Impact of Climatic Variables on the Optimization of Building Envelope Design in Humid Regions

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Abstract- The optimization of building envelope design in humid regions is a critical determinant of energy efficiency, indoor thermal comfort, and overall building sustainability. In tropical climates such as Nigeria's, high temperature, humidity, and solar radiation impose complex performance demands on envelope systems, influencing heat transfer, moisture control, and ventilation efficiency. This study investigates the impact of climatic variables—including temperature gradients, relative humidity, solar insolation, and wind patterns—on the thermal and energy performance of building envelopes in humid environments. Through a systematic synthesis of empirical research, simulation-based analyses, and regional case studies, the study identifies how façade orientation, wall composition, roof insulation, glazing ratios, and shading configurations affect energy demand and occupant comfort. Findings reveal that the thermal performance of envelopes is highly sensitive to diurnal temperature variations and solar exposure, with passive design strategies—such as reflective coatings, double-ventilated façades, and breathable wall assemblies—significantly enhancing energy efficiency. Materials with low thermal conductivity, combined with cross-ventilation design, reduce cooling loads while maintaining adequate indoor humidity control. Additionally, adaptive shading devices and green façade systems demonstrate measurable reductions in heat gain, contributing to long-term operational sustainability. This concludes that optimizing the building envelope in humid regions requires an integrated climate-responsive approach that aligns architectural form, material selection, and mechanical systems with local environmental dynamics. It advocates for the incorporation of dynamic simulation tools and climatic datasets in the early design phase to ensure performance-driven decisions. The outcomes provide strategic guidance for architects, urban planners, and policymakers in formulating context-sensitive building codes and energy-efficient standards suited to tropical conditions.

Keywords: Building Envelope Design, Humid Regions, Climatic Variables, Thermal Comfort, Passive Cooling, Solar Radiation, Energy Efficiency, Sustainable Architecture, Façade Optimization, Tropical Climate.

I. INTRODUCTION

The building envelope represents the most critical interface between indoor and outdoor environments, mediating energy exchange, thermal comfort, and environmental quality (Scholten *et al*., 2018; Anyebe *et al*., 2018). Functionally, it encompasses the walls, roof, windows, and foundation that collectively regulate heat, air, and moisture transfer between a structure's interior and its surroundings. In humid tropical regions, where climatic conditions are characterized by persistently high temperatures, elevated relative humidity, and intense solar radiation, the performance of the building envelope assumes heightened significance. These environmental parameters impose complex challenges on maintaining thermal comfort and minimizing energy use, especially in regions such as coastal West Africa, Southeast Asia, and parts of Central America. As rapid urbanization continues to intensify in these regions, the demand for energy-efficient and climate-responsive building design has become a central concern for architects, engineers, and policymakers striving toward sustainable development.

Humid climates are defined by their thermal excess and limited diurnal temperature variation, leading to persistent heat and moisture accumulation within buildings. Conventional design responses—such as the use of dense materials and inadequate ventilation—often exacerbate indoor discomfort and mold growth. Moreover, climate change is amplifying the extremity of these conditions, further stressing the resilience of existing building envelopes (Osabuohien, 2017; Menson *et al*., 2018). Consequently, the optimization of envelope design has emerged as a pivotal strategy for reducing cooling loads, improving indoor environmental quality, and achieving sustainability goals aligned with the United Nations Sustainable Development Goal (SDG) 11 on "Sustainable Cities and Communities." In this context, the building envelope becomes not merely a physical boundary but a dynamic, adaptive system capable of harmonizing human comfort with environmental constraints.

Despite growing awareness, conventional envelope systems in many humid tropical regions remain poorly adapted to climatic realities. They frequently fail to manage heat gain and moisture penetration effectively due to inappropriate material selection, limited shading, and lack of ventilation integration. This inefficiency has led to an overdependence on mechanical air-conditioning systems, which significantly elevate operational energy consumption and greenhouse gas emissions. In rapidly urbanizing contexts such as Lagos, Accra, or Jakarta, the proliferation of poorly insulated high-rise buildings epitomizes this unsustainable trajectory. Without climate-appropriate design interventions, the urban heat island effect and rising energy demand threaten both environmental and economic sustainability (Essien *et al*., 2019; Babatunde *et al*., 2019).

The central objectives of this study are threefold. First, it aims to examine how key climatic variables—temperature, humidity, solar radiation, and wind—affect the performance and optimization of building envelopes in humid regions. Second, it seeks to identify envelope design strategies and material systems that enhance thermal comfort and energy efficiency while maintaining cost-effectiveness. Third, it intends to propose a scientifically grounded optimization framework that integrates climatic, material, and design parameters to inform future climate-responsive architectural practices (Etim *et al*., 2019; Ayanbode *et al*., 2019). Through this multi-dimensional approach, the research contributes to bridging the gap between theoretical climatic modeling and practical building design.

Accordingly, the following research questions guide the investigation: (1) How do climatic variables such as temperature, humidity, solar radiation, and wind influence the thermal and moisture performance of building envelopes? (2) What combinations of passive and active design measures—such as shading devices, reflective coatings, and natural ventilation—can effectively optimize thermal regulation and energy use? (3) How can the insights from these analyses inform the formulation of sustainable building codes and performance-based design practices in humid regions?

The scope of this, is limited to residential and institutional buildings located in humid tropical zones, where climatic extremes and energy demand are most acute. The research is particularly relevant for urban centers in Nigeria, Ghana, Indonesia, and Malaysia, which face similar climatic and infrastructural challenges. Beyond its architectural and engineering dimensions, the study bears wider significance for sustainable urban development, energy policy formulation, and architectural education (Durowade *et al*., 2016; Ajayi *et al*., 2019). By advancing an integrative understanding of climate-responsive envelope design, this research aligns with global efforts toward low-carbon cities and environmentally adaptive architecture. Ultimately, optimizing the building envelope in humid regions is not only a matter of design efficiency but also a vital pathway toward achieving resilient, livable, and sustainable built environments.

