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Research Article

Sustainability beyond the surface: Evaluating the long-term environmental and energy performance of selected cladding materials for housing retrofits

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ABSTRACT

External walls, constituting the largest exposed surface area of the building envelope, face heightened susceptibility to environmental influences. In this study location, aesthetic considerations often overshadow environmental impact and comfort requirements in selecting exterior cladding materials. This paper investigates the energy performance, global warming potential, and thermal comfort aspects of carefully selected cladding materials, informed by an exhaustive literature review, for application in retrofit projects in Abuja, Nigeria. Energy consumption, carbon emissions, and temperature distributions were simulated using materials in a hypothetical single-floor residential building finished with cement-sand plaster. The findings show that gravel stone exhibits the most negligible environmental impact. In contrast, aluminum and lightweight metal cladding panels contribute significantly to the embodied carbon of the building despite ranking as the most expensive materials. Insulating the test building with polyurethane boards yields substantial energy savings of up to 9% in cooling electricity, averting the need for added cladding. This study emphasizes the significance of adopting a multi-criterion approach in selecting façade cladding materials, prioritizing environmental and thermal considerations over aesthetic and cost benefits. The implications extend beyond mere emissions reduction, shedding light on the vital interplay between material choices on comfort and energy efficiency in building design.

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1. INTRODUCTION

In building design, a noticeable conflict has emerged between the pursuit of aesthetic ideals and the imperatives of sustainability [1]. The allure of cultural values and visual appeal often precedes the crucial energy efficiency considerations in buildings. In the contemporary landscape, marked by an energy crisis, the separation of structural and cladding functions in buildings has posed challenges to architects, demanding a delicate balance between durability and the fundamental properties of external finishes [2]. Recognizing the urgency of sustainability, architects are transcending the confines of mere artistic expression. Collaborating with diverse professionals, they now strive for a holistic sustainability approach [3, 4]. This drift is particularly evident in treating wall claddings, which fulfill multiple roles—providing protection, enhancing aesthetic appeal, and regulating building thermal conditions. The building envelope, a cor-

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nerstone of structural integrity, is connected to the exterior sphere and constantly influences dynamic environmental factors [5]. Evaluating the sustainability performance of cladding materials within this complex context involves addressing uncertainties related to quantification and the complex interplay of various parameters [6].

The symbiotic relationship between the building envelope and the surrounding environment is pivotal, with implications for occupants, structural integrity, and the global climate. However, when designed in harmony with nature, the impact of cladding materials on these aspects becomes negligible [7]. Balaji et al. [8] accentuate the significance of wall configuration in achieving superior thermal performance. Factors such as the coefficient of thermal conductivity, wall thickness, and mortar thickness play a fundamental role in determining the heat transfer rates of cladding materials [9]. Materials with higher thermal conductivity transfer heat more readily than those with lower conductivity. In the context of building cladding materials, as used by the author, materials with a higher coefficient of thermal conductivity will allow heat to pass easily through the cladding materials, leading to increased heat transfer rates through the wall components. Similarly, it was found using Gray theory analysis that the coefficient of thermal conductivity of wall materials and wall and mortar thicknesses are influencing factors that correlate with the wall heat transfer coefficient. However, the climatic conditions of the building's location significantly influence their effectiveness [5], making considerations for time lag and decrement factors paramount in tropical regions [8].

In the contemporary built environment industry, a paramount concern is the reduction of buildings' energy consumption. Various factors, including material properties, building size, geographical location, and environmental conditions, collectively shape the energy performance of buildings according to Atashbar and Noorzai [10] and Balaji et al. [8]. A global imperative for sustainable buildings to mitigate emissions and address climate change has shifted the focus from aesthetics [11] to a more comprehensive evaluation encompassing quality, cost, and environmental impact [12, 13]. Therefore, beyond satisfying thermal requirements, cladding selection necessitates considering physical qualities, ecological impact, and financial implications [2]. A holistic understanding of a material's sustainability, as advocated by Takano et al. [14], demands a lifecycle approach.

The global trend of housing retrofit in the construction industry seeks to enhance the energy efficiency of existing housing stock [15]. Modifying wall fabrics, glazing, or incorporating thermal insulators can significantly impact energy savings and influence the sizing of HVAC systems [16–18]. As part of this trend, cladding systems emerge as crucial contributors to sustainable energy performance, albeit with challenges during selection. The decision-making matrix balances cost, embodied carbon, aesthetics, thermal properties, maintenance, and lifecycle impact [14]. Regional preferences further complicate the scenario, with Northern Europe favoring local timber for cladding, while the UK leans towards rendered concrete blocks and brick for their external visual appeal [19]. Cost considerations, however, are driving a shift away from traditional materials [12].

The choice of cladding materials is inherently complex and necessitates a case-by-case examination [20]. On the other hand, Dodge and Liu [21] encourages selecting environmentally friendly materials to minimize adverse environmental impacts, emphasizing their effects on the user's comfort, the building's lifespan, and maintenance considerations [22]. When viewed through a building's microclimate lens, cladding performance takes precedence over efficacy. Building practitioners must refrain from focusing solely on cost reduction, recognizing that the most cost-effective materials may not always align with environmental sustainability requirements. Hence, a delicate equilibrium between ecological considerations and the practicalities of design function and economy should guide the selection and use of building materials [23].

While many building materials claim environmental friendliness based on a specific aspect of the lifecycle [21], the efficacy of cladding materials extends beyond reducing carbon emissions. Considerations like life expectancy and maintenance values should also factor into material choices [13]. As construction becomes more intricate and material options proliferate, the responsibility of material selection may extend beyond architects due to knowledge gaps or project complexity [24]. Enhancing existing housing stock, especially external walls, to adapt to changing climates and meet carbon emissions reduction targets is becoming crucial [4]. Yet, public resistance persists as long as sustainability efforts seem technical and aesthetically unpleasant. However, while integral to architectural sustainability, aesthetics should not define the concept; it encompasses broader considerations, including social equity, environmental impact, and the preservation of cultural values [25].

This study proposes an approach for selecting external cladding materials in existing buildings or retrofit projects in Nigeria. Focused on a test building with a conventional cement-sand plaster exterior, the investigation involves remodeling using various cladding materials through computer simulations. The study presents a ranking system based on embodied carbon, electricity for cooling, building energy per conditioned area, and operative temperature on the South-facing wing. The results aim to enlighten practitioners on the multifaceted aspects of cladding selection, offering guidance in decision-making processes.

2. LITERATURE REVIEW

Green architecture has reached a critical juncture where careful considerations ensure that a building's façade remains visually appealing without compromising essential sustainability values [3]. However, a study reveals that climate conditions and material performance often take a backseat in material selection, with a predominant focus on cost, aesthetics, and societal influence. Craig et al. [19] further emphasizes a preference for external cladding materials' "traditional" look over novel alternatives. The challeng-

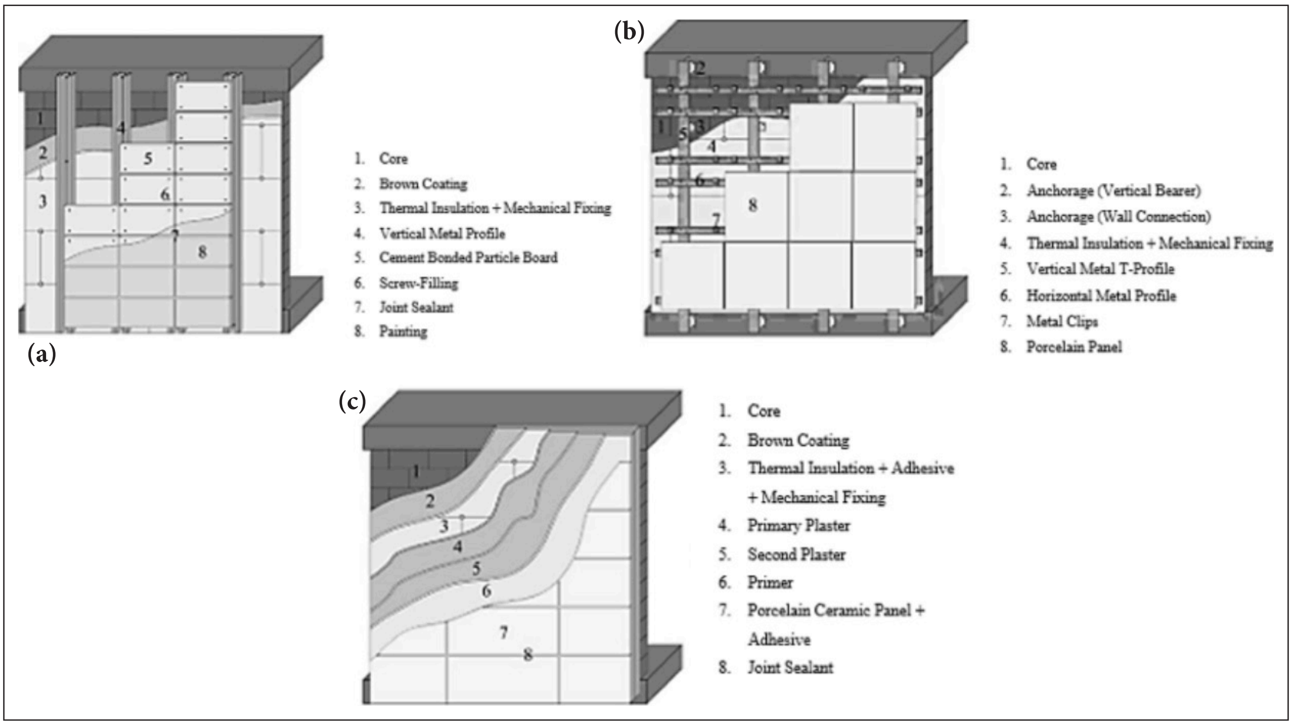

Figure 1. Cladding construction techniques- **(a)** screwed system, **(b)** fixed system, **(b)** bonded system [36].

es associated with modern materials, including weathering (patina), durability, and assembly, have been highlighted Slaton [26]. While modern materials demonstrate reduced susceptibility to water leakage or mold growth compared to traditional masonry wall construction, concerns persist regarding strength loss and anchorage deterioration, especially in modern thin claddings. Dissanayake et al. [27] argue that any building material utilizing waste materials or minimizing natural resource consumption holds promise for sustainability.

