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Investigating the impact of building materials on energy efficiency and indoor cooling in Nigerian homes

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ABSTRACT

Urbanization, technological advancements, and lifestyle changes result in varying use of energy consumption throughout a building's life cycle. Building materials play a significant role in determining the energy efficiency of a structure, making it crucial to assess its energy consumption. The goal of the study is to investigate the relationship between building materials and energy efficiency and to assess their impact on interior cooling in Nigerian residential buildings, to provide insights and recommendations for optimizing energy performance and enhancing thermal comfort. The study relied on literature reviews, a case study, simulation and energy performance analysis of a typical three-bedroom apartment in three main distinct climatic zones of Nigeria to investigate the impact of building materials on energy efficiency and indoor cooling. The psychometric chart emphasised the importance of sun shading, dehumidification, and cooling (with potential humidification) for achieving thermal comfort while the advanced simulation capabilities of the DesignBuilder software provided valuable insights revealing that in Maiduguri, Minna and Lagos, the use of insulations on the building fabric and shaders resulted in a remarkable 37.9%, 33.4%, 27.6% reduction in the annual cooling load, and leading to a decrease of 4549 kWh, 4122 kWh, 3280 kWh, electricity consumption annually respectively. The study findings emphasize the importance of selecting energy-efficient building materials and implementing effective design strategies to enhance thermal comfort and reduce energy consumption. By implementing the recommended strategies, substantial energy savings can be achieved, resulting in reduced electricity consumption, cost savings, improved comfort and contributing to the advancement of sustainable building practices in Nigeria and beyond.

1. Introduction

Building energy consumption is always growing due to population increase, high rate of urbanization, technological development, and lifestyle changes [1]. Around 40% of the world's energy is consumed by the building industry, which also emits 33% of CO^2 [2]. Energy efficiency is a crucial technique for reducing the cost of energy production, using natural resources, and mitigating climate change [3]. The main source of energy consumption, particularly in developing nations, comes from the residential sector [4]. For instance, in China and Malaysia, respectively, the second and third major energy consumers are in the residential sector [5]. The residential sector in Nigeria uses roughly 65% of the country's total yearly energy consumption [6]. As a result, the residential sector is a key area to consider as it relates to energy analysis for efficient energy. In carrying out building energy analysis, operational and embodied energy is essential. Operational energy is the quantity of energy needed to sustain the operational functions during the

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duration of a structure's lifespan such as lighting, appliances, heating, and cooling, etc. as opposed to embodied energy, which deals with the energy consumed during the construction of a building [7]. To create energy-efficient buildings, design and non-design techniques for retrofitting or behavioural modification are based on the evaluation of the energy performance of existing structures [8], thus it is essential to consider both the embodied energy of the building materials and how they both affect the operational energy use. Significant energy savings can be achieved in buildings if they are designed properly and constructed with the right building materials [9], and existing buildings need to be continuously assessed for energy integration and optimization [10]. The building materials become an important factor that affects that links both the embodied and operational energy and impacts them greatly. Thus, a key factor in assessing the structure's energy efficiency is the amount of energy required by the building components throughout their life cycles [11]. An important element in determining the building's energy efficiency is the quantity of energy utilised by the construction materials [12]. The justification for this study lies in the growing importance of energy efficiency and indoor comfort in residential buildings, particularly in the context of Nigerian homes. With the increasing population, urbanization, and lifestyle changes, there is a corresponding rise in building energy consumption and its environmental impact. The residential sector is a significant contributor to energy consumption in Nigeria and addressing energy efficiency in this sector can lead to substantial energy savings and environmental benefits. The goal of this article is to investigate the relationship between building materials and energy efficiency and assess their impact on interior cooling in Nigerian residential buildings, to provide insights and recommendations for optimizing energy performance and enhancing thermal comfort. The objectives of this study include evaluating the energy performance of Nigerian residential buildings using energy modelling software, analysing the impact of local climatic conditions on interior cooling requirements, and investigating how building materials can mitigate heat gain and maintain comfortable indoor temperatures. Furthermore, the study aims to conduct case studies of existing residential buildings in Nigeria in different climatic regions to assess the energy consumption and occupants' thermal comfort related to different building materials. The findings of this research will contribute to the state-of-the-art knowledge of building materials, energy efficiency, and interior cooling in Nigerian homes. The outcomes can inform policymakers, architects, and builders in making informed decisions regarding the selection and use of building materials, thereby promoting sustainable practices, reducing energy consumption, and improving the overall quality of residential buildings in Nigeria.

1.1. Nigerian energy consumption

Due to climate changes among cities and household forms, residential energy consumption varies greatly across geographical regions [7]. Individual and household situational variables that affect energy-related practices influence household energy use [13]. Several studies have found that socioeconomic statuses, such as income [14], home ownership [15], household size [16], dwelling type/size, and the number of appliances [17–19], have an impact on the variability of energy usage in households, as illustrated in Fig. 1. Furthermore, psychological characteristics such as occupant attitude, behavioural control, and awareness are significant determinants of energy usage [15]. Additionally, factors that may influence energy usage in buildings include building materials, tenant characteristics and behaviours, ventilation systems, artificial lighting and appliances, and building design [20]. Despite the enormous influence these elements may have on thermal comfort and energy consumption in buildings, Ochedi &Taki [20], contend that they may be handled using energy efficiency measures.

According to the BEEC [21], middle-income and high-income households consume energy in varying capacities. The chart in Fig. 1 unveils that in high-income households, ventilation and cooling amounts to 29% of the total energy consumed while in middle-income households only 10%. Moreover, lighting consumes 18% in the first and 27% in the second. Domestic usage like hot water and cooking amounts to 14% and 27% respectively while refrigeration is 12% and 21% respectively [22,23].