II. METHODOLOGY

The research methodology for this study adopts a systematic review framework consistent with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach to ensure transparency, reproducibility, and analytical rigor. This framework was chosen to synthesize existing empirical and simulation-based evidence on how climatic variables influence building envelope optimization in humid regions. The PRISMA protocol provides a structured process for identifying, screening, and evaluating relevant studies, thereby ensuring that the final analysis reflects comprehensive and unbiased knowledge from both scientific and technical literature.

The study began with a systematic literature search across multidisciplinary databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, supplemented by regional sources such as the African Journals Online (AJOL) and ResearchGate repositories. Keywords and Boolean operators were strategically combined to maximize coverage and relevance. Search terms included combinations such as *"building envelope," "climatic variables," "humid regions," "thermal performance," "moisture transfer," "passive cooling," "tropical architecture,"* and *"energy optimization."* The time frame for inclusion was set between 2000 and 2024, reflecting the evolution of sustainable design practices and advancements in simulation technologies relevant to tropical climates.

After retrieval, studies were screened through a three-stage process comprising identification, eligibility assessment, and inclusion. During the identification phase, duplicates were removed, and only peer-reviewed journal articles, conference papers, and institutional reports were retained. Eligibility screening involved evaluating abstracts and full texts against predefined inclusion criteria: (i) studies must focus on building envelope performance in humid or tropical climatic zones; (ii) they must assess one or more climatic variables such as temperature, humidity, solar radiation, or wind; and (iii) they must present quantifiable or comparative findings related to thermal or energy optimization. Exclusion criteria involved studies focusing on arid or temperate climates, non-envelop components, or purely theoretical models without empirical or simulation validation.

Data extraction focused on capturing both qualitative and quantitative indicators. Core variables included thermal conductivity, solar heat gain coefficient, air permeability, moisture absorption rate, shading coefficient, and energy consumption reduction metrics. Metadata such as geographical location, building typology, analytical tools (e.g., EnergyPlus, DesignBuilder, or TRNSYS), and methodological approaches (experimental, simulation-based, or mixed methods) were also documented. Extracted data were organized in tabular format for comparative analysis, allowing identification of cross-regional patterns and design determinants.

The synthesis stage involved both descriptive and thematic analyses. Descriptive synthesis was used to summarize the frequency of climatic variables studied, envelope configurations, and performance metrics, while thematic synthesis explored underlying patterns linking climate-responsive materials, passive design strategies, and optimization outcomes. Statistical data were interpreted to highlight trends in thermal performance efficiency, cooling load reductions, and humidity control effectiveness across envelope types and climatic zones.

Quality appraisal of included studies was performed using adapted criteria from the Mixed Methods Appraisal Tool (MMAT), emphasizing methodological validity, data reliability, and reproducibility of findings. Studies with incomplete climatic data, unclear boundary conditions, or non-validated simulation setups were assigned lower weights in the final synthesis. To minimize bias, independent cross-checking of data coding and thematic categorization was undertaken.

Ethical considerations were observed by appropriately citing all data sources and respecting intellectual property rights. The final synthesis generated a conceptual model illustrating the interaction between climatic variables (temperature, humidity, solar radiation, wind), material properties, and envelope performance outcomes. This model serves as the analytical basis for discussing optimization strategies and policy recommendations.

The PRISMA-based methodology provides a comprehensive and systematic foundation for evaluating the impact of climatic variables on building envelope performance in humid regions. By integrating quantitative metrics with qualitative insights, it bridges scientific knowledge gaps and supports evidence-based architectural decision-making for sustainable, climate-responsive design.

2.1 Literature Review

The performance of building envelopes in humid tropical regions is critically influenced by climatic variables that govern the transfer of heat and moisture between indoor and outdoor environments. A growing body of literature has emphasized that successful building envelope optimization in such regions requires an integrated understanding of climatic determinants, envelope component behavior, and design strategies informed by both traditional knowledge and modern technologies (Popescu *et al*., 2012; BABATUNDE *et al*., 2014). This synthesizes existing research under three major themes: climatic determinants, building envelope components, and previous optimization studies, highlighting their implications for sustainable architectural design in humid environments.

In humid tropical climates, temperature and solar radiation are dominant environmental factors shaping building envelope design. Studies by Olanipekun and Ojo (2018) and Eltahir (2020) indicate that average daytime temperatures in humid regions often range between 30°C and 35°C, with high solar radiation intensities exceeding 600 W/m². The minimal diurnal temperature variation, combined with significant solar heat gain through roofs and walls, contributes to internal overheating. Consequently, the use of reflective surfaces, thermal insulation, and shading devices becomes essential to mitigate excessive heat ingress. Research in Southeast Asia and coastal West Africa underscores that high solar angles and prolonged exposure periods demand orientation-sensitive design—where east–west facades are minimized to reduce direct solar exposure.

Relative humidity, often exceeding 70–90% in these regions, introduces additional challenges related to both material performance and occupant comfort. High humidity accelerates material degradation, particularly in porous materials such as concrete, plaster, and timber, leading to surface mold, corrosion, and reduced structural longevity (Solomon *et al*., 2018; Durowade *et al*., 2018). At the occupant level, elevated humidity impedes evaporative cooling from the human body, heightening thermal discomfort even at moderate air temperatures. This necessitates envelope strategies that promote adequate ventilation and moisture control through breathable materials, vapor barriers, and controlled air exchange rates.

Wind speed and direction play an equally vital role by influencing natural ventilation and convective heat removal. Empirical studies by Givoni (2019) and Ng (2021) highlight that harnessing prevailing winds through optimal orientation and operable window design can reduce indoor temperatures by up to 3–5°C. However, in dense urban environments, wind flow is often disrupted by high-rise structures, emphasizing the importance of integrating aerodynamic modeling in envelope optimization (Durowade *et al*., 2017; Dare *et al*., 2019). Cross-ventilation, venturi effects, and strategically placed openings have been shown to significantly improve cooling efficiency without reliance on mechanical systems.