Moreover, studies show that cladding material choices evolve due to technological advances and contemporary material inventions meeting functional requirements. Historical trends in the US residential construction industry have witnessed shifts in the last decade, exemplified by using wood, aluminum siding, fiber cement, and vinyl for external wall cladding [12]. Notably, fiber cement boards have garnered interest from developers as a façade cladding material [6]. In urban space design, ceramic cladding emerges as a potentially transformative sustainable architectural material for the 21st century [7].

Over the years, the efficacy of different cladding materials has been extensively investigated across various regions globally, considering their application, selection and performance based on energy savings [15, 17, 28], environmental impact [11, 15, 21], cost [22, 29] and thermal comfort [20, 30]. Similarly, these materials have been researched worldwide in various climates, with some options considered in this study. Notable cladding materials investigated in prior research include aluminium [21], wood [31], polystyrene [27], terracotta [32], marble, stone [33], Ceramic [7], boards [34, 35], resin panels [26], recycled waste [6], concrete [28], plaster [20] and Date Palm Midribs (DPM) [15].

2.1. Cladding Construction Techniques

According to Metin and Tavil [36], the facade cladding construction techniques encompass three primary methods: the screwed system, the fixed system, and the bonded system (Fig. 1). The choice among these methods depends on material type, desired aesthetics, application cost, specific building requirements, and cladding location. Claddings can be installed directly onto the structural building system, the core of the external wall, or over the core of the external wall. When choosing between facade cladding construction techniques, architects must consider various factors to ensure the selected approach aligns with the building project's requirements, budget, aesthetics, and performance objectives. They must therefore:

I. Understand the properties and characteristics of the available cladding material.
II. Assess how the chosen cladding material and construction technique contribute to the visual appearance of the building facade.
III. Determine whether the cladding system needs to accommodate additional features or functionalities such as integrated solar panels, ventilation systems, or rainwater management solutions.
IV. Assess the long-term performance and durability of the chosen cladding materials and construction techniques.
V. Evaluate the cost implication of different cladding materials and construction techniques.

2.1.1. Screwed System

The screwed system, also known as the "rivet system" [37] or "screw face" fixing, is a cost-effective way of installing facade cladding that works well with various material types. Cladding panels in this system are mechanically attached to the building using screws. While this system offers several advantages, such as ease of installation and cost-effectiveness, it also presents potential challenges. Here are some of the challenges, along with possible mitigation strategies.

Thermal Bridging: Screws or fasteners used in this system can create thermal bridges, where heat is transferred through the fasteners, leading to energy loss and reduced thermal performance of the building envelope. To avoid this, the authors suggest the use of thermal break materials or isolators between the fasteners and the cladding panels to minimize heat transfer or the use of screws with lower thermal conductivity in conjunction with insulating gaskets.

Visual Appeal: The presence of visible screws on the facade may detract from the aesthetic appeal of the building, especially for projects with sleek or minimalist design intentions. To mitigate this challenge, it is advisable to conceal screws within the joints or seams of the cladding panels where possible or incorporate design elements or features that strategically integrate the fasteners into the overall facade design, turning them into intentional design elements rather than distractions.

Corrosion and Maintenance: Exposing metal fasteners to weather elements and moisture can lead to corrosion of screws over time, potentially compromising the structural integrity of the cladding system, thus, increasing maintenance requirements. To avoid this, it is suggested to use corrosion-resistant materials such as stainless steel or galvanized steel for screws.

2.1.2. Fixed System

The fixed system relies on hidden mechanisms to provide a seamless appearance to the building façade. Studies indicate that the fixed system contributes the most to the sustainability of the construction process [36]. This system poses challenges while contributing to better thermal performance due to a complex installation process that can increase construction and maintenance costs.

2.1.3. Bonded System

The bonded system employs adhesive or bonding agents to attach the cladding material to the building structure. This approach offers the advantage of a monolithic appearance for the external facade, enhanced durability, and reduced thermal bridging compared to the screwed system. However, costs may increase where specific skills and adhesives are needed.

2.2. Cladding Choice on Building's Performance

The escalating demand for quality housing is projected to increase energy usage [27]. Atashbar and Noorzai [10] demonstrated that optimal material selection for residential building facades can lead to a 40% reduction in annual average energy consumption. For example, opaque materials have been shown to have a short time lag and can decrease indoor temperature by approximately 9 ^{0}C [30]. Pekdogan and Basaran [17] also assert that opaque materials, such as stone cladding, contribute to significant energy savings. A study investigating various materials for a traditional single-family home in Ohio, USA, found that vinyl siding was the most environmentally friendly and cost-efficient option despite limited recycling potential and shorter service life. Similar investigations in the hot climate of the UAE favored stone cladding systems for their exceptional performance, closely followed by aluminum cladding panels (ACP) and plaster systems. As Hamoush et al. [33] suggested, engineered stone contributes to substantial energy savings, reducing the cooling load in the UAE by 4% compared to ACP and 1.5% compared to plaster.

Moreover, using locally sourced or industrial waste materials for cladding, such as Date Palm Midribs (DPM), has demonstrated significant energy savings, as highlighted by Darwish et al. [15] achieving a 13% reduction in cooling and 4% in total energy consumption. Specifically, DPM fibers have been recognized as a sustainable and energy-efficient material for cladding and construction due to the inherent properties of the fiber, which can be processed into strips and fiber boards. They have natural insulating properties that can help regulate indoor temperatures by reducing heat transfer through the building envelope. The production process of DPM involves minimal energy input compared to many industrial waste materials. Since they are harvested from agricultural waste or by-products of date palm cultivation, they have low embodied energy, meaning they need less energy for extraction, processing, and manufacturing than conventional building materials.

Further, the adoption of locally produced timber for cladding, driven by cost considerations and a commitment to improving housing sustainability, is gaining traction [19]. However, comparative cost analyses by Mac-Barango [29] and Alegbe [38] on concrete blocks against timber indicate that timber cladding can significantly increase construction costs. While timber is valued for its ecological advantages, such as carbon storage [39], it is not without challenges, particularly its interaction with moisture. This can lead to issues like timber discoloration in specific climates [12, 31]. Prevailing wind direction can also influence timber discoloration, especially in tropical monsoon climates [40]. It is, thus, worthwhile to undertake a condensation analysis to ascertain the possibility of mold growth when wood-based materials define the facade of buildings.

Taylor et al. [11] compared to the global warming potential of different cladding materials, they revealed that plywood and masonry wall cladding had the lowest carbon emissions. Conversely, reinforced concrete foundations were associated with the highest global warming potential. The buildings studied were different in size and design, which may have influenced the outcome of carbon emissions. Investigations by Özel [28] in Elazığ, Türkiye, highlighted the highest peak load and maximum temperature swings for concrete walls among various materials. Concrete, metal, and brick were identified as the top three exterior wall cladding emitters. Reducing carbon emissions in a building depends on factors such as the building system, operational schedule, and the source of electricity [13]. In conclusion, the literature review highlights various pivotal factors that shape the choice of cladding materials. These encompass differences in material availability and usage depending on location, the continuous evolution of cladding materials, and the complex interaction between numerous factors influencing the energy performance of these materials.

3. MATERIALS AND METHODS

3.1. Cladding Materials Selection Process

This research adopted a comparative and experimental design to examine the energy performance of 19 carefully selected cladding materials derived from an extensive literature review in contrast to widely used cement-sand plaster on a test building. The selection of cladding materials for the study followed a systematic process to ensure the representation of diverse materials commonly used in building construction within tropical regions. Three primary criteria guided the selection process:

I. Commonly Used Materials: Cladding materials were chosen based on their prevalence in tropical construction projects, ensuring that the selected materials were representative of those encountered in practice. For example, materials such as clay and stone are commonly used in tropical climates due to their durability and thermal properties.

II. Material Diversity: Selection criteria encompassed a wide range of material types, including natural materials (e.g., straw, clay, gravel stone), synthetic materials (e.g., PVC tiles, aluminum panels), and composite materials (e.g., resin-bonded fibreboard, polyurethane cellular board). This diversity facilitated a comprehensive comparison of material properties and performance characteristics relevant to tropical construction environments.

III. Availability and Accessibility: Priority was given to cladding materials that are readily available in the market and commonly used in construction projects. This consideration ensured the practical relevance and applicability of the study findings to real-world scenarios in tropical regions, especially Nigeria.

