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Optimizing Building Envelope Design for Cooling Loads Reduction in Abuja

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The increasing global urban population and its accompanying increase in energy demands have intensified the need for energy-efficient building designs, particularly in tropical climates like Abuja. This study explores optimizing building envelope components—insulation, high-performance glazing, and green roofs—to mitigate cooling loads and enhance energy efficiency. A theoretical review methodology was employed, synthesizing recent literature to assess the thermal performance of envelope systems. Findings reveal that improvements in insulation, advanced glazing technologies, and green roof integration can significantly reduce cooling energy consumption while promoting sustainability. The study provides practical insights for architects, engineers, and policymakers aiming to achieve thermal comfort and energy efficiency in Abuja's hot climate.

Keywords: Building envelope design, Cooling load reduction, Insulation in hot climates, Energy efficient window glazing, Green roofs, Energy conservation.

I. Introduction

According to data from United Nations, about 68% of global population will live in cities in the year 2050 (Nations, 2023). As global population increases, housing stock inceases in number leading to increased energy consumption in buildings relating to heating and cooling (IEA, 2013).

Climate change and increasing global temperatures are realities of today requiring global efforts to mitigate. The built environment is both a major contributor to global greenhouse gas (GHG) emissions and the most vulnerable to climate change induced phenomena (Browne et al., 2024)

Cities in developing countries are not exempt from these realities. More than half of Iran's population currently live in cities and this figure is predicted to rise up to 66% by the year 2050 (Vakilinezhad & Khabir, 2023). Urbanisation in Egypt is causing energy consumption for cooling to rise above 50% (Ragab & Abdelrady, 2020).

According to the National Building Energy Efficiency Code (BEEC) of Nigeria in their technical study published in 2017 reported that energy used in cooling a single residential house, multi apartment building and office building are 144, 163 and 249Kwh/m2/year accounting for 50%, 71% and 87% respectively. In hot climates like Abuja, much of the energy consumption is used for cooling. According to the IEA, a huge amount of energy consumption in buildings located in tropical climates mainly consist those consumed by Ventilation, Air Condition and Heating (VACH) systems and although this consumption depends on many other factors, the major contributor is thermal transfer through the building envelope systems between the internal and external building environment. Tropical climates are characterised by increased cooling loads as a result of poor envelope performance. Therefore, achieving improved envelope properties can be a potential for achieving energy efficiency and energy security in tropical climates. The efficiency of VACH systems depend on a number of factors including envelope, climate and occupant behavioural patterns. in urban areas, UHI effects can increase urban microclimate by up to 4 degrees and energy consumption by up to 25% (Chiradeja et al., 2023).

Buildings with inefficient envelopes, including poor insulation and glazing, exacerbate cooling loads and energy use. Optimizing the building envelope—through improved insulation, high-performance glazing, and green roofs—can significantly reduce cooling energy demands and improve thermal comfort. This paper explores strategies to optimize building envelope components to enhance energy efficiency and reduce cooling loads in Abuja's hot climate, with a focus on practical solutions for both new and existing buildings.

Aims and Objectives

This paper aims to explore and analyze available literature on optimizing building envelope properties to reduce cooling loads and achieve energy efficiency in Abuja's hot climate. It focuses on strategies to enhance the performance of building envelope components such as walls, roofs, and floors, minimizing cooling demands. Additionally, it examines challenges like airtightness, infiltration, and exfiltration that contribute to increased cooling loads. The study seeks to provide theoretical insights for architects, engineers, and policymakers on effective approaches to optimizing building envelope design for improved energy conservation.

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II. Method

This study adopted a systematic literature review (SLR) approach as a qualitative research method to analyze and synthesize existing scientific literature on optimizing building envelope properties to reduce cooling loads, with a focus on Abuja. The methodology was designed to ensure rigor and replicability in identifying, analyzing, and synthesizing relevant studies. The steps are outlined below.