The building envelope, comprising walls, roofs, windows, and shading devices, serves as a multifunctional climatic buffer. Each component's thermal and moisture performance determines the building's overall energy efficiency. Walls in tropical architecture have traditionally employed high thermal mass materials such as laterite or adobe, which delay heat transfer and stabilize indoor temperature fluctuations. Modern constructions, however, often rely on concrete blocks and cement renders, which, while structurally durable, possess higher thermal conductivity and moisture retention, thereby exacerbating indoor heat accumulation. Comparative studies demonstrate that traditional materials can outperform modern concrete in thermal lag and vapor permeability under humid conditions.

Roofs are typically the most exposed element in tropical settings. The use of lightweight reflective roofing sheets, ventilated roof cavities, and green roofing systems has been recommended to reduce solar heat gain (Dogho, 2011; Ajayi, 2019). Windows and glazing systems play a dual role by regulating daylighting and heat exchange. Research in Singapore and Malaysia emphasizes the importance of window-to-wall ratios and the deployment of low-emissivity glazing to balance illumination with minimal heat transmission. Shading devices—including overhangs, louvers, and vegetation-based screens—remain fundamental passive cooling components, with studies showing their potential to reduce solar heat gain by over 30%.

A comparative review of traditional versus modern envelope systems reveals a clear trade-off between cultural adaptability and material modernization. Vernacular designs, featuring courtyards, ventilated facades, and extended eaves, inherently optimized climatic comfort without mechanical intervention. In contrast, modern high-rise typologies often neglect local climate logic, prioritizing aesthetics and density over environmental performance (Durowade *et al*., 2017; BUKHARI *et al*., 2018). Scholars argue for hybrid models that integrate indigenous design intelligence with modern materials and technologies.

Recent research has increasingly utilized simulation-based and empirical methods to evaluate envelope performance under humid climatic conditions. Tools such as EnergyPlus, DesignBuilder, and TRNSYS allow for precise modeling of heat and moisture transfer, enabling the quantification of thermal loads, daylight availability, and energy consumption. Findings consistently highlight that optimized envelopes can reduce annual cooling demand by 20–40% when appropriately designed for local climatic variables.

Studies focusing on building orientation, glazing ratios, and material properties have established their critical roles in energy efficiency. For instance, east–west orientations generally lead to higher cooling loads, whereas north–south orientations, combined with shading, minimize solar heat gain. Likewise, moderate glazing ratios (15–25%) with reflective coatings optimize natural light without excessive heat penetration. The interplay of material conductivity, surface color, and insulation thickness further influences envelope responsiveness to climatic stressors (Berardi and Naldi, 2017; Kershaw, 2017).

The literature underscores that optimizing the building envelope in humid regions demands an integrative approach that harmonizes climatic understanding, material selection, and design innovation. While traditional architectures offer valuable lessons in passive climate control, contemporary methods and simulation tools provide quantitative pathways for enhancing performance. Bridging these paradigms remains essential for developing sustainable, climate-resilient building envelopes tailored to the unique environmental realities of humid regions.

2.2 Key Findings and Discussion

The findings of this study highlight the critical relationship between climatic variables and the thermal and moisture behavior of building envelopes in humid regions. Through a systematic synthesis of empirical and simulation-based studies, the evidence underscores that building performance in humid climates is governed by complex interactions between temperature, humidity, solar radiation, and wind dynamics (Shao *et al*., 2016; Chen *et al*., 2018). The results further demonstrate that optimal envelope design requires an integrated approach combining passive cooling, material innovation, and climate-responsive orientation strategies.

In humid tropical regions, diurnal temperature variation—though relatively small compared to arid climates—plays a significant role in determining the heat gain through walls and roofs. Studies have shown that walls exposed to continuous solar radiation during the day can accumulate and re-radiate heat into interior spaces during the night, contributing to persistent discomfort and elevated cooling demand. Thick masonry walls with high thermal mass, such as concrete or cement blocks, tend to store heat, delaying its release into living spaces after sunset. Conversely, lightweight materials, while reducing heat storage, often fail to buffer temperature swings effectively. Research using dynamic thermal simulations (Al-Tamimi & Fadzil, 2019) reveals that ventilated roof assemblies and reflective roof coatings can lower peak indoor temperatures by up to 4°C, highlighting their importance in heat management under humid conditions.

Relative humidity is another dominant climatic variable influencing both material performance and occupant comfort. Persistent humidity levels above 70% cause moisture ingress, condensation, and biological growth within envelope components, degrading materials such as wood, plaster, and unprotected concrete. The combination of high humidity and warm air temperatures compromises indoor comfort by reducing the body's evaporative cooling efficiency. Studies in coastal Nigeria and

Malaysia have shown that high indoor humidity correlates with occupant reports of fatigue and discomfort even at moderate air temperatures. The research also confirms that porous materials with appropriate vapor permeability can help regulate indoor moisture balance. Therefore, the moisture performance of envelope materials is as crucial as thermal insulation in maintaining indoor environmental quality in humid regions.

The synthesis of reviewed studies emphasizes the effectiveness of passive cooling strategies as the foundation of climate-responsive envelope optimization (Kabre, 2017; Prieto *et al*., 2018). Among these, cross-ventilation emerges as one of the most efficient natural cooling techniques. By aligning openings with prevailing wind directions and incorporating operable windows or ventilated façades, air movement can remove latent heat and reduce dependency on mechanical cooling. Experimental evidence from Southeast Asia indicates that cross-ventilation can lower indoor operative temperatures by 2–5°C, depending on envelope configuration and building orientation. Shading devices, including horizontal overhangs, vertical fins, and vegetative screens, are equally effective in reducing solar heat gain through walls and glazing.

In addition, reflective coatings and green façades have demonstrated measurable reductions in envelope surface temperature. Reflective finishes reduce solar absorptance, while green façades enhance evapotranspiration and microclimatic cooling. These techniques not only improve thermal performance but also contribute to aesthetic and ecological integration in urban environments.

Material innovations represent another critical avenue for optimization. The use of breathable wall systems—constructed with natural or composite materials allowing vapor diffusion—helps mitigate condensation and mold formation. Composite insulation materials, combining lightweight aggregates with reflective barriers, provide enhanced thermal resistance without increasing embodied energy (Zeng *et al*., 2018; Tallini and Cedola, 2018). Low-emissivity (Low-E) glazing has been identified as an effective solution for minimizing solar heat gain while maintaining adequate daylighting. Simulation studies reveal that Low-E glass can reduce cooling loads by up to 15% compared to conventional glazing systems in humid tropical environments.