The search for relevant literature employed a rigorous approach leveraging reputable academic databases such as Scopus, Web of Science, and Google Scholar. A targeted search strategy was utilized using keywords, Boolean operators, and explicit vocabulary terms (e.g., 'cladding materials,' 'building envelope,' 'tropics'). Articles published from 2010 onwards were selected to ensure relevance to current construction practices within tropical climates, with reports, books, and theses excluded to prioritize peer-reviewed research. Retrieved articles underwent screening based on title, abstracts, and full text to assess their relevance and eligibility for inclusion in the literature review. This ensured a robust and all-inclusive analysis of the selected cladding materials.

The primary focus of this study is to evaluate these materials' environmental performance, energy consumption, and cost implications, aiming to suggest a basis for cladding selection for retrofit projects in Nigeria through a multi-criterion ranking system. Contemporary EnergyPlus (EPW) weather files specific to Abuja were generated using Meteonorm (V 8.0.3), ensuring a precise representation of real-world environmental conditions. These weather files were imported into the DesignBuilder (V 6.1.0.6) energy simulation program, facilitating an all-inclusive building performance analysis.

3.2. Simulation Environment Setup and Parameters

Detailed attention was paid to various parameters across categories to establish a robust simulation environment. For instance, residential spaces were modeled in the Activity system settings using the "Domestic Bedroom" template to reflect typical occupancy patterns accurately. Moreover, all zones within the test building were included in thermal and radiance daylight calculations, allowing for a holistic understanding of environmental dynamics. Occupancy density was fixed at 0.0229 persons/m^2 with a metabolic factor of 0.90, ensuring a precise representation of human heat gains for a maximum of two users in all occupied areas. Additionally, scheduled-based clothing was defined to align with typical clothing behaviors. Thermal calculations were also conducted annually, with cooling setpoints configured at 25^{0}C for comfort conditions and a setback temperature of 28^{0}C to optimize energy efficiency.

Furthermore, construction boundary parameters utilized the Uninsulated Heavyweight template to represent the building's initial construction characteristics accurately. Model infiltration was set at 1.0 air changes per hour (ac/h), simulating realistic air exchange rates peculiar to residential buildings in the study location. Window openings had two layers of 3mm generic clear glass with two horizontal dividers. In contrast, vertical dividers were omitted to simplify the simulation while capturing essential building envelope characteristics. Also, exterior lighting schedules were established with an absolute power setting of 100 watts, designed to turn off during daylight hours to conserve energy automatically. For HVAC operations, mechanical systems were exclusively employed for cooling, with electricity sourced from the grid as the primary fuel. Furthermore, humidity control settings were configured for dehumidification to address prevalent high humidity levels recorded in the location.

3.3. Base Model Calibration and Validation of Simulation Parameters

To ensure the accuracy and reliability of the simulation results, rigorous steps were taken to validate the parameters of the simulation environment. Firstly, the input data, including weather files and building geometry, were carefully cross-referenced with data from the Nigerian Meteorological Agency (NIMET) and benchmarked against historical data to verify their consistency and accuracy. Furthermore, a sensitivity analysis was conducted using the initial setup to identify critical factors influencing energy consumption in the base model, revealing that occupancy level, wall thickness, and insulation are the primary drivers of energy use intensity. These factors guided the alterations needed for the building simulations.

The model underwent detailed iterative calibration to align simulation results with benchmarked empirical data and improve accuracy. Initially set at 0.1187 persons per square meter (equivalent to 8 occupants), the occupancy level was adjusted to 0.0229 persons per square meter (2 occupants) to reflect better the actual usage scenario appropriate for the hypothetical building's area. Each adjustment involved recalculating energy consumption, highlighting that varying the number of occupants significantly affected the building's energy usage. The wall thickness and insulation levels were also iteratively adjusted to optimize thermal performance. The initial model included a 150mm wall without insulation, yielding a U-value of 1.385 W/m^2K. Increasing the wall thickness to 225mm reduced the U-value to 1.054 W/m^2K. Adding a 35mm PUR insulation further improved the U-value to 0.436 W/m^2K. However, it was observed that increasing the insulation thickness to 75mm led to higher energy consumption, likely due to over-insulation effects.

Moreover, thicker insulations always increase the overall costs of the building project [41]. Therefore, 35mm PUR insulation was selected as the optimal thickness, balancing energy efficiency and the potential for introducing cladding materials for further energy performance experiments. This iterative process of adjusting parameters ensured the model's thermal properties aligned with real-world performance metrics in the tropics. A better alignment between real-world scenarios and simulation parameters is necessary to reduce the prediction gap of results [42].

The test building, featuring a cross-shaped form (Fig. 2) and encompassing a total floor area of 71.85 m^2, was in the first simulation stage, modeled using 225mm concrete hollow blocks and finished with 35mm cement-sand plaster on the exterior and interior surfaces. Occupying a single floor level, the building consists of equal units on all orientations (North, South, West, and East), with a central space providing access to all four spaces.

The building plan is hypothetical, and the size does not indicate retrofit projects in Nigeria, as this can vary in length and scale. The adopted plan, however, reflects standard features in a typical project with rooms flanked towards different orientations. The building represents real-world scenarios with manageable spaces for conducting experiments in a controlled environment. The cladding application followed the screwed, fixed, or bonded system, depending on the suitability of each cladding material with the construction system. A combination of these systems was employed to suit the unique properties of each material. The study method provides a foundation for future research in cladding selection when dealing with large and complex retrofit buildings.

In the first investigation stage, multiple simulations were conducted by cladding the original wall with each cladding material, generating comprehensive data on energy consumption, environmental impact, and cost implications. Simulations were carried out simultaneously on the north, south, west, and east sides to discern potential variations in energy impact. During the second phase of the experiment, a 35mm diffusion light polyurethane board insulator was uniformly applied to all the materials. This insulator, with a conductivity of 0.0260 W/m-K, density of 35 kg/m^3, and an embodied carbon of 3.0 $KgCO_2/Kg$, was added to assess the impact of insulation on the selected materials.

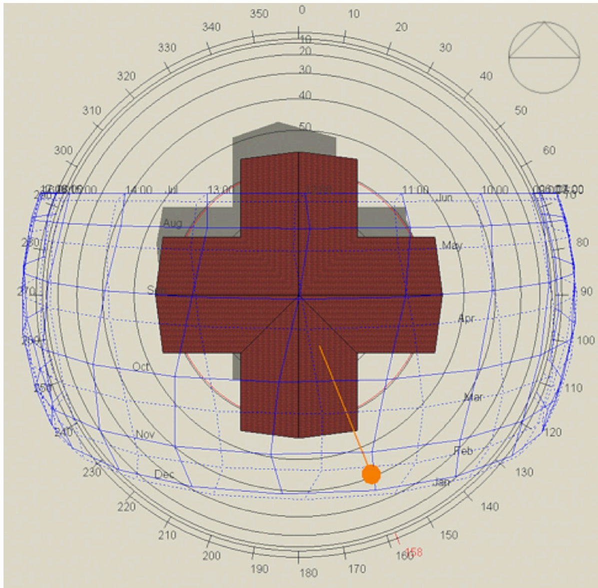

Figure 2. Top view of test building with sun path in DesignBuilder.

An analytical comparison of the simulation results with data from relevant literature was conducted to validate the simulation model. This approach is particularly suitable for simulations not incorporating field measurement data [43]. The energy consumption results for the hypothetical building, both with and without insulation, were compared against values reported in benchmark studies. These studies were chosen based on their relevance to the energy performance of insulated and non-insulated buildings and their alignment with the findings of this research. The selected benchmarks include energy performance data for residential and tertiary building stock in Spain [44, 45], public and commercial buildings in China [46, 47], public buildings in Malaysia [48], and residential buildings in Libya and Nigeria [49, 50]. These studies provided diverse energy consumption data to validate the simulation results.

3.4. Data Analysis and Visualization

Statistical analysis and visualization of the simulation results were conducted using a combination of Microsoft Excel and Tableau (version 2018.3). Initial data exploration and analysis were performed using the Data Analysis ToolPak add-in in Excel, facilitating a comprehensive statistical assessment. Descriptive statistics were employed to characterize the data's dispersion and distribution, including measures of central tendency such as mean and median and measures of variability such as standard deviation and range. Graphical representations, including histograms and radar charts, were used to visualize the distribution and identify any outliers or patterns within the data. To enhance the clarity and quality of data visualization, Tableau was employed to create high-quality visual representations that effectively depict statistical findings, easing a clearer understanding of data trends and distributions.