In Nigeria, residential households account for the largest share of energy consumption amounting to about 65% of energy usage with an estimate by the Nigerian Energy Commission that 72% of the population depends on fuel, wood and 70% of other traditional forms of energy sources for household energy supply [24]. With 80% of power generation coming from gas; and the remaining from oil,

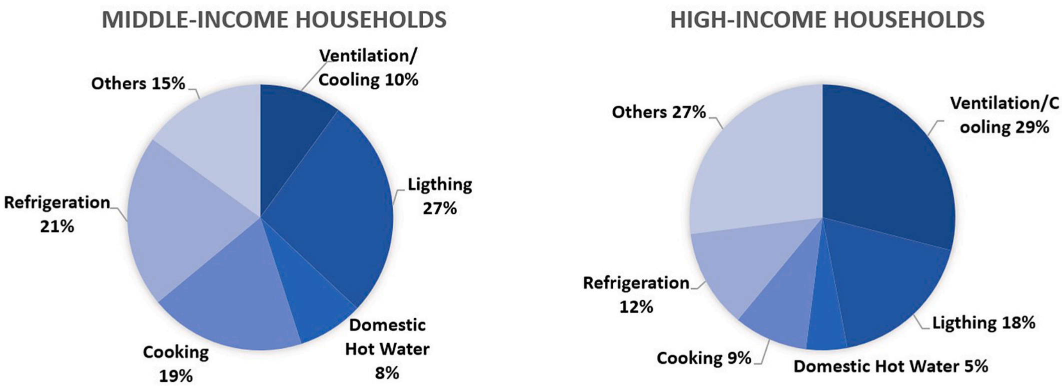

Fig. 1. Nigerian household energy consumption per income status.
Source: Adapted from National Building Energy Efficiency Code [21].

Nigerians' power consumption is also augmented by oil-fired backup generators. With natural gas being the major source of power, the new shift to solar power is a welcome idea [25].

With little than 39% of the Nigerian population without access to electricity and 90% without access to clean cooking energy [26], there is a need to reduce energy consumption to boost energy use efficiency. For effective energy management and efficiency in energy consumption, certain factors such as the architectural design practice, appliance efficiency in use and tenant behaviour are to be considered. To develop sustainable management of housing, energy-conscious plans and designs must be made within the built environment, improving energy use efficiency through better planning and design from construction to occupancy while considering the environment [27].

1.2. Common building materials used in Nigeria and their impact on energy efficiency

Climate and the availability of local building materials are important natural variables that influence and define the planning and implementation of architecture in various zones or places [28]. Mud and clay, which are plentiful natural resources in all areas of Nigeria, notably in the south, have been utilised to build. Houses made with earth are naturally cool in the summer and warm in the winter, requiring less usage of cooling or heating technologies and resulting in lower energy consumption in the structure. Wood is also another abundant resource although very sensitive as well. A wooden home provides strength and longevity to the structure while also delivering visual delight to its owners and builders throughout construction (bamboo). Although wood does not possess the cooling effect like clay, its durability prevents continuous repairs hence reducing energy consumption [28].

Stone has also been used as a valuable building material for domestic huts as well as recent buildings, especially in timber-scarce regions providing a cave-like sensation and intense load-bearing capacity as well as aesthetics make stone a useful building material. It also has abilities like clay especially to absorb heat making homes warmer in winter and reducing energy consumption rates [29]. Cement, glass, plaster and steel although not native to Nigeria also provide durability and thermal insulation capacity especially for buildings. With concrete being the most used building material in the world, constituted of binders like cement, lime and even mud, being either coarse or fine aggregate and mixed with water, it is seen as the second most consumed substance on earth and has the ability to endure high temperatures due to its high specific heat capacity and low thermal conductivity. Concrete does, however, need improvements in the heating and cooling systems of buildings which is a major contributor to worldwide energy consumption [30]. Glass also has been widely used especially in windows and doors as well as the interior aesthetic of buildings, with its excellent, thermal capabilities, the incorrect choice of glass and improper installation leads to poor performance of glass materials hence there is a failure of glass to properly insulate the house, especially in Nigeria where exposure to temperature changes is sudden and spontaneous [31].

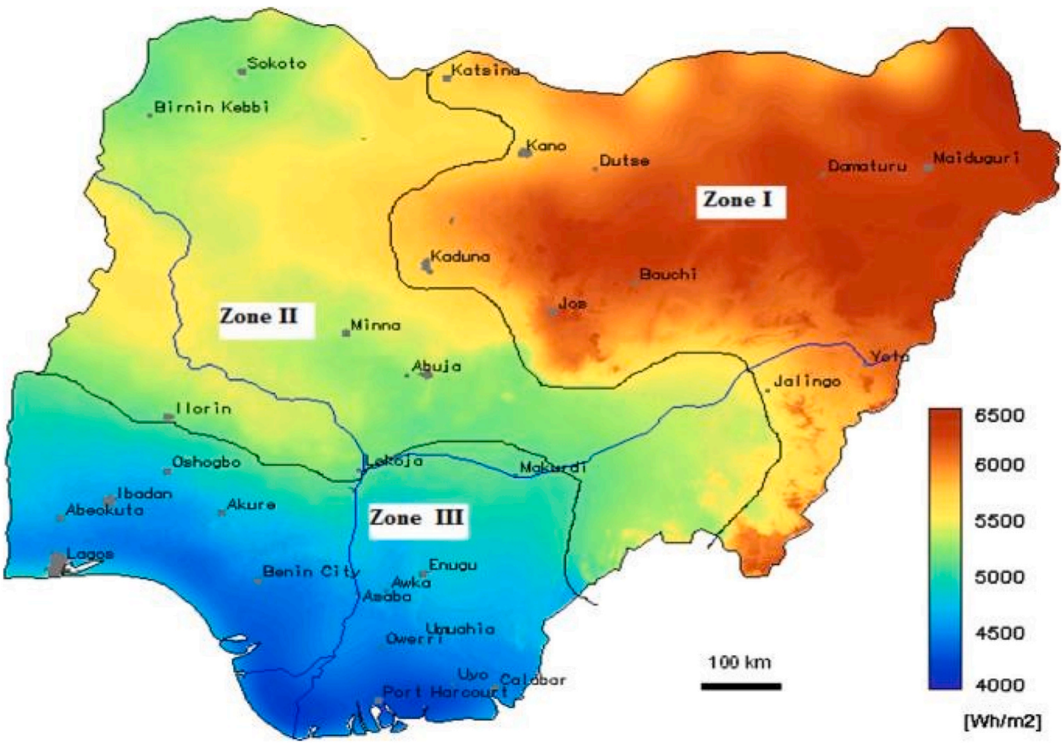

Fig. 2. Solar radiation zones of Nigeria.
Source: Demand side management and efficient lighting initiatives in Nigeria [33].