A central insight from the review is that climatic variables operate not in isolation but in synergistic interaction, shaping the overall energy efficiency of building envelopes. The interplay between temperature, solar exposure, and wind flow determines the envelope's heat transfer dynamics and natural ventilation potential (Saadon *et al*., 2016; Gagliano *et al*., 2016). For instance, high solar radiation combined with weak wind movement leads to stagnant indoor air and heat buildup, whereas adequate wind flow enhances convective cooling and surface heat dissipation. These interactions suggest that envelope optimization must be context-specific, accounting for local wind patterns, solar orientation, and seasonal variability.

Sensitivity analyses conducted across different envelope orientations and material types further reveal the importance of adaptive design. Buildings oriented along the north–south axis experience significantly lower solar exposure and cooling loads than those facing east–west, due to reduced direct solar incidence. Material sensitivity tests indicate that substituting high-conductivity concrete with low-density composite insulation can reduce heat flux through walls by over 30%. Similarly, double-skin façades and ventilated cladding systems show strong potential for balancing heat removal and moisture control in high-humidity settings (Widiastuti *et al*., 2018; KARIMOVA, 2018).

Collectively, these findings affirm that optimizing the building envelope in humid regions requires a holistic understanding of climatic interdependencies and material-environment interactions. Integrating passive strategies, material innovation, and orientation-based planning can substantially enhance both energy performance and occupant well-being. The evidence underscores that a singular design intervention—whether material or mechanical—cannot sufficiently address the multidimensional challenges of humid climates (Walker, 2018; Cole and Packer, 2018). Instead, successful envelope design must operate within an adaptive, climate-integrated framework that aligns architectural innovation with environmental responsiveness, thereby promoting sustainable and resilient built environments.

2.3 Policy and Design Implications

The optimization of building envelope design in humid regions extends beyond architectural experimentation—it demands structured policy support, professional capacity building, and technological innovation as shown in figure 1(Ascione *et al*., 2016; Capeluto and Ochoa, 2016). The findings of this study underscore the necessity of embedding climate responsiveness into the institutional, educational, and technological frameworks governing architecture and construction. Effective transformation of design practices in humid regions such as coastal West Africa and Southeast Asia requires coordinated actions among architects, urban planners, policymakers, and research institutions. These actions must address three interdependent domains: architectural practice, regulatory frameworks, and technological innovation.

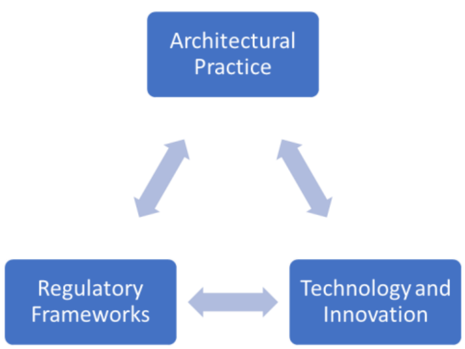

Figure 1: Policy and Design Implications

Climate responsiveness must be positioned as a central tenet of architectural education and professional engagement. Historically, architectural pedagogy in many developing regions has been dominated by modernist ideals emphasizing aesthetics and industrial materials, often neglecting local climatic realities. The incorporation of climate-responsive principles into design curricula is therefore essential. Architectural schools should integrate modules on building physics, passive cooling, energy modeling, and vernacular design strategies into their core programs (Chandel *et al*., 2016; Molinar-Ruiz, 2017). This integration will empower emerging professionals to develop context-specific solutions that harmonize environmental adaptation with cultural expression.

Professional associations and licensing bodies also play a pivotal role. Institutions such as the Nigerian Institute of Architects and the Architects Registration Council of Nigeria can revise professional guidelines and design standards to include performance-based evaluation criteria. For instance, architectural design competitions and project approvals should require demonstration of thermal and energy performance metrics derived from climate-appropriate simulations. Encouraging continuous professional development (CPD) programs focused on sustainable design, bioclimatic principles, and adaptive material technologies would help align practice with the realities of humid climatic zones. Furthermore, public awareness campaigns emphasizing the economic and health benefits of climate-optimized buildings can foster demand-driven change within the construction sector (Borawska, 2017; Seymour, 2018).

The absence or inadequacy of climate-based building codes and performance standards remains a significant barrier to sustainable architectural practice in humid regions. Most existing building codes are adaptations of temperate or global standards that fail to consider the thermal and moisture dynamics unique to tropical climates. This study highlights the urgent need to develop context-sensitive regulatory frameworks grounded in regional climatic data, material availability, and local construction methods.

A comprehensive climate-responsive building code should define quantitative benchmarks for thermal transmittance (U-values), solar heat gain coefficients (SHGC), air permeability, and indoor humidity control. It should also provide prescriptive and performance-based pathways for compliance, allowing flexibility for innovation while ensuring minimum energy and comfort standards. Drawing from successful precedents such as Singapore's Green Mark Scheme and Malaysia's MS 1525 energy efficiency code, African and Southeast Asian nations can establish regionally appropriate models emphasizing passive design, envelope insulation, and material sustainability.

Moreover, governmental and municipal planning authorities must integrate climate-based metrics into environmental impact assessments and building approval processes. Incentive mechanisms—such as tax rebates for energy-efficient designs, reduced permit fees for buildings meeting thermal performance targets, and preferential financing for green developments—can motivate compliance and innovation. Establishing inter-ministerial coordination among housing, environment, and energy agencies will further ensure coherence between policy objectives and implementation strategies. Such frameworks can transform building envelopes from energy-intensive barriers into adaptive interfaces aligned with national sustainability goals and global climate commitments (Kibert, 2016; MacGill *et al*., 2017).