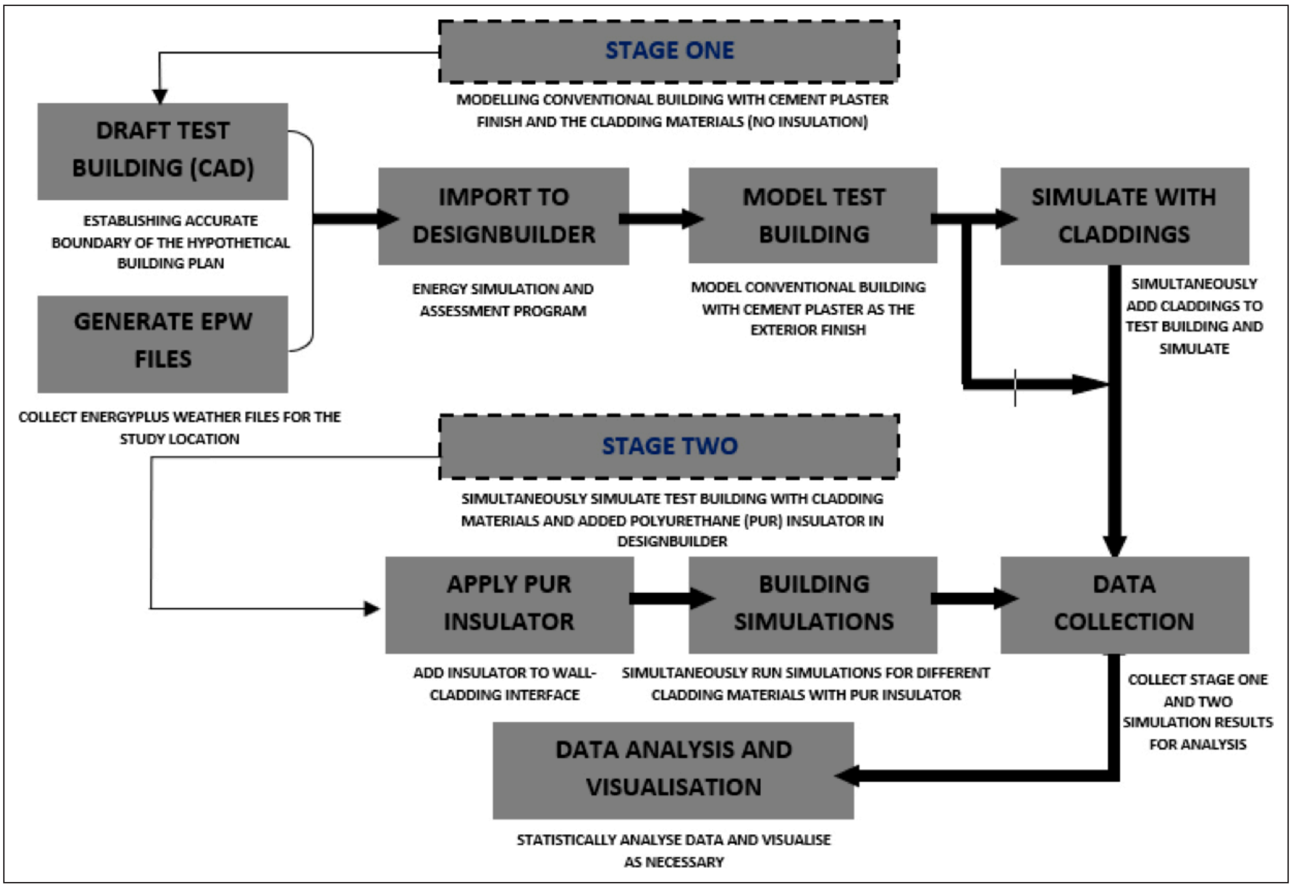

Figure 3. Methodology framework.

In addition to descriptive statistics, inferential statistical techniques were employed to investigate relationships and differences within the dataset. Analysis of Variance (ANOVA) was used to assess differences in energy performance among the various cladding materials. This allowed for a comparison of means across multiple groups and provided insights into the impact of different materials on energy consumption. Furthermore, a t-test analysis was conducted to compare specific variables, such as embodied carbon and cost, between distinct groups or conditions. These tests provided valuable insights into the significance of differences observed within the dataset. Regression analysis was also employed to explore the relationship between key variables, such as cladding material properties and their influence on energy performance. The combination of these tools enabled a comprehensive analysis of the simulation data, providing helpful information into the performance of different cladding materials and their implications for building energy efficiency and sustainability.

Several key performance metrics were carefully considered to broadly evaluate the cladding materials' environmental sustainability, energy efficiency, and cost-effectiveness. These metrics were chosen to provide a holistic assessment of the materials' performance across various dimensions. The impact of the materials' embodied carbon on the building's total global warming potential throughout its lifecycle was a primary consideration in assessing environmental sustainability. The materials' contributions to reducing indoor temperature and cooling loads were also evaluated to determine the building's energy efficiency.

Furthermore, the cost of implementing different cladding options was analyzed to ascertain the most cost-effective alternative. This included upfront costs and potential long-term savings or expenses associated with maintenance, repairs, and energy consumption. By examining these key metrics, cladding materials that offer optimal environmental sustainability, energy efficiency, and cost-effectiveness were identified, informing decision-making in building design and construction.

Building fabric insulation plays a vital role in improving the thermal performance of buildings [51–53]; thus, adding insulation offered valuable insights in the context of the experiments. The framework of the methodology is depicted in Figure 3.

4. RESULTS AND DISCUSSIONS

Selecting an appropriate cladding material for existing cement-sand plastered buildings is a complex undertaking, influenced by factors such as thickness, material density, embodied carbon, and conductivity, as shown in Table 1. A regression analysis explored the relationship between several factors, including the embodied carbon of cladding materials and the building's total embodied carbon. The study revealed a moderate to strong relationship between the embodied carbon of the cladding materials and the building's

Table 1. Thermophysical properties of experimented cladding materials

S/No	Cladding materials	Density (Kg/m^3)	Conductivity (W/mk)	Material's embodied carbon ($KgCO_2/Kg$)	Wall's U-value (W/m^2k)
1	Conventional Cement Plaster	1860	0.720	0.19	1.054
2	Straw Fireboard	300	0.100	0.53	0.770
3	Plate Glass	2710	0.760	0.85	0.883
4	Aluminium Panels (With Air Gap)	7680	45	8.55	0.855
5	Expanded Impregnated Cork Board	150	0.043	0.19	0.567
6	Polyvinylchloride (PVC) Tiles	1200	0.190	2.41	0.973
7	Clay Tiles	1120	0.520	0.46	1.033
8	Burnt Brick Tiles	1890	0.800	0.46	1.033
9	Cement-bonded Particle Board	1200	0.230	0.60	0.986
10	Vermiculite Insulating Brick	700	0.270	0.44	0.927
11	Gravel Stone	1840	0.360	0.02	0.956
12	Polyurethane Cellular Board	24	0.023	3.00	0.405
13	Hardboard Solid wood	600	0.080	0.89	0.635
14	Resin-Bonded Fibre Board	240	0.042	0.59	0.561
15	Flax Shive Resin Bonded Board	500	0.012	0.51	0.259
16	Particle Board	640	0.0129	0.51	0.458
17	Foil-Laced, Glass Fibre-Reinforced Polyisocyanurate Board	32	0.019	0.58	0.358
18	Perlite Plaster	400	0.080	0.12	0.721
19	Expanded Rigid Rubber Board	70	0.032	3.51	0.490
20	Lightweight Metallic panels	1250	0.290	8.55	0.859

total embodied carbon (R^2=0.462). The implication is that the materials' embodied carbon influences the building's total embodied carbon. Additionally, the analysis yielded a statistically significant F-value of 0.000974 ($F<0.005$), indicating the variables' significance.

Among the materials examined, boards demonstrate promise as effective cladding materials, particularly when insulated. Insulated walls are crucial in reducing peak loads on interior surfaces [28]. However, gravel stone cladding is the most consistent material considering energy efficiency, cooling load, embodied carbon, and thermal comfort. Introducing cladding to the test building results in an overall cost increase and a surge in embodied carbon. In the experimental setup, the simulated cost increase is attributed to material expenses and labor costs, including geographical-based labor rates. Adding an extra layer to a building inevitably increases these associated costs. In the case of cladding, compared to conventional plaster, the increase in cost is due to the cladding material and installation costs. For instance, cladding with hardboard solid wood resulted in a negligible cost increase of 0.02%, while using aluminum cladding panels incurred the highest cost increase of 6.26%.

Concerning embodied carbon, buildings with cladding exhibit higher levels than those with conventional plaster, primarily due to the added materials, energy, and resources needed for production, transportation, and installation. The choice of cladding material significantly influences the magnitude of this increase. The conventional cement-plaster wall finishes with 0.19 $KgCO_2$/kg of embodied carbon contribute to the building's total embodied carbon, amounting to 25,869.80 $KgCO_2$. As illustrated in the ranking schedule in Table 2, the test building with conventional plaster shows the lowest embodied carbon and cost, primarily because no additional cladding was incorporated.

In contrast, the aluminum cladding panel, with an embodied carbon of 8.55 $KgCO_2$/kg, elevates the total building's carbon footprint to 267,829.20 $KgCO_2$, representing a 90.34% increase. These figures underscore the substantial impact of a material's embodied carbon on a building's overall sustainability profile.

It is important to note that while cladding may entail higher upfront costs and embodied carbon, it offers long-term benefits such as improved energy efficiency, enhanced durability, and aesthetic appeal. These benefits can justify the initial investments associated with cladding, especially when considering the building's lifecycle. Additionally, advancements in sustainable cladding materials and construction practices continue to drive improvements in environmental performance, mitigating the environmental impacts associated with cladding installations.