III. Literature Search Protocol

A structured search protocol was employed to systematically identify relevant literature:

Search Strategy and Databases

Academic databases such as Google Scholar, ResearchGate, and ScienceDirect were used to source literature. The search utilized a combination of keywords and Boolean operators. Primary keywords included:

- Building envelope design
- Cooling load reduction
- Insulation in hot climates
- Energy-efficient window glazing
- Green roofs
- Energy conservation

Inclusion and Exclusion Criteria

Inclusion Criteria:

- Studies published between 2020 and 2024.
- Research focusing on tropical or hot climates.
- Studies discussing energy efficiency, cooling loads, and optimization strategies for building envelopes.

Exclusion Criteria:

- Literature unrelated to building envelope optimization.
- Studies focused exclusively on heating or other climatic conditions.
- Papers published outside the specified timeframe.

Selection Process

- An initial review of titles and abstracts was conducted to filter out irrelevant studies.
- Selected papers were subjected to full-text review to ensure alignment with the research objectives (Booth et al., 2021).

Thematic Analysis

A deductive thematic analysis, based on Braun and Clarke's (2006) framework, was employed to identify patterns and insights within the selected studies. The process involved the following steps:

- Familiarization with the Data: Thorough reading of selected studies to understand their content.
- Generation of Initial Codes: Coding key elements such as insulation, glazing, airtightness, and cooling load reduction.
- Searching for Themes: Grouping codes into broader themes, including building envelope performance, material optimization, and urban heat island mitigation.
- Reviewing Themes: Validating themes to ensure consistency with the study objectives.
- Defining and Naming Themes: Finalizing themes and aligning them with the study focus.
- Producing the Report: Synthesizing themes into a comprehensive narrative supported by evidence.

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A flow diagram of the thematic analysis process is presented in Figure 1.

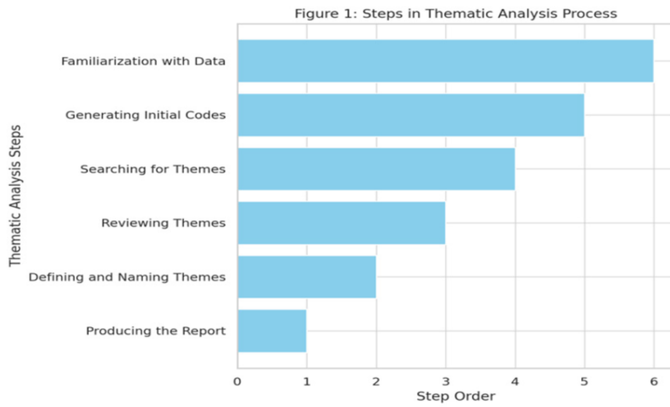

Figure 1: Steps in Thematic Analysis Process Source: (Braun and Clarke's 2006)

Schematic Literature Review (SLR)

To ensure comprehensive coverage, the SLR method was incorporated, comprising the following steps:

- Identification of Critical Elements: Key aspects of building envelope design, such as insulation, glazing, and green roofs, were identified.
- Critical Review of Sources: Each study was analyzed for relevance, methods, and findings (Petticrew & Roberts, 2008).
- Tabular Presentation of Results: Findings were summarized in a table (see Table 1), listing authors, publication year, study focus, methodology, and key findings.
- Checklist Development: A checklist of optimized building envelope strategies was developed to guide practical applications.

Table 1: Summary of literature findings

Author (s)	Year	Study Focus	Methodology	Key findings
Chiradeja et al.	2023	Urban heat island effects and energy consumption in hot climates	Quantitative analysis of urban microclimates	UHI effects increase microclimate temperatures by 4°C and energy consumption by 25%
Ragab & Abdelrady	2020	Energy consumption trends in Egypt's urban environments	Case studies and statistical analysis	Urbanization causes cooling energy consumption to exceed 50%
Vakilinezhad & Khabir	2023	Urbanization and energy efficiency in Iran's cities	Policy analysis and urban population trends	Urbanization projected to increase energy demands by 30% by 2050
Browne et al.	2024	Built environment and its impact on climate change	Review of climate and energy policies	Built environment is both a major GHG emitter and highly vulnerable to climate change

Source: (Petticrew & Roberts, 2008)

Acomprehensive summary table (Table 1) consolidates key findings from the literature, providing an accessible reference for architects, engineers, and policymakers.