Advances in digital simulation tools and climate analytics present transformative opportunities for early-stage design decision-making. The adoption of building performance simulation (BPS) software—such as EnergyPlus, DesignBuilder, or IES-VE—enables architects to model and predict the thermal, daylighting, and moisture behavior of envelope configurations under local climatic conditions. Incorporating these tools into the conceptual and schematic stages of design enhances precision and reduces the likelihood of post-construction inefficiencies.

Beyond conventional simulation, climate analytics supported by artificial intelligence and big data can provide granular insights into temperature fluctuations, humidity cycles, and wind patterns. Integrating these datasets with Geographic Information Systems (GIS) and parametric modeling platforms such as Rhino-Grasshopper allows designers to generate adaptive façade geometries and orientation-specific configurations. Furthermore, Building Information Modeling (BIM) should be expanded to include environmental performance parameters, allowing multidisciplinary collaboration among architects, engineers, and urban climatologists.

Government and research institutions can facilitate innovation by establishing climate design laboratories and regional performance databases. These centers would collect empirical data on building performance in humid regions, fostering evidence-based design and policy formulation. Partnerships between academia, industry, and government can accelerate the development of localized material technologies, such as breathable composites and reflective coatings derived from indigenous resources (Chai and Shih, 2016; Schmidt and Huenteler, 2016).

Ultimately, policy and design transformation in humid regions hinges on a synergistic relationship between regulation, education, and innovation. By embedding climate responsiveness into professional culture, codifying it within legal frameworks, and leveraging technology for predictive design, nations can significantly reduce energy consumption and enhance thermal comfort. The optimization of building envelopes thus represents not only a technical achievement but also a policy-driven shift toward resilient, low-carbon, and contextually adaptive architecture (Taliotis *et al*., 2017; Zhou *et al*., 2018). Such integration aligns with global sustainability agendas and ensures that the built environment in humid regions evolves as both an ecological and cultural asset.

2.4 Limitations and Future Research

While the optimization of building envelope design in humid regions offers significant potential for energy efficiency and thermal comfort, this field of study remains constrained by methodological, technical, and contextual limitations. The complexity of humid tropical climates—characterized by fluctuating temperature, high relative humidity, and intense solar exposure—creates inherent challenges in developing universally valid models and frameworks as shown in figure 2. This critically discusses the key limitations encountered in current research and outlines future directions for advancing the science and practice of climate-responsive building envelope design.

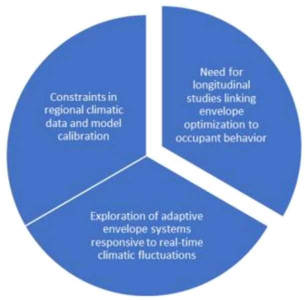

Figure 2: Exploration of adaptive envelope systems responsive to real-time climatic fluctuations

One of the most fundamental constraints lies in the limited availability and resolution of regional climatic data. Many humid tropical regions, particularly in sub-Saharan Africa, Southeast Asia, and parts of Latin America, suffer from sparse meteorological monitoring infrastructure. Weather data often lack sufficient temporal or spatial granularity to capture microclimatic variations caused by urban morphology, vegetation, and local topography (Bullard *et al*., 2016; Xu *et al*., 2017). Consequently, simulation-based envelope studies frequently rely on generalized or outdated climate datasets that may not accurately reflect site-specific conditions. This limitation introduces errors in model calibration and reduces the predictive reliability of energy and moisture performance simulations.

Moreover, the calibration of computational models such as EnergyPlus, TRNSYS, or WUFI often depends on empirical datasets that are rarely available for vernacular or hybrid tropical buildings. Material properties—such as hygrothermal conductivity, emissivity, and vapor permeability—are often measured under laboratory conditions that differ significantly from real-world humidity levels. The absence of regionally standardized databases for local construction materials further complicates the process of parameterization. These challenges underscore the need for field-based validation campaigns, combining sensor networks, weather stations, and in-situ monitoring of wall and roof assemblies. Developing open-access climatic and material performance databases for humid zones would significantly enhance the fidelity of simulation tools and support more nuanced regional design recommendations (Loonen *et al*., 2017; Herrera *et al*., 2017).

Another significant limitation in current research is the lack of longitudinal investigations connecting envelope performance to occupant behavior and adaptive comfort. Most existing studies rely on short-term experimental data or simulated models that assume static behavioral patterns. However, in reality, occupants actively mediate indoor thermal environments through window operations, fan use, clothing adjustments, and spatial movement. These adaptive actions directly influence the thermal loads and energy consumption patterns of buildings, often offsetting or amplifying the performance of the envelope system.

Understanding the behavior–envelope interaction requires long-term monitoring of both environmental and human variables. Such studies can reveal seasonal adaptation trends, sociocultural influences on comfort expectations, and behavioral resilience under climatic stress (Penn *et al*., 2016; Liu *et al*., 2017). For example, the frequency of mechanical cooling usage in coastal West African households varies not only with temperature but also with income levels, gender roles, and daily routines. Without capturing these dynamics, envelope optimization models risk oversimplification and limited real-world applicability.

Future research should therefore prioritize occupant-centered performance studies, employing mixed methods that integrate quantitative monitoring with qualitative surveys. Combining environmental sensors with Internet of Things (IoT) platforms can enable continuous data collection on temperature, humidity, and energy use, while behavioral mapping and ethnographic methods can contextualize how residents interact with their built environment. The inclusion of psychological comfort metrics—such as perceived thermal satisfaction—alongside physical measurements will also enrich understanding of how envelope optimization translates into lived experiences (Atzeri *et al*., 2016; Castaldo *et al*., 2018).

A third frontier for future research lies in the development of adaptive building envelope systems that dynamically respond to real-time climatic conditions. Current envelope designs in humid regions are predominantly static, relying on passive strategies such as fixed shading, natural ventilation openings, and material insulation. While these measures are effective under predictable climatic regimes, they often underperform during extreme or rapidly changing weather events, such as heatwaves or monsoon transitions.