4.1. Energy Performance

The greenness of individual components within a building directly influences the overall sustainability of the building structure, its operation, and its energy efficiency [7]. The energy performance of the cladding materials was

Table 2. Performance-based ranking of uninsulated cladding materials

S/No	Energy per total building area (Kwh/m²)	Cooling electricity (Kwh/m²)	Building's embodied carbon ($KgCO_2$)	Cost	Building's mean annual operative temperature (°C)	Hours above 28 °C (South-facing wing)
1	Gravel Stone	Gravel Stone	Conventional Cement Plaster	Conventional Cement Plaster	Gravel Stone	Flax Shive Resin Bonded Board
2	Particle Board	Lightweight Metallic panels	Particle Board	Hardboard Solid wood	Lightweight Metallic panels	Foil-Laced, Glass Fibre-Reinforced Polyisocyanurate Board
3	Lightweight Metallic panels	Flax Shive Resin Bonded Board	Foil-Laced, Glass Fibre-Reinforced Polyisocyanurate Board	Resin-Bonded Fibre Board	Plate Glass	Polyurethane Cellular Board
4	Flax Shive Resin Bonded Board	Foil-Laced, Glass Fibre-Reinforced Polyisocyanurate Board	Expanded Impregnated Cork Board	Particle Board	Flax Shive Resin Bonded Board	Expanded Rigid Rubber Board
5	Foil-Laced, Glass Fibre-Reinforced Polyisocyanurate Board	Polyurethane Cellular Board	Gravel Stone	Polyvinylchloride (PVC) Tiles	Perlite Plaster	Particle Board
6	Polyurethane Cellular Board	Perlite Plaster	Perlite Plaster	Straw Fireboard	Foil-Laced, Glass Fibre-Reinforced Polyisocyanurate Board	Resin-Bonded Fibre Board
7	Perlite Plaster	Expanded Rigid Rubber Board	Polyurethane Cellular Board	Perlite Plaster	Polyurethane Cellular Board	Expanded Impregnated Cork Board
8	Expanded Rigid Rubber Board	Resin-Bonded Fibre Board	Resin-Bonded Fibre Board	Vermiculite Insulating Brick	Expanded Rigid Rubber Board	Hardboard Solid wood
9	Resin-Bonded Fibre Board	Expanded Impregnated Cork Board	Clay Tiles	Expanded Rigid Rubber Board	Resin-Bonded Fibre Board	Perlite Plaster
10	Expanded Impregnated Cork Board	Particle Board	Straw Fireboard	Cement-bonded Particle Board	Expanded Impregnated Cork Board	Straw Fireboard
11	Hardboard Solid wood	Hardboard Solid wood	Expanded Rigid Rubber Board	Expanded Impregnated Cork Board	Hardboard Solid wood	Lightweight Metallic panels
12	Plate Glass	Plate Glass	Flax Shive Resin Bonded Board	Flax Shive Resin Bonded Board	Straw Fireboard	Plate Glass
13	Straw Fireboard	Straw Fireboard	Cement-bonded Particle Board	Clay Tiles	Particle Board	Aluminium Panels (With Air Gap)
14	Conventional Cement Plaster	Conventional Cement Plaster	Vermiculite Insulating Brick	Foil-Laced, Glass Fibre-Reinforced Polyisocyanurate Board	Aluminium Panels (With Air Gap)	Gravel Stone
15	Polyvinylchloride (PVC) Tiles	Aluminium Panels (With Air Gap)	Burnt Brick Tiles	Polyurethane Cellular Board	Vermiculite Insulating Brick	Vermiculite Insulating Brick

Table 2 (cont). Performance-based ranking of uninsulated cladding materials

S/No	Energy per total building area (Kwh/m^2)	Cooling electricity (Kwh/m^2)	Building's embodied carbon ($KgCO_2$)	Cost	Building's mean annual operative temperature (^{0}C)	Hours above 28 ^{0}C (South-facing wing)
16	Vermiculite Insulating Brick	Vermiculite Insulating Brick	Hardboard Solid wood	Plate Glass	Polyvinylchloride (PVC) Tiles	Polyvinylchloride (PVC) Tiles
17	Aluminium Panels (With Air Gap)	Polyvinylchloride (PVC) Tiles	Polyvinylchloride (PVC) Tiles	Gravel Stone	Burnt Brick Tiles	Cement-bonded Particle Board
18	Cement-bonded Particle Board	Cement-bonded Particle Board	Plate Glass	Burnt Brick Tiles	Cement-bonded Particle Board	Burnt Brick Tiles
19	Clay Tiles	Clay Tiles	Lightweight Metallic panels	Lightweight Metallic panels	Clay Tiles	Clay Tiles
20	Burnt Brick Tiles	Burnt Brick Tiles	Aluminium Panels (With Air Gap)	Aluminium Panels (With Air Gap)	Conventional Cement Plaster	Conventional Cement Plaster

assessed across three key energy parameters: energy per building area, total electricity consumption, and cooling electricity. Analysis of Variance (ANOVA) test was conducted to evaluate the impact of cladding material choice on these energy metrics and shed light on the factors influencing the overall energy efficiency of the building. The results of the tests revealed significant variations in energy performance among the different cladding materials investigated. Across all three parameters, the choice of cladding material exerted a discernible effect on energy efficiency ($F(2, 57)=1285.59$, $p<0.05$). Specifically, the between-groups variance (SS=400067.0165) significantly exceeded the within-groups variance (SS=8869.009755) for all three energy parameters, showing notable disparities in energy performance across the range of cladding materials tested. The calculated F-statistic of 1285.59, coupled with a p-value of 3.82176E-48, highlights the statistical significance of these findings. Notably, with an alpha value of 0.05, the probability of observing such substantial differences in energy performance by random chance alone is exceedingly low.

The findings further reveal that gravel stone, occurring naturally as loose aggregates of rock fragments, exhibits the lowest energy consumption as a cladding material. In comparison, the building with cement-sand plaster has a total building energy per normalized floor area of 258.20 kWh/m^2. However, the Energy Use Intensity (EUI) decreased by 8% when clad with gravel stone. The energy savings achieved by gravel stone cladding are synonymous with similar investigations conducted by those who gained significant energy savings through cladding materials inclusion in the building envelope. It is essential to note that adding cladding does not entirely reduce energy consumption. For instance, materials such as polyvinyl chloride (PVC) tiles, vermiculite insulating brick, aluminum panels (with air gap), cement-bonded particle board, clay tiles, and burnt brick tiles all increased the EUI of the building (Fig. 4). Burnt brick tiles, for example, increased the energy use of the building by 2%.

Nevertheless, when insulation was attached to these cladding materials on the exterior of the test building, results differed. Remarkably, simply cladding the cement-plaster building with a polyurethane insulating board reduces the energy consumption of the building by 6%, offering the most substantial energy savings without further cladding (Fig. 5). Several factors contribute to this phenomenon, including variations in insulation effectiveness against the cladding materials, thermal bridging, air leakage, and interstitial condensation. This is evident from the condensation analysis conducted in the experimental setup, which produced the Glaser diagrams for aluminum cladding panels, clay brick, and PVC tiles cladding shown in Figure 6. These diagrams illustrate how adding cladding can inadvertently introduce thermal bridges or compromise the airtightness of the building envelope, thereby offsetting the intended energy-saving benefits.

Furthermore, certain cladding materials' inherent properties may result in poor thermal resistance or inadequate insulation, leading to increased heat transfer through the

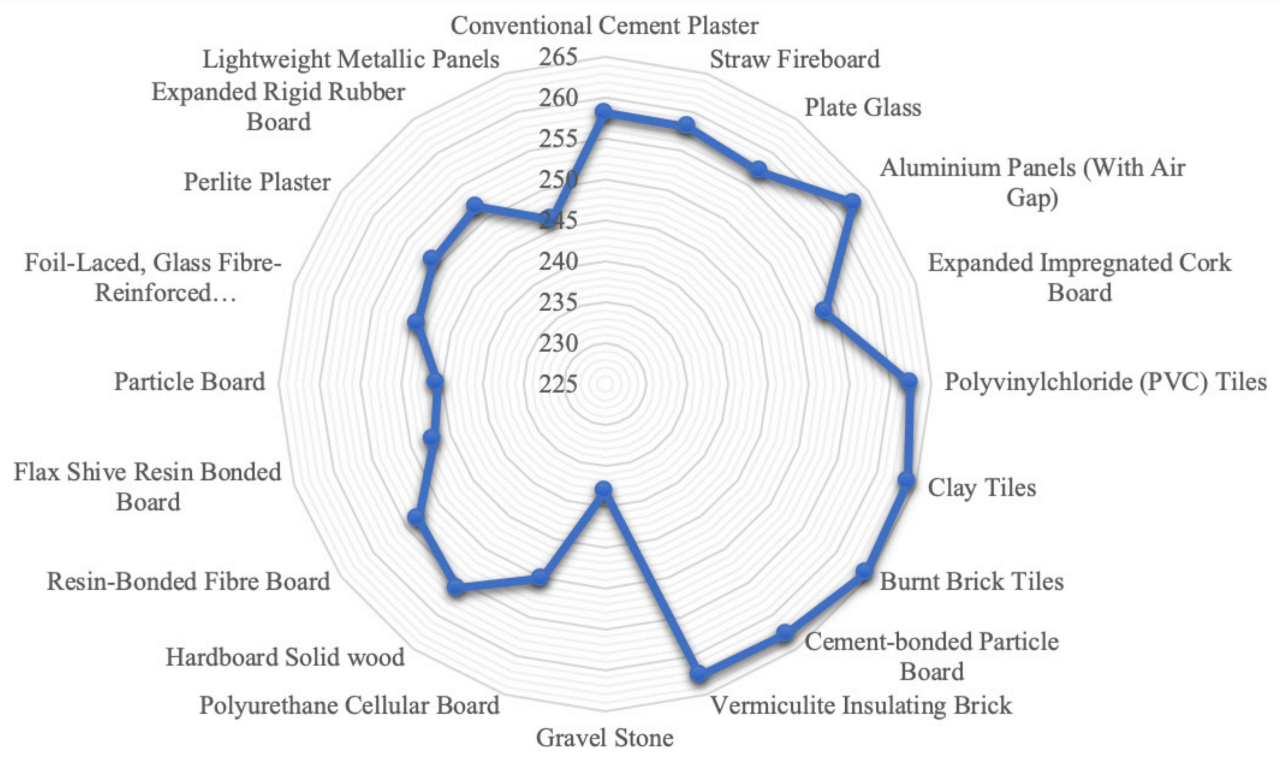

Figure 4. Energy consumption of uninsulated cladding materials.