1.3. Climatic region and solar radiation zones in Nigeria

Due to climate changes among cities and household forms, residential energy consumption varies greatly across geographical regions [7]. Nigeria has three characteristic climatic conditions, the tropical monsoon climate in the south characterizes by strong rainfall from March to October. Its annual rainfall conditions range from 200 mm to a little over 4000 mm. Secondly, the tropical savannah climate characterizes wet and dry seasons from April–September and December–March respectively. It is also responsible for the harmattan winds from the Sahara and as much as 1200 mm of rainfall annually with seasonal flooding to go. Thirdly, the Sahelian or Semi-arid climate in the far north of the country experiences as little as 500 mm of rainfall but drier and solar-radiated weather conditions exposing vegetation and buildings to direct rays from the scorching sun as well as flash flooding because of high yearly weather variations [32]. These three distinct climatic regions characterise the three solar radiation zones in Nigeria as seen in Fig. 2.

The study areas are Maiduguri, Borno State in the northeast, Minna, Niger State in Northcentral and Ikeja, Lagos State in the southwest. These locations were carefully chosen to represent the three radiation zones in Nigeria with their various characteristics summarized in Table 1.

2. Methodology

2.1. Literature review

Firstly, a desktop study reviewed available literature to study to provide justification for the study and understand the concepts around building energy consumption, global energy consumption, building, materials and its effects on energy efficiency, climate and its effects on buildings. Such a methodology, which is crucial to mapping and evaluating the research area, motivating the study's goal, and justifying the research question and hypotheses [35], can be broadly characterized as a systematic way of compiling and synthesizing prior research [36,37].

2.2. Case study of the building

Secondly, in several domains and disciplines, academics have attempted to use the case study method [38–40]. Full observation, reconstruction, and analysis of the instances under study are important to help explain both the process and the consequence of phenomena [41], and this enables a researcher to carefully assess data within a particular context [42]. This study carried out a case study on a proposed typical three-bedroom apartment built in Nigeria. It consists of 3 bedrooms, a kitchen, a living, a dining room, a bathroom and toilets as seen in Figs. 3–5. The floor area of the house is 157.24m2, and the total area is 525m2. The volume of the building is 448.13m3. The building has a level above the ground of 0.6 m and is oriented towards the south. The windows are positioned on all sides of the building, facing south, east, west, and north. The HVAC (Heating, Ventilation, and Air Conditioning) system employed in the building is a split unit. The building was modelled using the Revit Architecture Software.

The walls are made of hollow blocks and externally rendered with a 275 mm block, which is hollow, lightweight, and covered with a 12 mm plaster render, resulting in a U-value of 1.86 W/m2K. The doors are made of wood and consist of a 3 mm plywood layer, a 34 mm thick foam core plywood door, and another layer of 3 mm plywood, contributing to a U-value of 0.230 W/m2K. The windows are made of glass with an aluminium frame, lacking a thermal break. They feature a single pane of glass and have a solar heat gain coefficient (SHGC) of 0.94, resulting in a U-value of 5.440 W/m2K.The roof ceiling comprises a suspended Polyvinyl Chloride (PVC) ceiling. Below the ceiling, there are layers consisting of a 25 mm screed, a 150 mm concrete floor, a 600 mm air gap, and a 12 mm gypsum layer. The combined layers contribute to a U-value of 1.450 W/m2K. The floor consists of ceramic tiles laid on a 150 mm thick concrete slab on the ground, resulting in a U-value of 0.470 W/m2K.

2.3. Simulation and energy performance analysis

2.3.1. Climate consultants 6.0

Milne et al. [43] stated that in order to achieve energy-efficient design, various building types must be used in various climates. To assist design professionals and homeowners in understanding the resources of their local environment and how it affects the

Table 1
The solar radiation zones in Nigeria.

Zones	Location	Annual Average of global solar radiation (kWh/m^2/day)	Sunshine duration (h/day)	Annual Average of solar energy intensity (kWh/m^2/year)	Altitude (m)	Latitude and Longitude
Zone I	Maiduguri, Borno State	5.7–6.5	6.0	2186	354	11.85°N, 13.083°E
Zone II	Minna, Niger State	5.0–5.7	5.5	2006	260	9.617°N, 6.533°E
Zone III	Ikeja, Lagos State	<5.0	5.0	1822	41	6.577°N, 3.321°E

Source: Adapted from Abam et al. [34].

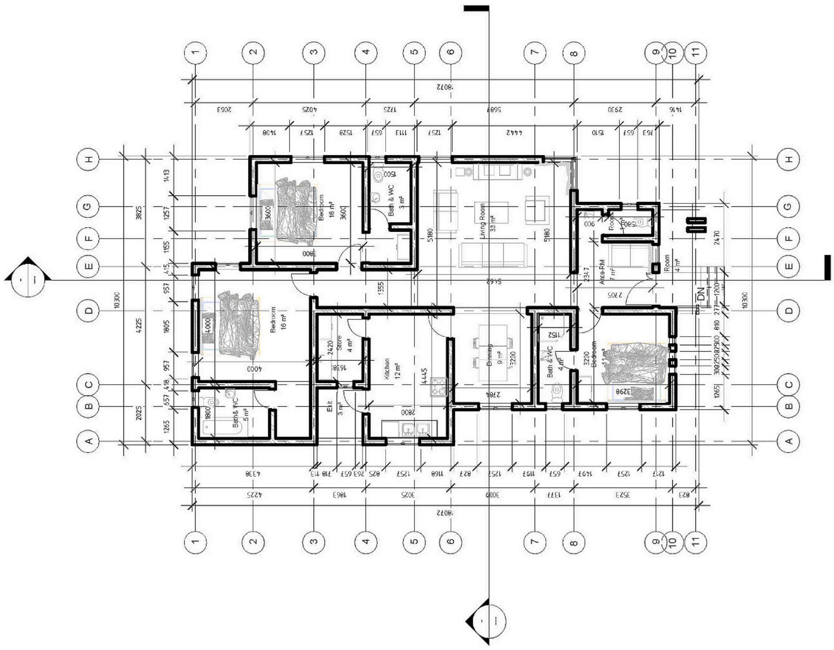

Fig. 3. The floor plan of the proposed 3 bedroom bungalow.