Emerging technologies offer promising pathways toward responsive and intelligent envelope systems (Ghaffarianhoseini *et al*., 2016; Casini, 2016). These include phase-change materials (PCMs) that regulate heat transfer through latent thermal storage, hygroscopic composites capable of self-regulating moisture absorption, and kinetic façades equipped with sensors that adjust shading and ventilation apertures in response to real-time environmental data. Integrating such systems with Building Management Systems (BMS) and predictive control algorithms could optimize thermal balance, reduce energy consumption, and enhance occupant comfort without compromising architectural aesthetics.

However, the practical implementation of adaptive envelopes in developing humid regions faces challenges related to cost, maintenance, and technological literacy. Therefore, future studies should explore context-appropriate adaptive mechanisms, prioritizing locally sourced materials and low-energy actuation technologies. Interdisciplinary collaboration among architects, materials scientists, and computer engineers is vital to developing affordable prototypes tailored to tropical environments. Life-cycle analysis (LCA) should also accompany these innovations to ensure that the environmental gains from adaptive performance outweigh their embodied energy and maintenance impacts (Ingrao *et al*., 2018; Nagarajan and Haapala, 2018).

The limitations of climatic data accuracy, behavioral modeling, and technological adaptability constrain the full realization of climate-optimized building envelopes in humid regions. Future research must adopt integrative and longitudinal methodologies, bridging the gap between environmental physics, human behavior, and technological innovation. By advancing data infrastructure, occupant-centered analytics, and adaptive design technologies, scholars and practitioners can collectively pave the way for next-generation building envelopes—systems that are not only thermally efficient but also socially attuned and ecologically resilient (Nagy *et al*., 2016; Gunay and Shen, 2017).

CONCLUSION

The optimization of building envelope design in humid regions underscores the intricate relationship between climatic variables and architectural performance. Temperature, humidity, solar radiation, and wind dynamics collectively determine the thermal and moisture behavior of building envelopes, influencing indoor comfort, energy demand, and material longevity. High ambient temperatures and intense solar exposure increase the risk of overheating, while elevated humidity accelerates material degradation and compromises indoor air quality. Similarly, wind speed and direction play a pivotal role in facilitating natural ventilation and reducing dependence on mechanical cooling. These interactions highlight that the building envelope is not merely a structural boundary, but a dynamic environmental interface that governs the energy and comfort balance within tropical and subtropical contexts.

Given these climatic complexities, the research reaffirms the imperative for integrated, climate-sensitive architectural design in humid regions. Passive strategies—such as cross-ventilation, shading, reflective surfaces, and the use of breathable, low-thermal-mass materials—must be combined with emerging digital simulation tools and real-time climatic analytics. Such integration can optimize design decisions at the early stages of building conception, ensuring that environmental responsiveness complements functional and aesthetic goals. Moreover, contextual adaptation—drawing from local materials, vernacular wisdom, and bioclimatic principles—remains central to achieving both sustainability and cultural continuity in tropical architecture.

Ultimately, the path toward sustainable built environments in humid regions demands interdisciplinary collaboration among architects, engineers, urban planners, and policymakers. Architects must translate climatic insights into innovative spatial and material solutions, engineers must refine modeling and energy systems, and policymakers must enforce adaptive building codes and incentives for green technologies. Through collective effort, the design and construction sectors can evolve toward buildings that harmonize with their environment—structures that are not only energy-efficient and resilient but also enhance the quality of life for their occupants in the face of a changing climate.

REFERENCES

[1] Ajayi, J. O., & [Additional authors if available]. (n.d.). An expenditure monitoring model for capital project efficiency in governmental and large-scale private sector institutions. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. https://doi.org/10.32628/IJSRCSEIT

[2] Ajayi, J. O., Erigha, E. D., Obuse, E., Ayanbode, N., & Cadet, E. (n.d.). Anomaly detection frameworks for early-stage threat identification in secure digital infrastructure environments. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. https://doi.org/10.32628/IJSRCSEIT

[3] Anyebe, B.N.V., Dimkpa, C., Aboki, D., Egbule, D., Useni, S. and Eneogu, R., 2018. Impact of active case finding of tuberculosis among prisoners using the WOW truck in North central Nigeria. *The international Union Against Tuberculosis and Lung Disease*, *11*, p.22.

[4] Ascione, F., De Masi, R.F., de Rossi, F., Ruggiero, S. and Vanoli, G.P., 2016. Optimization of building envelope design for nZEBs in Mediterranean climate: Performance analysis of residential case study. *Applied energy*, *183*, pp.938-957.

[5] Atzeri, A.M., Cappelletti, F., Tzempelikos, A. and Gasparella, A., 2016. Comfort metrics for an integrated evaluation of buildings performance. *Energy and Buildings*, *127*, pp.411-424.

[6] Ayanbode, N., Cadet, E., Etim, E. D., Essien, I. A., & Ajayi, J. O. (n.d.). Developing AI-augmented intrusion detection systems for cloud-based financial platforms with real-time risk analysis. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. https://doi.org/10.32628/IJSRCSEIT

[7] Babatunde, L. A., Cadet, E., Ajayi, J. O., Erigha, E. D., Obuse, E., Ayanbode, N., & Essien, I. A. (n.d.). Simplifying third-party risk oversight through scalable digital governance tools. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. https://doi.org/10.32628/IJSRCSEIT

[8] BABATUNDE, O.A., ADERIBIGBE, S.A., JAJA, I.C., BABATUNDE, O.O., ADEWOYE, K.R., DUROWADE, K.A. and ADETOKUNBO, S., 2014. Sexual activities and practice of abortion among public secondary school students in Ilorin, Kwara State, Nigeria. *International Journal of Science, Environment and Technology*, *3*(4), pp.1472-1479.

[9] Berardi, U. and Naldi, M., 2017. The impact of the temperature dependent thermal conductivity of insulating materials on the effective building envelope performance. *Energy and Buildings*, *144*, pp.262-275.

[10] Borawska, A., 2017. The role of public awareness campaigns in sustainable development. *Economic and Environmental Studies*, *17*(4 (44)), pp.865-877.

[11] BUKHARI, T.T., OLADIMEJI, O., ETIM, E.D. and AJAYI, J.O., 2018. A Conceptual Framework for Designing Resilient Multi-Cloud Networks Ensuring Security, Scalability, and Reliability Across Infrastructures. *IRE Journals*, *1*(8), pp.164-173.