Data Synthesis and Validation

Data extracted from selected studies were synthesized using Excel to ensure accuracy and consistency. Cross-referencing was employed to identify overlaps, resolve contradictions, and address gaps in the literature.

IV. Presentation of Findings

Findings from the literature review were presented in a narrative format and summarized in tabular form. Themes such as insulation techniques, glazing performance, and airtightness were mapped to their potential impact on cooling loads and energy

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efficiency, emphasizing practical applications for Abuja's hot climate.

Abuja Climate Data

Abuja's climate is classified as tropical wet and dry and is characterised by a warm rainy season and a dry hot season. The hot season is partly cloudy between January 29 to April 12 with the hottest month identified as March with temperatures between 21degrees Celsius and 35 degrees Celsius. The wet season is also usually warm but overcast, occurs between June 21 and October 6 with the coldest temperatures recorded in the month of December between 17 degrees Celcius and 30 degrees Celcius. Typically, the temperatures in Abuja range between 17 degrees Celcius and 35 degrees Celcius and hardly goes below 13 degrees Celcius or above 38 degrees Celcius (Abuja Climate, Weather by Month, Average Temperature (Nigeria) - Weather Spark, 2024).

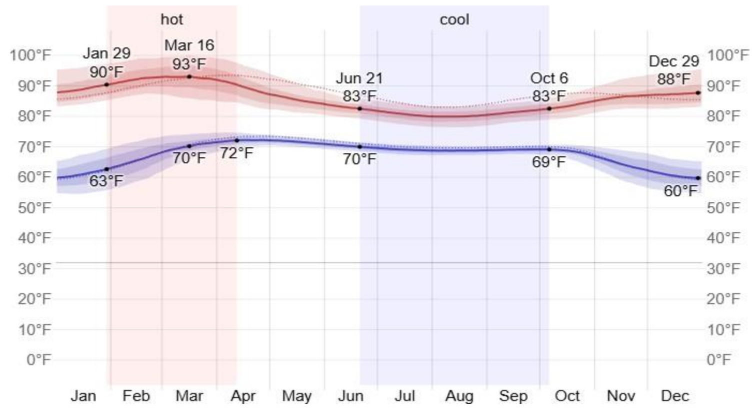

Figure 2: Average Temperatures in Abuja (Abuja Climate, Weather by Month, Average Temperature (Nigeria) Source: (Weather Spark, 2024)

V. Discussion

In hot climates, cooling loads are directly linked with the performance of the building envelope components. According to the International Energy Agency (IEA) in their 2013 publication titled Technology Roadmap, Energy Efficient Building Envelopes, building envelope components include roof, air leakage (airtightness, infiltration, and exfiltration), walls, windows and transparent facades, and ground floor slab/basement slab and walls. Optimizing the thermal performance of these components can greatly reduce cooling loads in buildings (Technology Roadmap - Energy Efficient Building Envelopes – Analysis - IEA, 2013). In hot climates like that of Abuja, buildings are exposed to very high amounts of solar heat radiation, requiring huge amounts of energy to maintain comfortable indoor air quality. According to recent studies done in Nigeria (Jegede & Taki, 2022., Adewale & Ene, 2024), due to the available level of technology, construction materials, and advancement of the construction industry, building envelopes do not perform optimally.

Jegede and Taki (2022) found that lowering the u-values of the ground floor, external walls, and roof achieved a reduction in operative temperature by 8% leading to a cooling load reduction of about 36%.