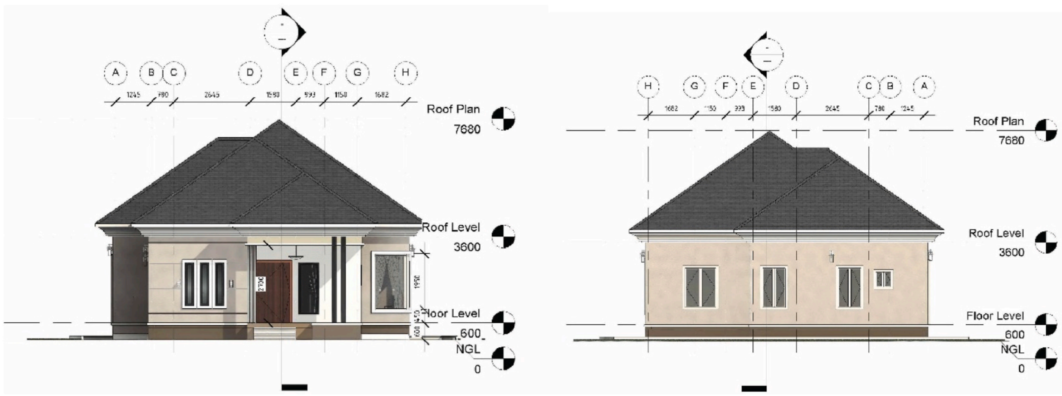

Fig. 4. A South and North Elevation view of the Proposed 3-Bedroom Bungalow.

performance of the structures, a climate consultant was created to achieve this. This study made use of the Climate Consultant version 6. Climatic Consultant 6.0 analyses and visualizes climatic data to inform building design and energy analysis. The Department of Energy provides the yearly 8760-h EnergyPlus Weather Format (EPW) format climatic data for free to thousands of stations worldwide.

2.3.1.1. Psychrometric chart. Climate Consultant 6.0 has a feature called a psychrometric chart. The temperature and humidity for each of the 8760 h in a year are shown by each dot on the psychrometric chart. Dots can fall into multiple strategy zones, leading to percentages exceeding 100% [44]. Specific zones on this map indicate various Design Strategies. The amount of time spent in each of the 14 Design Strategy Zones gives a general idea of the most effective passive heating or passive cooling solutions [43]. To produce a unique set of Design Guidelines, Climate Consultant 6.0 analyses the distribution of this psychrometric data in each Design Strategy zone [[43,44]].

2.3.1.2. Creating Design Guidelines for the building. The most effective passive and active design techniques were developed using the Climate Consultant programme and the weather files for Maiduguri, Borno State, Minna, Niger State, and Ikeja, Lagos State EPW. This resulted in a special set of design principles for the structure. The simulation by Climate Consultant likewise utilised the ASHRAE Standard 55 [45] as the comfort model. According to Milne [43], Climate Consultant is a graphic-based computer programme that aids users in designing more energy-efficient buildings that are each especially suited for their region in the world. It is very difficult to obtain weather files due to the difficulties in accessing the EPW and the fact that only 54 of Nigeria's 9300 expected weather observatory stations exist [46], but the climate data was obtained from climate.onebuilding.org, a repository of free climate data for building performance simulation. It includes climatic data from average meteorological years. Even though "EPW" is the preferred file format, each climate location also contains zip files for CLM (ESP-r weather format), WEA (Daysim weather format), PVSyst (PV Solar weather design format), DDY (ASHRAE Design Conditions or "file" design conditions in EnergyPlus format), RAIN (hourly precipitation in m/hr, where available), and STAT (expanded EnergyPlus weather statistic (Climate.onebuilding.org). Files with names like *USA_AK_Adak.AP.704,540_TMY3 (TMY3 dataset), BRA_AC_Feijo.AP.819,240_INMET (INMET dataset), and CHN_AH_Anquin.584, 240_CSWD (CWSD dataset)* are used to store data about organisations. The TMYx dataset was produced by the site's founders. TMYx files are typical meteorological data that are generated using the TMY/ISO 15927–4:2005 technique from hourly weather data in the ISD (US NOAA's Integrated Surface Database) till 2021. More than 16,100 TMYx sites are now accessible, according to Ref. [47].

2.3.2. DesignBuilder

Using the EnergyPlus simulation engine with the DesignBuilder as a Graphical User interface (GUI) to enable a comprehensive simulation of the energy consumption of the building [48], the DesignBuilder software was used to create an energy model with the building parameters from the case study. To run the simulations the EPW files gotten for each climatic zones (Maiduguri, Minna and Lagos) were used separately to run separate annual simulations for each building in their respective climatic regions. The annual existing energy consumption was analysed for each of the buildings. This simulation was further carried out on the building in each climatic region with the addition of insulation in the fabric of the building to analyze the energy performance and the annual consumption analysed. Thirdly, this same analysis was carried out on buildings in different climatic regions when insulation and window shades were included in the building and the annual energy consumption was analysed. Furthermore, a comparative analysis was done for the existing energy consumption of the building, the energy consumption of the building when insulation was introduced, and the energy consumption of the building, when insulation and window shades were included in the building in the three different climatic regions for each month, was analysed. Also, an energy graph was generated to reflect this analysis.