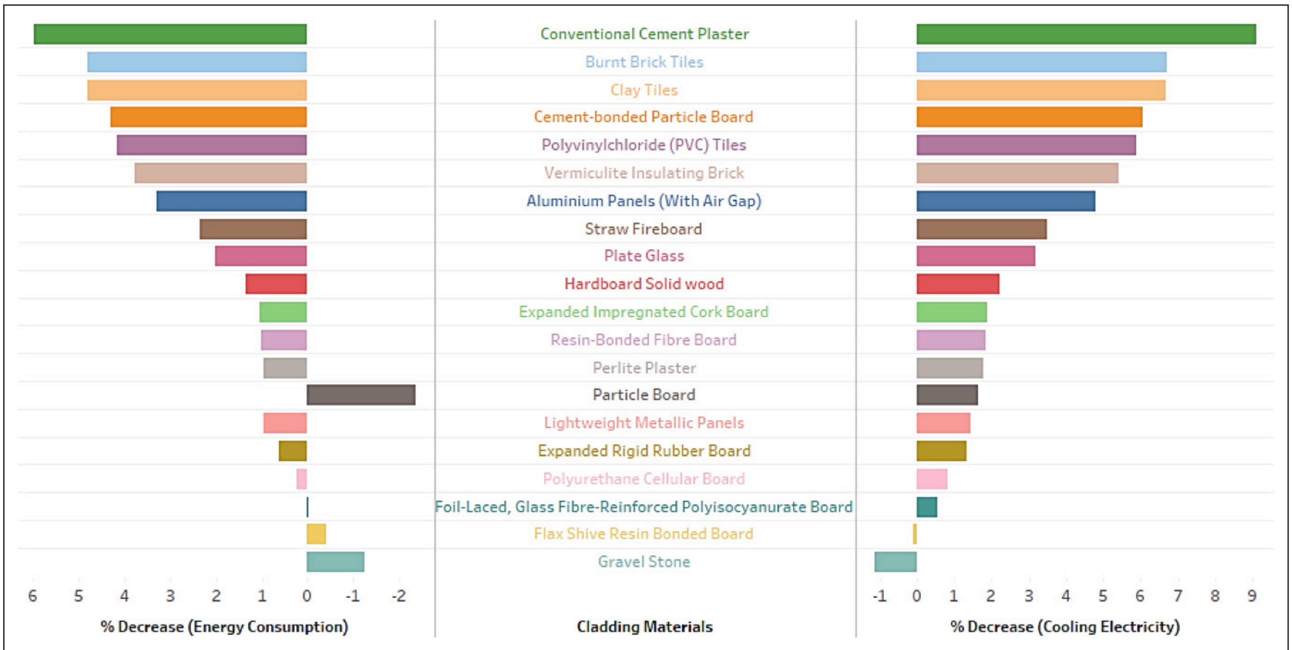

Figure 5. Energy savings on insulated cladding materials.

building envelope. Additionally, cladding installation and construction technique variations, which depend on the material type and design considerations, can further impact energy efficiency outcomes.

While Insulation can enhance the thermal performance of cladding systems by reducing heat loss or gain through the building envelope, its effectiveness may be influenced by interactions with other building components, such as windows, doors, and HVAC systems. In scenarios where insulation is added to cladding materials, the energy consumption of dissimilar materials can be affected differently. Materials with inherently poor insulation properties may experience minimal improvements in energy efficiency despite adding insulation. Conversely, materials with better insulation properties may benefit more from insulation additions, reducing energy consumption. Figure 7 compares the energy consumption of the cladding materials with and without insulation. The cement-plaster building exhibited

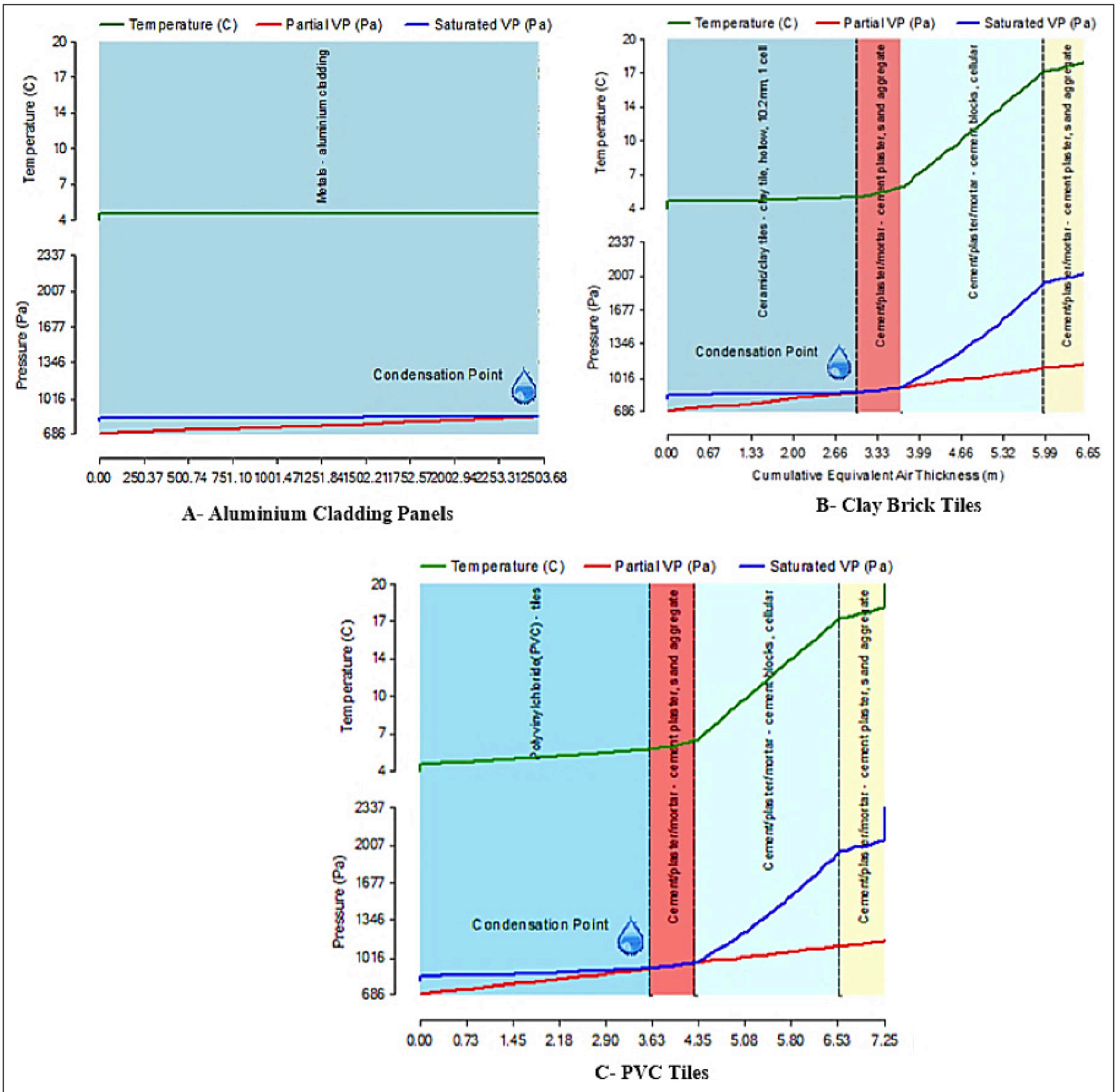

Figure 6. Glaser diagrams- Interstitial condensation on aluminum cladding panels **(a)**, clay brick tiles **(b)**, and PVC tiles **(c)**.

a notably higher energy consumption of 258.20 kWh/m² than the insulated scenario, where energy consumption decreased to 242.75 kWh/m². This considerable difference underscores the significant impact of insulation on building energy efficiency. The observed dramatic difference, particularly for the cement-plaster building, can be attributed to the insulation's ability to mitigate heat transfer through the building envelope. Insulation helps retain conditioned air within the building, reducing the need for cooling and thus lowering overall energy consumption. Additionally, the variation in energy consumption across different cladding materials further contributes to the range of values depicted in the figure.

While gravel stone maintains the lowest energy consumption for insulated buildings, it does not integrate well with the insulator used, resulting in an approximately 1% increase in EUI. The thickness of the insulation layer may not have been sufficient to provide adequate thermal resistance to mitigate heat transfer through the building envelope, leading to increased energy consumption. Certain cladding materials may exacerbate heat transfer or moisture issues, counteracting the intended benefits of the insulation layer.