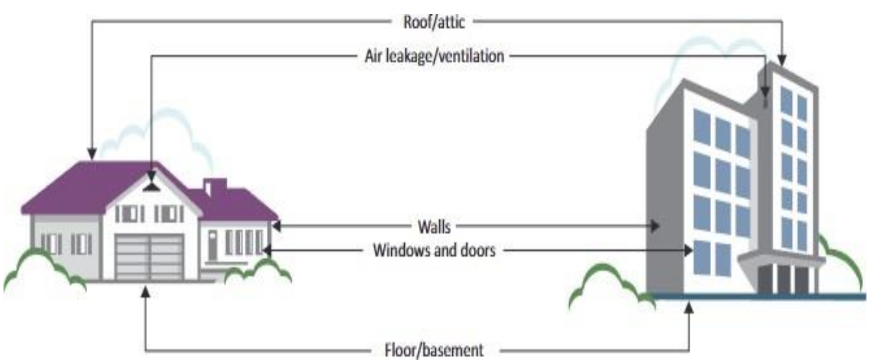

Figure 3: Building Envelope Components Source: (IEA, 2013)

Wall Insulation

Thermal transmittance (u-value), or sometimes referred to as thermal resistance is a measure of the rate at which heat is transmitted through a building component or an assembly measured in W/m2K (Rodriguez-Soria et al., 2014). Air is the medium of this transfer and it occurs through the boundary between conditioned space and unconditioned space. Thermal resistance provided by the external wall component of the building envelope represent a significant contribution to the overall thermal resistance of the entire building envelope system (Pourghorban et al., 2020).

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In Abuja, a vast majority of the building stock is built with external single-skin walls comprised of hollow blocks and structural reinforced concrete providing very low thermal properties. To address this, choosing the right type and thickness of insulation to apply to external walls depends on both cost analysis and cooling loads, which in turn are a function of the climatic type (Ozel, 2013)

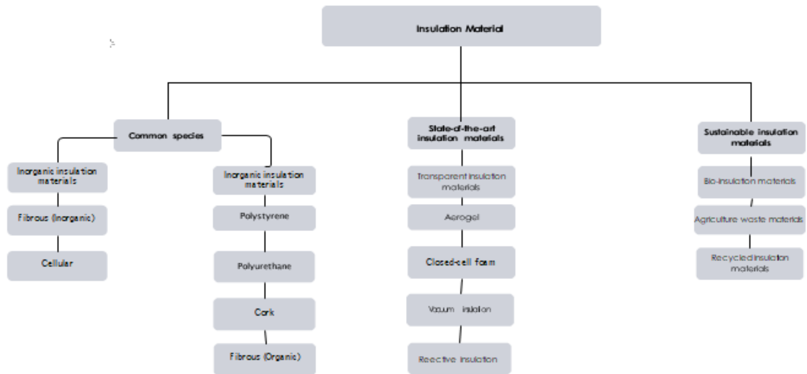

Figure 4: Classification of insulation materials for building application Source: (Dong et al., 2023)

A recent study in Morocco by Chihab et al. (2024) found that filling the cavities of a hollow clay wall with expanded polystyrene (EPS) significantly improved the thermal properties of the wall by reducing thermal transmittance by 30%, thereby reducing the thermal load by about 28% when compared to the traditional build up where the cavities are air-filled.

Pourghorban et al. (2020) explored the use of reflective insulation systems in external walls in hot-arid climates with a view to understanding their thermal performance. The study found that reflective insulation systems with an airgap of 20mm performed optimally reaching a reasonable balance between thermal resistance and material build-up. They also pointed out that their reflective properties helped reduce heat transfer by both radiation and convection.

High-Performance Glazing

In hot climates, windows and transparent envelopes systems present higher opportunities for heat transfers which in turn raise the air temperature in indoor environments, thereby increasing energy consumption for cooling and CO2 emissions (Chiradeja et al., 2023). High performance glazing design will improve the overall envelope performance. Recent studies (Magzoub et al., 2024, Ahmed & Asif, 2020, Chiradeja et al., 2023) have identified several technological advances in achieving higher thermal properties for windows and transparent facades.