3. Results and discussions

The first sets of results emanated from the first simulation carried out using the climate consultant software. These results were discussed based on the three zones or climatic regions based on the study.

3.1. Climate consultant –psychrometric chart

The Psychrometric chart has presented several main ideas that, if implemented, will boost the bungalow's comfort level in their respective regions.

3.1.1. Zone I- Maiduguri, Borno State

As seen in Fig. 6, the comfort level for Maiduguri is 16.9% 1480 h of 8760 h and insignificant to achieving comfort in the buildings. To achieve thermal comfort in the building, the following strategies need to be implemented based on the psychometric charts as seen in Fig. 7.

- **Cooling, add humidification if needed**: Cooling is required for about 4478 h in a year, contributing 51.1% towards achieving thermal comfort.
- **Sun shading of windows:** The use of sun shading devices significantly improves comfort for a total of 2734 h, contributing 31.2% towards thermal comfort.
- **Dehumidification only**: Dehumidification is required for about 1204 h in a year, contributing 13.7% towards achieving thermal comfort.
- **Internal Heat Gain:** Internal heat gain contributes to 11.8% of thermal comfort, totaling 1033 h in a year. It refers to the heat generated within the building from appliances, lighting, and human occupancy. Employing energy-efficient appliances, LED lighting, and proper insulation can help minimize internal heat gain and maintain a comfortable indoor environment.

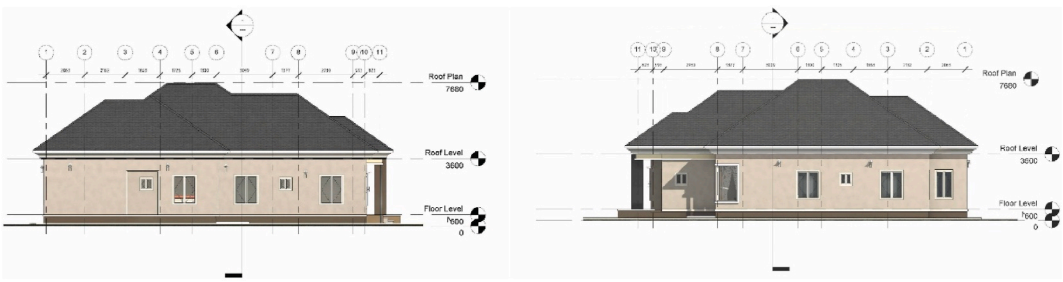

Fig. 5. A West and East Elevation view of the Proposed 3-Bedroom Bungalow.

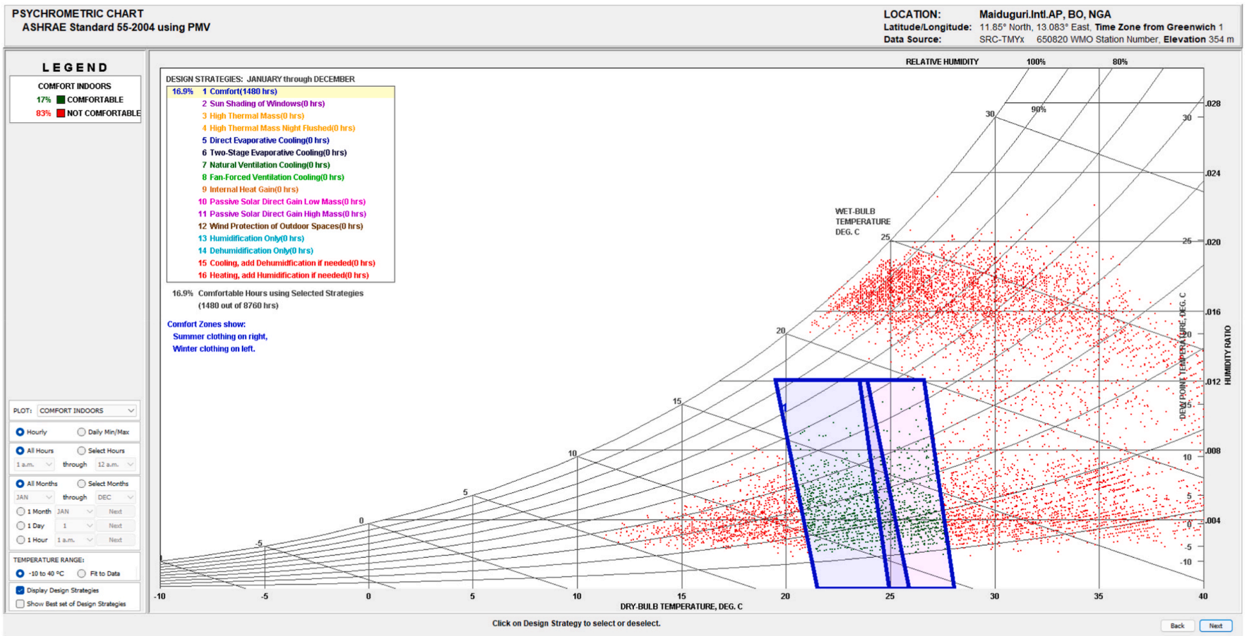

Fig. 6. Psychrometric chart Result for Maiduguri, Borno state showing the comfort level without selected design strategies.

