overcoming the institutional, behavioral and knowledge-based barriers limiting implementation of technologies that already exist. The evidence reviewed in this study consistently indicates that passive architectural design, efficient building systems and renewable energy technologies are sufficiently mature to achieve operational net-zero performance across a wide range of tropical building typologies. The principal challenge now lies in translating this technical capability into widespread professional practice through coordinated policy reform, financial innovation, educational development, improved climatic data infrastructure and expanded empirical research. Consequently, the transition toward tropical NZEBs should be viewed not simply as a technological evolution but as a comprehensive transformation of the regulatory, professional and cultural systems that shape building design and operation throughout the global tropics.

Barrier Analysis Matrix

Table 3 presents a structured analysis of the five key barriers to tropical NZEB adoption, with associated contributing factors, impacted stakeholders, and recommended interventions.

Table 4: Barrier analysis matrix for tropical NZEB adoption, contributing factors, impacted stakeholders, citation frequency in the 250-paper corpus, and recommended interventions. (Authors' synthesis, 2026)

Barrier		Contributing Factors	Impacted Stakeholders	Citation Frequency	Recommended Intervention
High Cost	Upfront	Expensive PV, HVAC, specialist design fees	Developers, Clients, Gov.	72% of corpus	Green bonds, incentives, standardized specifications
Absent Building Codes	NZEB	Institutional capacity gaps, political will	Policymakers, Regulators	67% of corpus	Adopt Singapore GreenMark, EDGE, GRIHA

Barrier	Contributing Factors	Impacted Stakeholders	Citation Frequency	Recommended Intervention
				with local calibration
AC Cultural Norm	Status symbolism, urbanization aspirations	Occupants, Developers	58% of corpus	Adaptive comfort education, incentivized green leasing
Skills Shortage	Curriculum gaps, no tropical NZEB CPD	Architects, Engineers	51% of corpus	University curriculum reform, regional NZEB CPD
Climate Data Scarcity	Limited weather stations, no TMY files	Designers, Simulators	43% of corpus	Invest in tropical weather station networks; open data

Conclusion

This systematic review of 250 peer-reviewed academic papers on Net-Zero Energy Building design for tropical climates has demonstrated, with comprehensive evidence, that net-zero energy performance is technically achievable across all major tropical building typologies, from the dense commercial towers of Singapore to the educational campuses of Ghana, from the residential compounds of India to the hotel resorts of Thailand. The review has catalogued a rich and growing toolkit of passive and active design strategies, natural ventilation, high-performance shading, green roofs, optimized orientation, BIPV, high-efficiency HVAC, and smart building management systems, whose integrated application consistently achieves EUI reductions of 55–78% relative to conventional tropical buildings and renewable energy fractions exceeding 100%, as illustrated in Figures 3, 5, and 7.

The review has equally documented, with equal precision, the barriers that stand between current tropical building practice and the widespread adoption of these strategies: barriers that are primarily institutional, economic, cultural, and educational rather than technical. The high upfront cost of NZEB construction, the absence of mandatory tropical-specific building energy codes, the cultural dominance of mechanically air-conditioned spaces as markers of modernity, the shortage of tropical NZEB-literate architects and engineers, and the scarcity of long-term post-occupancy performance data collectively constitute a complex, multi-layered obstacle that no single intervention can overcome.

What is required is a coordinated, multi-actor programme of action spanning regulatory reform, financial instrument development, professional capacity building, academic curriculum transformation, and sustained research investment, all calibrated to the specific

institutional capacities, economic conditions, and cultural contexts of diverse tropical nations, and all pursued with the urgency that the accelerating global climate crisis demands. The tropical built environment, currently the world's fastest-growing source of building energy demand and carbon emissions, carries within it the seeds of a transformative climate solution: the abundant solar resource of the tropics is not merely a design challenge to be shaded away, but the primary energy source for a net-zero building future that is climatically, technically, and economically within reach. The question is not whether tropical buildings can achieve net-zero energy performance. The evidence reviewed in this paper confirms that they can. The question is whether the architectural profession, the building industry, and the policy community will choose, with appropriate urgency, to make it so.

Recommendation

For Policymakers and Regulators

Governments across the tropical world should urgently enact mandatory NZEB-calibrated building energy codes with tropically appropriate performance metrics, phased implementation timescales, and enforcement mechanisms. The Singapore BCA Green Mark Super Low Energy standard provides the most advanced tropical regulatory model globally and should be adapted, with local climate, cost, and construction industry adjustments, by regulatory authorities in Nigeria, Ghana, Kenya, Indonesia, Vietnam, Bangladesh, India, and other major tropical nations. Carbon pricing mechanisms, green mortgage products, public sector NZEB procurement mandates, and zero-interest "Green Building Finance" loan facilities should be introduced to address the cost barrier, the most frequently cited impediment to tropical NZEB adoption. International development finance institutions including the World Bank, IFC, and African Development Bank should expand their tropical green building finance portfolios substantially, recognizing that NZEB adoption in rapidly urbanizing tropical economies is one of the highest-leverage climate mitigation investments available to the international community.

For Architects and the Design Profession

Tropical architecture firms should establish a formal "Efficiency First" design protocol that mandates comprehensive passive design optimization, using climate analysis, CFD simulation, solar geometry analysis, and day lighting modeling, before mechanical and renewable energy systems are specified. The design sequence should follow the hierarchy established in the NZEB framework presented in Figure 6: climate analysis → passive design optimization → active systems right-sizing → energy balance verification and renewable energy specification. Professional bodies including the Architects Registration

Council of Nigeria (ARCON), the Board of Architects Malaysia (LAM), the Singapore Institute of Architects (SIA), and equivalent bodies across the tropical world should incorporate mandatory NZEB continuing professional development (CPD) into their professional practice frameworks and make tropical NZEB literacy a condition of practicing certificate renewal.

For Academic Institutions

Architecture, engineering, and environmental science schools in tropical nations should fundamentally revise their undergraduate and postgraduate curricula to make tropical NZEB design methodology a central, compulsory element of professional education. This should include dedicated studio projects that require students to design verifiably net-zero buildings using climate analysis tools, building energy simulation software, and renewable energy yield modeling platforms. Research institutions should prioritize longitudinal post-occupancy monitoring studies of tropical NZEBs, establishing building performance observatories that generate the long-term measured data currently absent from the evidence base. South-South research partnerships between institutions in Singapore, India, Malaysia, Brazil, South Africa, and Nigeria should be fostered through international research funding mechanisms to build the tropical NZEB evidence base that currently tilts heavily toward high-income tropical nations.

For Future Research

Future research should prioritize: (i) post-occupancy performance monitoring of tropical NZEBs across diverse building typologies, using consistent EUI measurement protocols compatible with IPMVP (International Performance Measurement and Verification Protocol) Option C or D methods; (ii) development and validation of adaptive thermal comfort models specific to individual tropical sub-climates and cultural contexts, particularly for Sub-Saharan African and Pacific Island nations currently lacking empirical comfort data; (iii) life cycle carbon assessment of tropical NZEB design strategies, including embodied carbon in construction materials, currently severely under-researched in tropical contexts; (iv) community-scale and district-level NZEB design approaches for informal and peri-urban settlements, where the largest share of future tropical building stock growth will occur.

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