As previously established, building glazing systems are more prone to thermal transfer, hence it is the starting point for building envelope optimization. Although the BEEC only stipulates a window-to-wall ratio (WWR) of 20%, there is a consensus among global researchers that improving the thermal performance of the building glazing system is crucial to achieving reduced cooling loads in tropical climates. Three main glazing techniques are identified: (1) Energy Active Windows (2) The use of multi- layer glazing (3) Application of Low Emissivity (Low-E) coatings on glass

Table 2: Glazing build up and its characteristics

Glazing type	No. of panes	Visible transmittance	Shading coefficient	Solar heat gain coefficient	U-value (W/m^2K)
Single-glazed clear 6 mm	1	0.88	0.95	0.81	6.4
Single tinted 6 mm	1	0.65	0.73	0.62	6.0
Double-glazed clear 6/12/6 mm	2	0.78	0.81	0.70	2.74
Double glazed clear low-e 6/12/6 mm	2	0.74	0.65	0.56	1.78

Source: (Mirrahimi et al. 2015)

Energy Active Windows

Energy Active Window (EAW) is a system of glazing that uses air movement to dissipate heat trapped between glazing panels. According to Magzoub et al. (2024), EAW possesses a very high potential for saving energy and resource management due to its ability to reuse waste air from VACH systems. Magzoub et al (2024) in their study in Saudi Arabia looked at achieving energy efficiency in buildings by employing multi-layer glazing and EAW design to maintain a low temperature on the internal surface of

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the window. They found that EAW increases glazing resistance to heat by reducing its thermal transmittance and can potentially reduce the energy used for cooling by up to 20%. They also found that increasing the air inlet velocity by 0.1m/s results in a reduction on inner glazing temperature by 0.17 degrees Celsius.

The use of multi-layer glazing

Due to their inherent build-up, double and triple-glazed windows and transparent facades possess a higher thermal resistance and a lower Solar Heat Gain Coefficient (SHGC). This system of glazing is able to achieve these properties due to the air gap between the glass panels acting as an insulation layer. In some cases, the air gap is filled with inert gases such as, Argon and Krypton to further reduce their thermal conductivity. Chiradeja et al. (2023) carried out a study in Thailand evaluating window systems and their Overall Thermal Transfer Value (OTTV), energy consumption, and cost of retrofitting existing buildings. Five glass configurations were tested, although one of the limitations of the study is the exclusion of triple-glazed build-up. The 5 configurations had 4 single-panel entries with different tint colors and 1 double-glazed entry. The different glass build-ups make varying degrees of energy savings and perform better than the base model. The highest energy savings was recorded with the build-up of double glass with an air gap in between accounting for the best reduction in energy consumption.

Application of Low Emissivity (Low-E) coatings

Somasundaram et al. (2020) studied the impact of Low-E coating on a double-glazed window for tropical climate applications to be used in retrofit projects. Their study emphasized the need to carry out optimization calculations between the lighting and cooling loads to achieve a balanced combination of solar film and Low-E based double glazing. This becomes a concern as the major function of the Low-E coating is to reduce visible light transmittance into indoor environments; therefore it should be used in areas with very high levels of daylighting to reduce glare and maintain recommended lux levels. Their study found a reduction in visible light transmittance by up to 75% achieving a reduced mean radiant temperature of 1.3 degrees Celsius at room centers and 1.9 Degrees Celsius at room corners leading to a reduction in cooling loads and a lightly higher set point for the room air temperature.