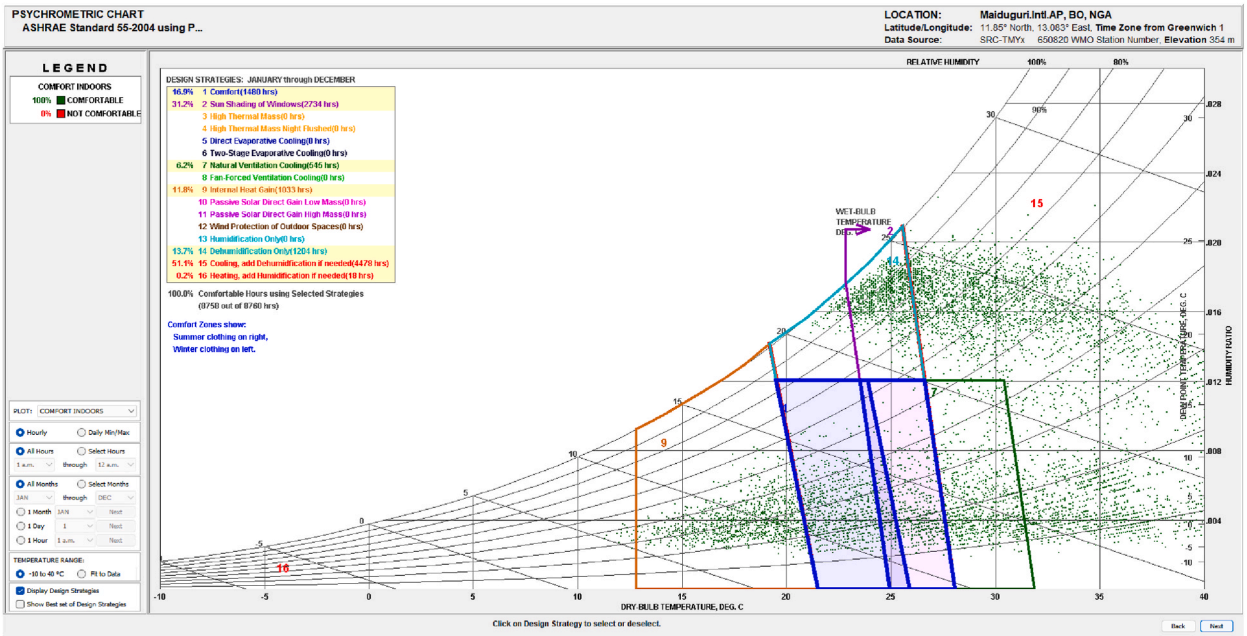

Fig. 7. Psychrometric chart Result for Maiduguri, Borno state showing design strategies to achieve indoor comfort.

- **Heating, add humidification:** Heating, along with potential humidification, accounts for 0.2% of thermal comfort, totaling 18 h in a year. This measure ensures warmth in colder periods and adequate humidity levels.
- **Natural ventilation**- The use of natural ventilation significantly improves comfort for a total of 545 h, contributing 6.2% towards thermal comfort. This will play a significant role in Maiduguri's hot and dry climate. Utilizing building designs that encourage natural airflow, such as operable windows and building orientation, can enhance cross-ventilation and provide a comfortable indoor environment without relying solely on mechanical cooling.

3.1.2. Zone II – Minna, Niger state

As seen in Fig. 8, the comfort level for Minna, Niger State as indicated by the chart is 13.1% (1146 out of 8760 h) and insignificant to achieving comfort in the buildings. In order to achieve thermal comfort in the building the following strategies need to be implemented based on the psychometric charts as seen in Fig. 9.

- **Sun shading of windows:** The use of sun shading devices significantly improves comfort for a total of 2655 h, contributing 30.03% towards thermal comfort.
- **Dehumidification only:** Dehumidification is required for about 2347 h, contributing 26.8% towards achieving thermal comfort.
- **Cooling, add humidification if needed**: Cooling, with potential humidification, is needed for approximately 4780 h, contributing 54.6% towards achieving thermal comfort.
- **Internal Heat Gain:** Internal heat gain contributes to 76 h, totaling 0.9% of thermal comfort. Minna experiences a transitional climate with moderate temperatures. Managing internal heat gain through energy-efficient appliances, lighting, and insulation can contribute to maintaining a comfortable indoor environment.
- **Natural Ventilation:** Natural ventilation helps decrease the cooling rate and contributes to 411 h, totaling 4.7% of thermal comfort. In Minna's transitional climate, natural ventilation can be employed to supplement cooling systems. Properly positioned windows, vents, or openings can facilitate airflow and enhance cross-ventilation, reducing the need for excessive mechanical cooling and promoting a comfortable indoor environment.

3.1.3. Zone III- Ikeja, Lagos State

As seen in Fig. 10 the comfort level for Ikeja, Lagos State is 0.7% (65 h of 8760 h) and insignificant to achieving comfort in the buildings. To achieve thermal comfort in the building the following strategies need to be implemented based on the psychometric charts as seen in Fig. 11.

- **Sun shading of windows:** The use of sun shading devices, such as blinds or shades, can significantly improve the comfort level of the bungalow. It is estimated that this measure will contribute to a 28.5% improvement in comfort for a total of 2495 h in a year.
- **Dehumidification only:** In certain climatic conditions where high humidity is a concern, dehumidification can be crucial to achieving thermal comfort in a building. In this case, dehumidification alone is required for a total of about 2790 h in a year, contributing approximately 31.8% towards achieving comfort.
- **Cooling, add humidification if needed**: In regions where both temperature and humidity levels are high, cooling becomes essential for achieving thermal comfort. In this scenario, cooling (such as air conditioning) is required for a total of about 5893 h in a year, contributing around 67.3% towards comfort.
- **Internal Heat Gain**: Internal heat gain refers to the heat generated within the building by various sources such as appliances, lighting, and human occupancy. In this context, internal heat gain is estimated to contribute to thermal comfort for a mere 5 h, which is equivalent to 0.1% of the year. In Lagos, where the climate is generally warm and humid, managing internal heat gain becomes crucial to maintain thermal comfort. This can be achieved by using energy-efficient appliances and lighting that generate