Other materials in the top 25% with the least EUI in this study include particle board, lightweight metallic panels, flax shive resin-bonded board, and foil-laced glass fiber-reinforced polyisocyanurate board (Table 2). These materials show a comparative energy reduction of 5% in the case of particle board cladding and 3.5% in foil-laced polyisocyanurate board. On the other hand, cooling loads vary for these materials despite having a low EUI. Precisely, unlike other materials in the top 25%, the cooling load for particle board

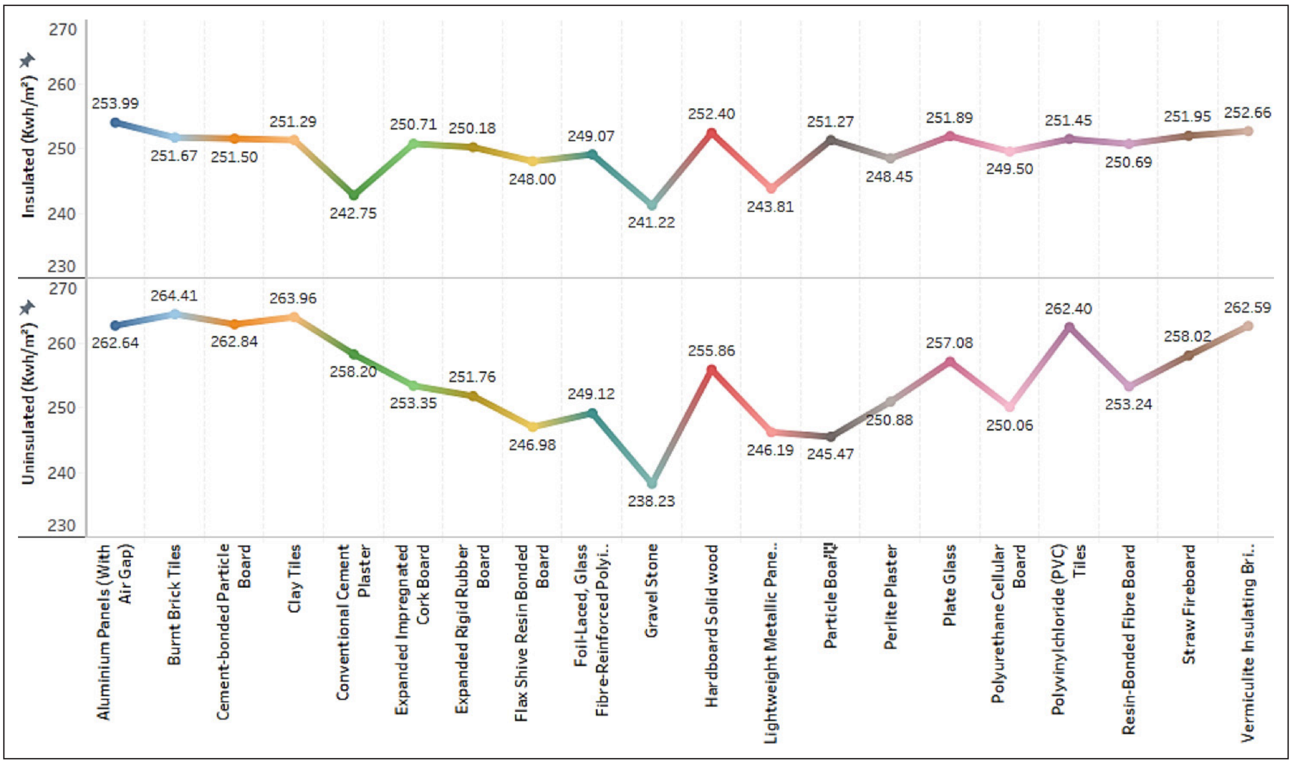

Figure 7. Energy consumption of cladding materials.

does not align with its reduced energy consumption. In the ranking of materials based on cooling load, polyurethane cellular board makes the list of the top 25%.

Gravel stone, without insulation, has the most significant savings on cooling energy, with an 11% reduction in electricity for cooling, compared to conventional buildings (Fig. 7). The potential of gravel stone to reduce indoor temperature was emphasized by Mediastika and Hariyono [30] and Hamoush et al. [33], who achieved a cooling load reduction of 4%. Conversely, materials at the bottom of the energy ranking include vermiculite insulating brick, aluminum panels (with air gap), cement-bonded particle board, clay tiles, and burnt brick tiles. Similar to an investigation by Taylor et al. [11], concrete, metal, and brick negatively impacted building performance. Their densities and conductivities may influence the energy performance of these materials. While aluminum cladding panels are proven effective in reducing energy consumption in hot climates [33], they increase energy consumption. Notwithstanding, lightweight metallic panels decreased energy consumption by approximately 5%. The selection of materials requires careful consideration, as their inherent properties can significantly impact thermal performance.

4.2. Cost and Embodied Carbon

The relative cost of building construction varies even within the same geographical region. The cost analysis presented in this study provides an overview of how cladding materials costs impact a building's budget. Choosing materials solely based on cost may have unintended environmental consequences. As highlighted by Takano et al. [14], an expensive building material can exhibit lower environmental impacts and offer high aesthetic quality. The findings of this investigation identify hardboard solid wood, resin-bonded fiberboard, particleboard, polyvinyl chloride (PVC) tiles, and straw fireboard as the top 25% most cost-effective materials.

Interestingly, only one of these materials, particle board, also ranks at the top regarding the most minor energy consumption, as discussed in section 5.1. This suggests that an inexpensive material can still positively impact a building's energy performance. Conversely, gravel stone, burnt brick tiles, lightweight metallic panels, and aluminum panels contribute to an increased building cost. To illustrate, while hardboard solid wood only marginally increases the building cost by 0.02%, adding aluminum cladding panels raises the building cost by approximately 6%.

The embodied carbon of a material plays a crucial role in a building's carbon emissions. The data collected for embodied carbon in this study excludes emissions arising from electricity consumption, as it was treated separately to assess specific impact areas. Table 1 shows that aluminum cladding and lightweight metal panels exhibit the highest embodied carbon (8.55 $KgCO_2/Kg$). The carbon data collected for buildings with these metal panels show a significant increase in embodied carbon, with about 37.88% and 90.34% increases for lightweight metallic and aluminum cladding panels, respectively. Materials with the least embodied carbon on the ranking table include particle board, foil-laced glass fiber-reinforced polyisocyanurate board, expanded impregnated cork board, and gravel stone. While particle board increases the test building's carbon by 0.2%, gravel stone adds to the building's carbon by 0.9%. Particle board presents the most minor carbon emission to the building, although it is not the material with the least inherent embodied carbon. The impact of cost on a building's embodied carbon shows that the most expensive materials also contribute to an increased building's embodied carbon. However, this should not be a primary criterion for selecting a cladding material, as a costly material can still reduce a building's carbon footprint. Gravel stone, for example, is ranked as one of the most expensive materials in this study but does not significantly increase the building's carbon emissions.

Notably, a t-test analysis conducted to compare the building's embodied carbon and associated cost revealed a statistically significant difference between the mean values of the two variables. The calculated t-statistic of -10.805 shows a substantial difference between the means, with the mean cost significantly lower than the mean embodied carbon. Furthermore, the p-value obtained for both one-tailed (7.44981E-10) and two-tailed (1.48996E-09) tests is extremely small, well below the used significance level of 0.05. This shows compelling evidence against the null hypothesis, supporting the assertion of a significant difference between the means. Practically, these results imply that while some materials may offer lower initial costs, they may entail higher environmental costs in terms of embodied carbon. Conversely, materials with lower embodied carbon may have a higher financial expense. This trade-off necessitates careful consideration during the material selection process to balance environmental sustainability and economic viability in building projects.

4.3. Indoor Comfort Level

The simulations conducted in this study were performed under-regulated indoor HVAC conditions. The choice of cladding material and system had minimal impact on the average indoor operative temperature of the building annually. Despite the test building with cement-sand plaster exhibiting the highest mean annual operative temperature, no cladding material achieved a reduction of 1°C. Nevertheless, gravel stone emerged as the cladding material, providing the best average yearly temperature for the building, which was 27.32°C. Gravel stone has a unique combination of properties that contribute to its effectiveness in enhancing indoor comfort levels. Its high thermal inertia enables it to absorb heat during the day and release it gradually at night, promoting temperature stability within indoor spaces.

Additionally, gravel stone exhibits exceptional heat absorption and radiation characteristics, complemented by its natural insulation properties. Studies have proven that the opaque nature of gravel stone also helps maintain lower indoor temperatures, further enhancing comfort levels. The exceptional performance of stone cladding in hot climates is further corroborated by Hamoush et al. [33], who suggested that the uniqueness of stone for indoor comfort and energy savings can be further harnessed when engineered.

Despite these advantages, the research uncovered unexpected findings regarding the performance of wood-based cladding materials on the south-facing wing, which is the most exposed part of the building on a typical sunny day. Specifically, resin-bonded, polyisocyanurate, and polyurethane boards showed slightly fewer discomfort hours annually than gravel stone (Fig. 8). This divergence can be attributed to the lower surface temperatures exhibited by wood-based products when exposed to direct sunlight.

Adding insulation with these claddings further enhanced indoor comfort for these materials. Initially, the range of discomfort hours the materials without insulation provided varied from 6.5°C (Flax Shive Resin-Bonded Board) to 23°C (Clay Tiles). But, with insulation added to the cladding materials and the cement-plaster building, the range narrowed to 6.5°C (Cement-Plaster Building) and 7.0°C (Lightweight Metallic Panels), emphasizing the significance of insulating buildings. The challenge of solar gains on the south-facing wing can be effectively controlled by retrofitting solar shading mechanisms to block the sun's rays [54, 55], enhancing energy efficiency. It is worth noting that while these measures can contribute to increased operational costs for retrofit projects [56, 57], they offer valuable solutions for managing solar gains and improving overall building performance.