Green Roofs

External heat enter building interiors by convection through walls and roof surfaces. In hot climates, roof surfaces can reach very high temperatures (50-60 degrees Celsius) depending on the material of the roof and they are capable of reducing the surface temperature of the lower surface of the roof thereby leading to a reduction of internal air temperature. (Ngakan Ketut Acwin Dwijendra et al., 2023). Defining the term green roof refers to a roof that is either fully or partly covered by vegetation and whose structure comprises different components namely: waterproof structure, drainage system, insulation membrane, plant bed, and an actual plant (Ngakan Ketut Acwin Dwijendra et al., 2023).

Structure of green roof

Green roof is a recent approach in architecture aligning with global sustainability goals and achieving great results in improving the quality of urban environments and making them more sustainable (Ragab & Abdelrady, 2020; Ngakan Ketut Acwin Dwijendra et al., 2023; Jamei et al., 2023). Researchers have identified two distinct types of green roofs based on the height of their growing medium: less than 20cm is an extensive system, while higher than 20cm is an intensive system (Ragab & Abdelrady, 2020; Ngakan Ketut Acwin Dwijendra et al., 2023; Jamei et al., 2023). In conclusion, these studies highlights that green roofs are most beneficial in hot climates and, irrespective of the depth of their growing beds, are effective in reducing energy demand for cooling.

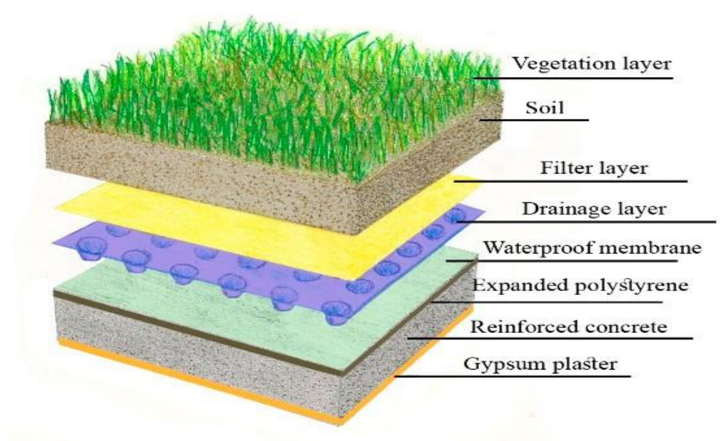

Figure 5: Layers of green roof Source: (Ragab & Abdelrady, 2020)

Green roofs help improve building energy performance in 2 main ways – (a) by improving the building insulation properties and, (b) by reducing the ambient temperature of the outdoor environment, and in both cases, there is a measurable reduction in cooling

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energy required by VACH systems (Ngakan Ketut Acwin Dwijendra et al., 2023). Jamei et al (2023) added that the main function of green roofs is to mitigate increasing urban air temperature, referred to as Urban Heat Island (UHI). Ragab and Abdelrady (2020) identified some challenges associated with green roof installations, they include the self-weight of the system in relation to the load-bearing capacity of the building structure making it somewhat challenging in retrofit opportunities, choosing appropriate drainage technique and waterproofing management to ensure the health and comfort of the occupants. As a result, the decision to include green roofs in new builds should be made early in the design phase to ensure appropriate provisions are made.