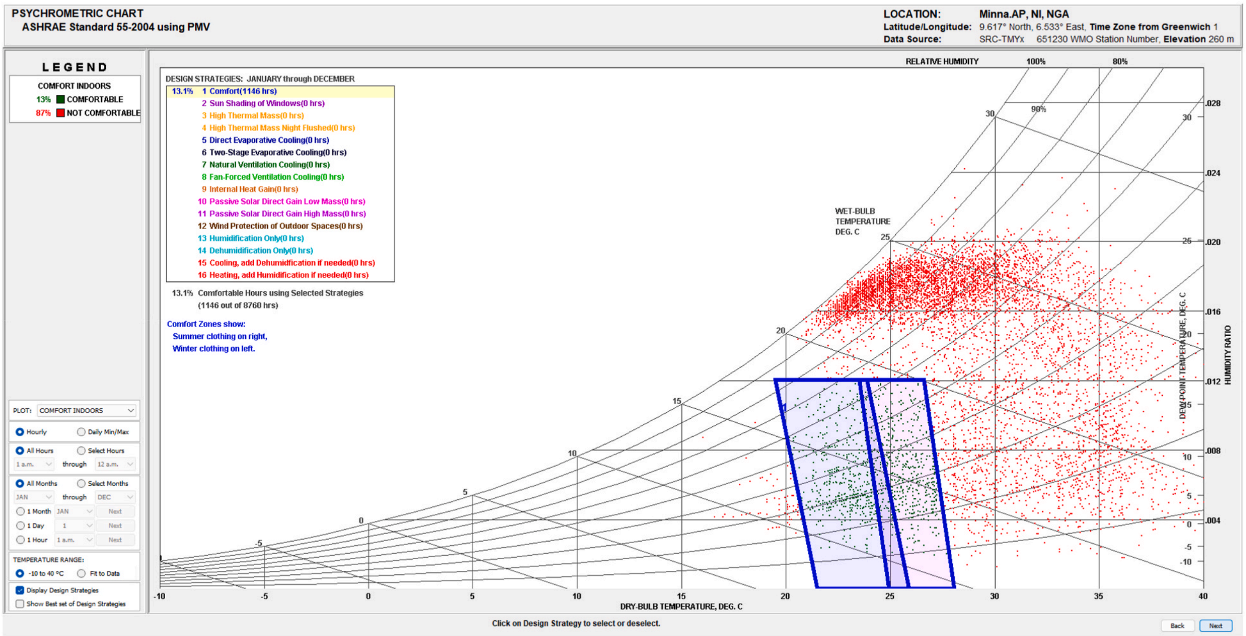

Fig. 8. Psychrometric chart Result for Minna, Niger state showing the comfort level without selected design strategies.

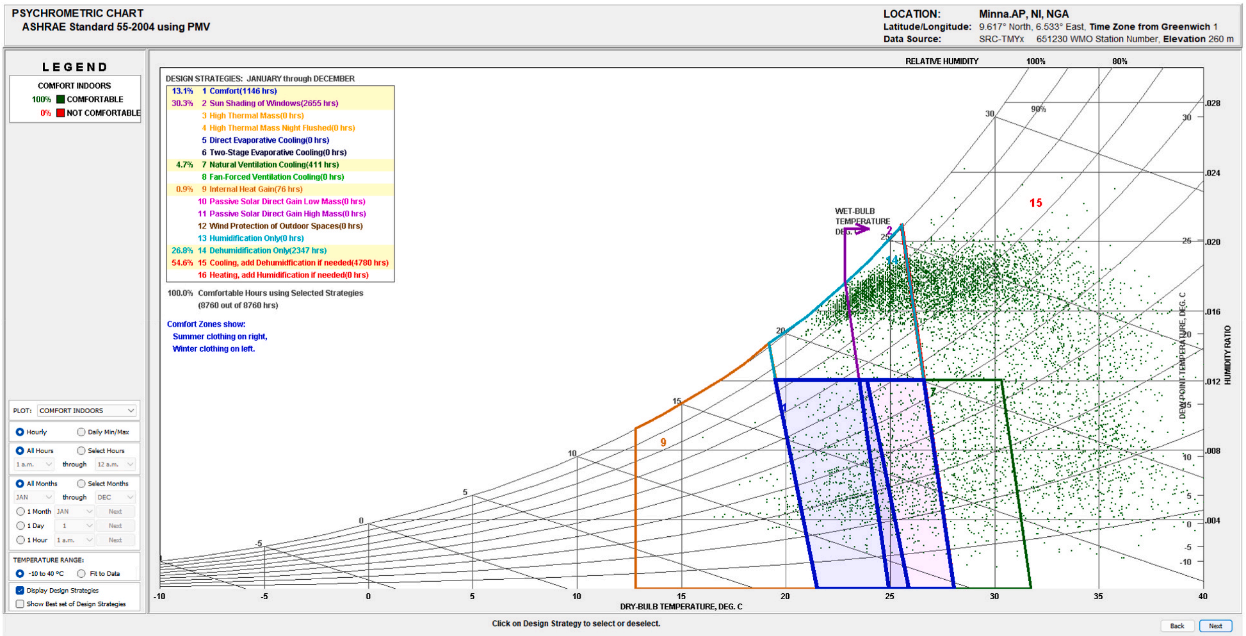

Fig. 9. Psychrometric chart Result for Ikeja, Lagos State showing design strategies to achieve indoor comfort.