[12] Bullard, J.E., Baddock, M., Bradwell, T., Crusius, J., Darlington, E., Gaiero, D., Gassó, S., Gisladottir, G., Hodgkins, R., McCulloch, R. and McKenna-Neuman, C., 2016. High-latitude dust in the Earth system. *Reviews of Geophysics*, *54*(2), pp.447-485.

[13] Capeluto, G. and Ochoa, C.E., 2016. *Intelligent envelopes for high-performance buildings: Design and strategy*. Springer.

[14] Casini, M., 2016. *Smart buildings: Advanced materials and nanotechnology to improve energy-efficiency and environmental performance*. Woodhead Publishing.

[15] Castaldo, V.L., Pigliautile, I., Rosso, F., Cotana, F., De Giorgio, F. and Pisello, A.L., 2018. How

subjective and non-physical parameters affect occupants' environmental comfort perception. *Energy and Buildings*, *178*, pp.107-129.

[16] Chai, S. and Shih, W., 2016. Bridging science and technology through academic–industry partnerships. *Research Policy*, *45*(1), pp.148-158.

[17] Chandel, S.S., Sharma, V. and Marwah, B.M., 2016. Review of energy efficient features in vernacular architecture for improving indoor thermal comfort conditions. *Renewable and Sustainable Energy Reviews*, *65*, pp.459-477.

[18] Chen, X., Yang, H. and Zhang, W., 2018. Simulation-based approach to optimize passively designed buildings: A case study on a typical architectural form in hot and humid climates. *Renewable and Sustainable Energy Reviews*, *82*, pp.1712-1725.

[19] Cole, M. and Packer, M., 2018. Design-based intervention research as the science of the doubly artificial. In *Cultural-Historical Activity Theory Approaches to Design-Based Research* (pp. 17-44). Routledge.

[20] Dare, S. O., Ajayi, J. O., & Chima, O. K. (n.d.). An integrated decision-making model for improving transparency and audit quality among small and medium-sized enterprises. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. https://doi.org/10.32628/IJSRCSEIT

[21] Dogho, M., 2011. The design, fabrication and uses of bioreactors. *Obafemi Awolowo University*.

[22] Durowade, K.A., Adetokunbo, S. and Ibirongbe, D.E., 2016. Healthcare delivery in a frail economy: Challenges and way forward. *Savannah Journal of Medical Research and Practice*, *5*(1), pp.1-8.

[23] Durowade, K.A., Babatunde, O.A., Omokanye, L.O., Elegbede, O.E., Ayodele, L.M., Adewoye, K.R., Adetokunbo, S., Olomofe, C.O., Fawole, A.A., Adebola, O.E. and Olaniyan, T.O., 2017. Early sexual debut: prevalence and risk factors among secondary school students in Ido-ekiti, Ekiti state, South-West Nigeria. *African health sciences*, *17*(3), pp.614-622.

[24] Durowade, K.A., Omokanye, L.O., Elegbede, O.E., Adetokunbo, S., Olomofe, C.O., Ajiboye, A.D., Adeniyi, M.A. and Sanni, T.A., 2017. Barriers to contraceptive uptake among women of reproductive age in a semi-urban community of Ekiti State, Southwest Nigeria. *Ethiopian journal of health sciences*, *27*(2), pp.121-128.

[25] Durowade, K.A., Salaudeen, A.G., Akande, T.M., Musa, O.I., Bolarinwa, O.A., Olokoba, L.B., Fasiku, M.M. and Adetokunbo, S., 2018. Traditional eye medication: A rural-urban comparison of use and association with glaucoma among adults in Ilorin-west Local Government Area, North-Central Nigeria. *Journal of Community Medicine and Primary Health Care*, *30*(1), pp.86-98.

[26] Essien, I. A., Ajayi, J. O., Erigha, E. D., Obuse, E., & Ayanbode, N. (n.d.). Supply chain fraud risk mitigation using federated AI models for continuous transaction integrity verification. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. https://doi.org/10.32628/IJSRCSEIT

[27] Etim, E. D., Essien, I. A., Ajayi, J. O., Erigha, E. D., & Obuse, E. (n.d.). Automation-enhanced ESG compliance models for vendor risk assessment in high-impact infrastructure procurement projects. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. https://doi.org/10.32628/IJSRCSEIT

[28] Gagliano, A., Nocera, F. and Aneli, S., 2016. Thermodynamic analysis of ventilated façades under different wind conditions in summer period. *Energy and Buildings*, *122*, pp.131-139.

[29] Ghaffarianhoseini, A., Berardi, U., AlWaer, H., Chang, S., Halawa, E., Ghaffarianhoseini, A. and Clements-Croome, D., 2016. What is an intelligent building? Analysis of recent interpretations from an international perspective. *Architectural Science Review*, *59*(5), pp.338-357.

[30] Gunay, B. and Shen, W., 2017. Connected and distributed sensing in buildings: Improving operation and maintenance. *IEEE Systems, Man, and Cybernetics Magazine*, *3*(4), pp.27-34.

[31] Herrera, M., Natarajan, S., Coley, D.A., Kershaw, T., Ramallo-González, A.P., Eames,

M., Fosas, D. and Wood, M., 2017. A review of current and future weather data for building simulation. *Building Services Engineering Research and Technology*, *38*(5), pp.602-627.

[32] Ingrao, C., Messineo, A., Beltramo, R., Yigitcanlar, T. and Ioppolo, G., 2018. How can life cycle thinking support sustainability of buildings? Investigating life cycle assessment applications for energy efficiency and environmental performance. *Journal of cleaner production*, *201*, pp.556-569.

[33] Kabre, C., 2017. *Sustainable building design: Applications using climatic data in India*. Springer.

[34] KARIMOVA, A., 2018. HIGH-PERFORMANCE SUSTAINABLE FACADES AND THEIR IMPACTS ON URBAN SPACE. *URBANIZM: Journal of Urban Planning & Sustainable Development*, (23).

[35] Kershaw, T., 2017, September. Heat Island Influence on Space-Conditioning Loads: Urban and suburban office buildings. In *Cities and Climate Conference 2017*.