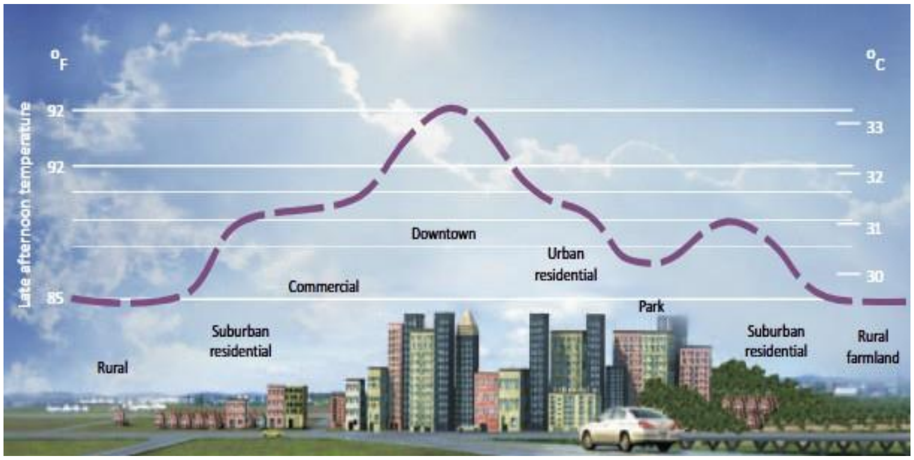

Figure 5: Urban heat islands increase energy consumption and pollution Source: (IEA, 2013)

Both Ragab and Abdelrady (2020) and Dwijendra et al. (2023) in their studies found that green roofs have the potential to reduce cooling loads by 30-40%. Additionally, Ragab and Abdelrady (2020) added that ambient temperatures recorded reductions up to 4 degrees Celsius. Similarly, Jamei et al. (2023) found that for hot climates, a planting medium of 40mm thickness when combined with a layer of insulation produced the most ideal configuration for achieving optimal results in reducing cooling loads. However, the study also established that no additional benefits will be added if the plant medium becomes thicker. Finally, integrating the system with an efficient irrigation system will heighten its performance.

Air Leakage, Airtightness, Infiltration and Exfiltration

Air leakage, infiltration, and exfiltration are all similar terms used to describe the flow of air through unintended openings in a building envelope system. Airtightness on the other hand directly impacts air leakage, infiltration, and exfiltration by reducing the air exchange through the envelope system (Mahmoud Magzoub et al., 2024). Poza-Casado et al (2020) in their study affirmed that airtightness plays a key role in achieving and maintaining thermal comfort in buildings, increasing the efficiency of VACH systems, and a reduction in cooling loads in hot climates like Abuja. Airtightness should be taken seriously as sustainability comes to the forefront of energy discussions in the building stock, whether in retrofit attempts or new buildings. The results from Poza- Casado et al (2020) show a significant impact from air infiltration through the envelope on energy consumption. In Spain, the impact was recorded to be more in heating due to its climatic type.

Ground Floor/Basement Floor and Slab Insulation

Thermal bridges occur in buildings at junctions between two or more envelope components such as the thermal bridge which exist between the ground floor walls and slab (Hameed Al-Awadi et al., 2022). In a study investigating building heat losses through slab on ground structures, Iwona Pokorska-Silva et al (2021) established that ground temperatures are formed by a number of different variables, comprising the soil structure, ambient temperature, vegetation cover, and the intensity of solar radiation. Due to the intensity of solar radiation present in hot climates, there is a huge potential for ground heat to permeate into air-conditioned spaces through existing thermal bridges in buildings thereby increasing the energy used by cooling systems to achieve thermal comfort in these spaces. As a result, insulation should extend to ground floor slabs and basement walls and slab where thermal bridges may lead to increased heat gains. Godlewski et al (2021) affirmed that insulated foundations have the potential to increase energy efficiency in buildings whilst also reducing operational costs.

V. Conclusion

Optimizing building envelope design is crucial for reducing cooling loads and enhancing energy efficiency in hot climates such as Abuja. This study has shown that improving key envelope components—such as insulation, high-performance glazing, airtightness, and the incorporation of green roofs—can significantly minimize energy consumption and ensure thermal comfort. While challenges like air infiltration and thermal bridging persist, they can be effectively addressed through thoughtful design and the selection of appropriate materials. The findings highlight the importance of prioritizing these strategies for both reducing operational costs and contributing to the broader goal of sustainable architecture. By adopting these energy-efficient solutions, buildings in Abuja can achieve substantial reductions in cooling energy demand, leading to economic and environmental benefits. In conclusion, this research calls on architects, engineers, and policymakers to embrace and implement these strategies to help create more sustainable and energy-efficient buildings in Abuja and similar hot climates.

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