4.4. Implications for Nigeria's Built Environment Sector

Nigeria aims to achieve net-zero emissions by 2060, as declared during the COP26 Climate Summit. The country was the 25th largest global emitter of greenhouse gasses in 2019, with the potential to meet 59% of its energy consumption needs by 2050 [58] through sustainable building practices with renewable energy integration. Significant benefits will ensue if the necessary building stakeholders embrace critical aspects of the research findings, including a reduction in carbon emissions within the built environment and a notable shift towards achieving net-zero carbon and emission reduction targets. Sustainable building practices with local materials foster better environments and reduce dependence on imported materials. Moreover, these practices could prompt government investment in more sustainable and low-carbon materials research, laying the groundwork for a resilient and eco-friendly built environment.

The research findings also shed light on the complexities of sustainable materials for projects within the Nigerian built environment industry, emphasizing the intricate considerations involved in material selection and building energy performance enhancement. This holistic perspective goes beyond surface aesthetics to address long-term environmental impact and sustainability. Amidst the dynamic landscape of sustainable building construction, industry stakeholders must balance the allure of aesthetically pleasing materials with the imperative to prioritize ecological performance. While initial costs may pose significant challenges, as expounded previously, the enduring cost-effectiveness and return on investment of green technologies offer promising opportunities to reshape Nigeria's construction sector.

With Nigeria's urban population projected to double its current figure by 2067 [59], the demand for sustainable housing solutions becomes increasingly urgent. Em-

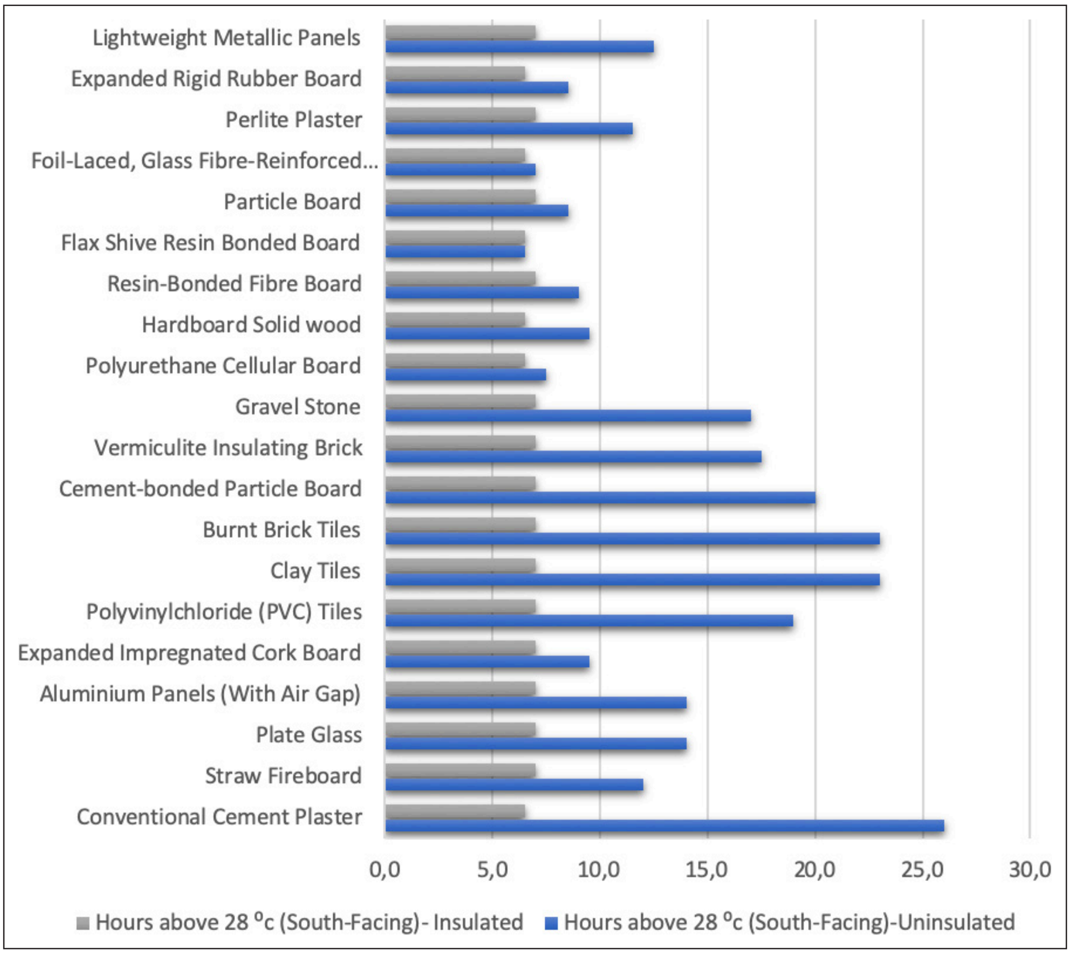

Figure 8. Discomfort hours generated by cladding materials.

bracing environmentally conscious materials in building design reduces operational costs, enhances property values, and drives job creation. Adopting green building initiatives aligns seamlessly with Nigeria's emissions reduction targets and climate resilience goals. However, realizing the full economic potential of sustainable practices requires proactive measures, including establishing green building policies and standards by policymakers and industry stakeholders [60–62]. Integrating renewable energy systems and locally sourced materials can strengthen Nigeria's energy security and resilience, reducing dependency on imported resources. Collaboration across governmental, industrial, and academic sectors is essential to overcome barriers such as financing constraints and technical expertise gaps. In light of projections indicating that future buildings in Nigeria may face extreme outdoor temperature shifts [16], adherence to the research findings reduces expenses for retrofitting future buildings. Early incorporation of sustainable measures can pre-empt costly adjustments down the line.

Additionally, these practices enhance estate values for buildings, as environmentally conscious designs and materials increasingly appeal to investors and occupants, aligning with the growing demand for sustainable and resilient structures. In embracing sustainable building practices, stakeholders can attract foreign investment, foster innovation, and stimulate local industries. By conscientiously evaluating the environmental performance of materials and adopting sustainable practices, Nigeria can chart a path toward economic prosperity, environmental stewardship, and climate resilience.

5. CONCLUSION AND RECOMMENDATION

In an era marked by energy crises, practitioners in the building industry face the daunting task of mitigating the environmental impact of buildings, known as significant contributors to global warming. Sadly, there is no one-size-fits-all solution to address the energy challenges faced by the industry. Ongoing studies cover a spectrum of sustainability, from building fabrics and microenvironments to renewable energy sources and building user control measures, all aimed at enhancing building energy efficiency, especially in the tropics.

This research significantly contributes to the evolving knowledge base on building sustainability, specifically by exploring the environmental impact and indoor comfort benefits of various cladding materials on a hypothetical building in Nigeria's temperate dry climate. Foreseeing substantial future investments by the government to enhance the building energy performance of the existing housing stock, this paper provides an experiential background for future research. It offers a comprehensive guide for cladding selection in the region, particularly for retrofit projects involving cement and plastered walls. Recognizing that a single criterion cannot decide the most environmentally friendly cladding materials, this study considered multiple factors, including energy user intensity (EUI), material and building embodied carbon, cooling load, and thermal comfort.

Using a ranking system for 19 cladding materials selected based on availability and feasibility in the region, compared to the cement-sand plaster building, simulation results reveal that only a few materials consistently reduce the EUI, embodied carbon, cooling load, and overheating hours of the building. In particular, gravel stone, particle board, and lightweight metallic cladding panels are the most energy-efficient in terms of energy consumed per building area. Gravel stone's superior performance can be attributed to its high thermal inertia, excellent heat absorption and radiation characteristics, and natural insulation properties. These properties allow gravel stone to stabilize indoor temperatures, reducing energy consumption and improving thermal comfort. On the other hand, particle boards and lightweight metallic cladding panels demonstrate energy efficiency and thermal comfort due to their inherent insulation properties, which help regulate temperature fluctuations and minimize heat transfer through the building envelope. Additionally, the reflective properties of metallic panels contribute to lower solar heat gain, further enhancing their performance in reducing cooling loads and overheating hours.

Concerning cooling load, gravel stone, lightweight metallic cladding panels, and flax shive resin-bonded board require the least electricity for cooling. Furthermore, gravel stone, lightweight metallic cladding panels, and plate glass provide the best operative temperature for the building annually. However, it is worth noting that these top-performing cladding materials can be costly, all making the list of expensive materials. Likewise, the simulations show that metals increased building costs and contributed to an increase in the building's embodied carbon by up to 90% compared to the test building with cement and plaster.

Significantly, gravel stone stands out as the most environmentally friendly material, whether or not the building structure is insulated. Nonetheless, adding a polyurethane board insulator to the exterior of the cement-sand plaster building shows promise for energy efficiency and thermal comfort, calling for further investigations. The insulating board might serve as an external fabric without added cladding, reducing the building's embodied carbon and comparative costs.

One limitation of this study is its geographical specificity to Abuja, Nigeria. Climate variations across different regions of the country may affect the generalisability of findings to locations with different climates. Nevertheless, the outcomes of this investigation provide a valuable trajectory for future researchers and building practitioners, emphasizing the need to look beyond the aesthetic and cost attributes in selecting façade cladding materials.

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ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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