[36] Kibert, C.J., 2016. *Sustainable construction: green building design and delivery*. John Wiley & Sons.

[37] Liu, Y., Dong, Y., Song, C., Wang, Y., Liu, L. and Liu, J., 2017. A tracked field study of thermal adaptation during a short-term migration between cold and hot-summer and warm-winter areas of China. *Building and Environment*, *124*, pp.90-103.

[38] Loonen, R.C., Favoino, F., Hensen, J.L. and Overend, M., 2017. Review of current status, requirements and opportunities for building performance simulation of adaptive facades. *Journal of Building Performance Simulation*, *10*(2), pp.205-223.

[39] MacGill, I., Bruce, A., Kuch, D., Marshall, L., Stringer, N. and Young, S., 2017. Submission to the Independent Review into the Future Security of the National Electricity Market.

[40] Menson, W.N.A., Olawepo, J.O., Bruno, T., Gbadamosi, S.O., Nalda, N.F., Anyebe, V., Ogidi, A., Onoka, C., Oko, J.O. and Ezeanolue, E.E., 2018. Reliability of self-reported Mobile phone ownership in rural north-Central Nigeria: cross-sectional study. *JMIR mHealth and uHealth*, *6*(3), p.e8760.

[41] Molinar-Ruiz, A., 2017. Cold-arid deserts: Global vernacular framework for passive architectural design.

[42] Nagarajan, H.P. and Haapala, K.R., 2018. Characterizing the influence of resource-energy-exergy factors on the environmental performance of additive manufacturing systems. *Journal of Manufacturing Systems*, *48*, pp.87-96.

[43] Nagy, Z., Yong, F.Y. and Schlueter, A., 2016. Occupant centered lighting control: A user study on balancing comfort, acceptance, and energy consumption. *Energy and buildings*, *126*, pp.310-322.

[44] Osabuohien, F.O., 2017. Review of the environmental impact of polymer degradation. *Communication in Physical Sciences*, *2*(1).

[45] Penn, H.J., Gerlach, S.C. and Loring, P.A., 2016. Seasons of stress: understanding the dynamic nature of people's ability to respond to change and surprise. *Weather, Climate, and Society*, *8*(4), pp.435-446.

[46] Popescu, I., Jonoski, A. and Bociort, L., 2012. Decision support systems for flood management in the Timis Bega catchment. *Environmental Engineering & Management Journal (EEMJ)*, *11*(12).

[47] Prieto, A., Knaack, U., Auer, T. and Klein, T., 2018. Passive cooling & climate responsive façade design: Exploring the limits of passive cooling strategies to improve the performance of commercial buildings in warm climates. *Energy and Buildings*, *175*, pp.30-47.

[48] Saadon, S., Gaillard, L., Giroux-Julien, S. and Ménézo, C., 2016. Simulation study of a naturally-ventilated building integrated photovoltaic/thermal (BIPV/T) envelope. *Renewable Energy*, *87*, pp.517-531.

[49] Schmidt, T.S. and Huenteler, J., 2016. Anticipating industry localization effects of clean technology deployment policies in developing countries. *Global Environmental Change*, *38*, pp.8-20.

[50] Scholten, J., Eneogu, R., Ogbudebe, C., Nsa, B., Anozie, I., Anyebe, V., Lawanson, A. and Mitchell, E., 2018. Ending the TB epidemic: role of active TB case finding using mobile units for early diagnosis of tuberculosis in Nigeria. *The*

International Journal of Tuberculosis and Lung Disease, *22*(11), p.S392.

[51] Seymour, J., 2018. The impact of public health awareness campaigns on the awareness and quality of palliative care. *Journal of palliative medicine*, *21*(S1), pp.S-30.

[52] Shao, Y., Ma, N., Chen, M., Zhang, C. and Cui, Y., 2016, March. Machine Learning in Landscape Architecture: A Comprehensive Review of Advancements, Applications, and Future Directions. Buildings 2025, 15, 3827. In *International Conference on Computing for Sustainable Global Development (Indiacom)* (Vol. 16, p. 18).

[53] Solomon, O., Odu, O., Amu, E., Solomon, O.A., Bamidele, J.O., Emmanuel, E. and Parakoyi, B.D., 2018. Prevalence and risk factors of acute respiratory infection among under fives in rural communities of Ekiti State, Nigeria. *Global Journal of Medicine and Public Health*, *7*(1), pp.1-12.

[54] Taliotis, C., Rogner, H., Ressl, S., Howells, M. and Gardumi, F., 2017. Natural gas in Cyprus: The need for consolidated planning. *Energy Policy*, *107*, pp.197-209.

[55] Tallini, A. and Cedola, L., 2018. A review of the properties of recycled and waste materials for energy refurbishment of existing buildings towards the requirements of NZEB. *Energy Procedia*, *148*, pp.868-875.

[56] Walker, M.J., 2018. Patient-specific devices and population-level evidence: evaluating therapeutic interventions with inherent variation. *Medicine, Health Care and Philosophy*, *21*(3), pp.335-345.

[57] Widiastuti, R., Caesarendra, W., Prianto, E. and Budi, W.S., 2018. Study on the leaves densities as parameter for effectiveness of energy transfer on the green facade. *Buildings*, *8*(10), p.138.

[58] Xu, Y., Ren, C., Ma, P., Ho, J., Wang, W., Lau, K.K.L., Lin, H. and Ng, E., 2017. Urban morphology detection and computation for urban climate research. *Landscape and urban planning*, *167*, pp.212-224.

[59] Zeng, Q., Mao, T., Li, H. and Peng, Y., 2018. Thermally insulating lightweight cement-based composites incorporating glass beads and nano-silica aerogels for sustainably energy-saving buildings. *Energy and Buildings*, *174*, pp.97-110.

[60] Zhou, N., Khanna, N., Feng, W., Ke, J. and Levine, M., 2018. Scenarios of energy efficiency and CO2 emissions reduction potential in the buildings sector in China to year 2050. *Nature Energy*, *3*(11), pp.978-984.