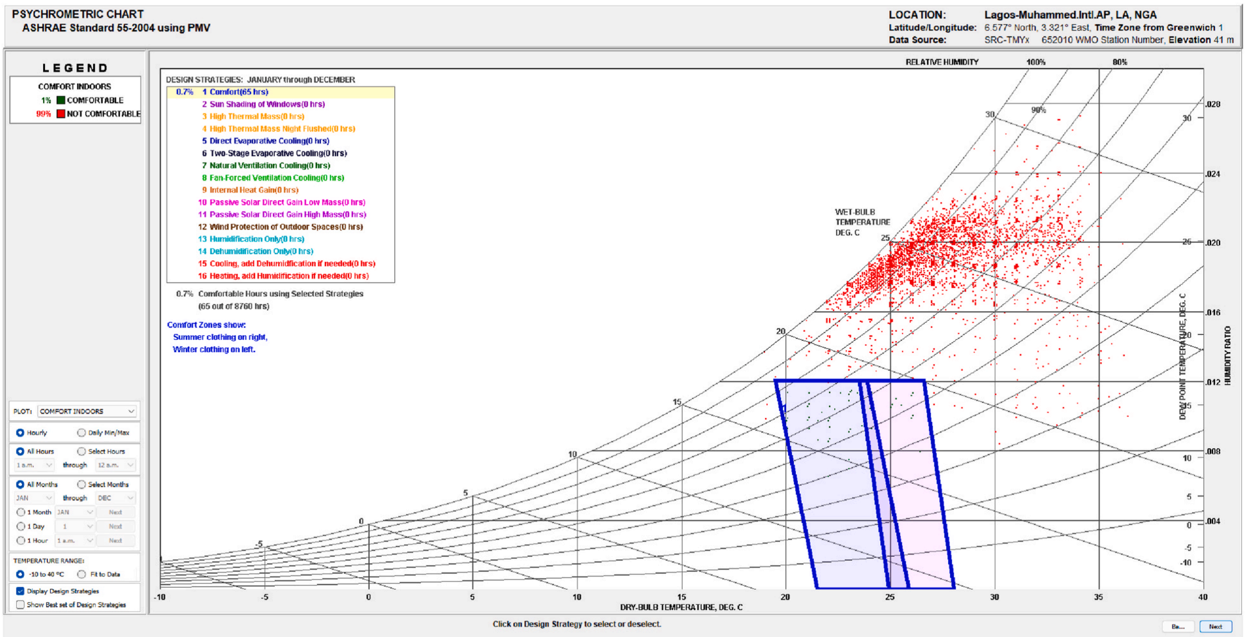

Fig. 10. Psychrometric chart Result for Ikeja, Lagos State showing the comfort level without selected design strategies.

less heat, implementing insulation measures to minimize heat transfer from the external environment, and optimizing occupancy patterns to reduce heat generation within the building.

3.1.4. Comparative analysis of the psychrometric charts for Maiduguri, Borno State; Minna, Niger state, and Ikeja, Lagos State

The results gotten from the psychometric chart emphasize the significance of sun shading, dehumidification, and cooling (with potential humidification) as the primary criteria for achieving thermal comfort. By implementing these strategies, it is possible to create a more comfortable and pleasant indoor environment for the occupants. Three primary approaches stand out throughout Nigeria's three regions, they are the sun shading of windows; dehumidification only, and cooling, add humidification if needed. In

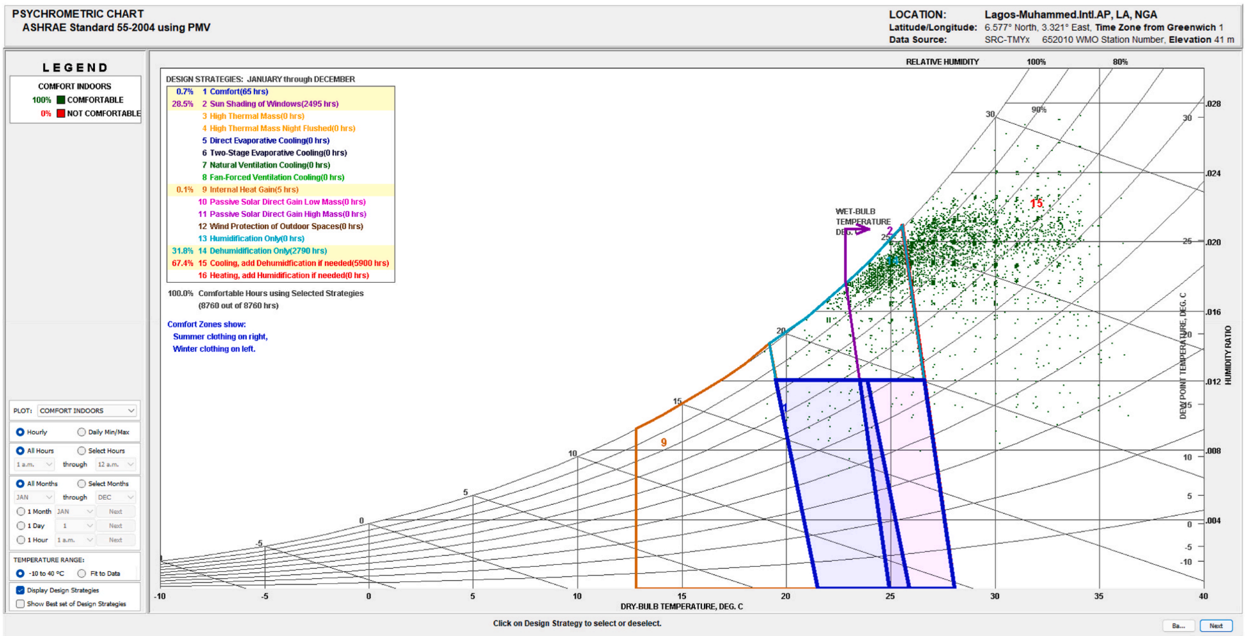

Fig. 11. Psychrometric chart Result for Ikeja, Lagos State shows design strategies for indoor comfort.

areas with extreme temperatures like Maiduguri, Borno State, sun shading devices such as overhangs or louvres are important for mitigating solar heat gain, while in Minna, Niger State, window awnings or natural shading through vegetation help maintain a comfortable indoor environment. In Lagos, sun shading devices like adjustable blinds or reflective window films are crucial due to high solar radiation. Dehumidification may not be a primary concern in Maiduguri due to low humidity, but in Minna, it can be used depending on conditions, and in Lagos, dehumidification systems are beneficial to prevent moisture-related issues. Cooling systems like evaporative coolers or air conditioners are necessary for Maiduguri and Minna, while in Lagos, air conditioning units can be installed, and if needed, humidification systems can be integrated to maintain suitable humidity levels.

3. 2. Simulation through DesignBuilder

DesignBuilder software tool was used for building energy analysis and thermal comfort assessments. In this analysis, a simulation was conducted on an existing building using consistent building materials from the case study across three different cities: Maiduguri, Minna, and Lagos State. The purpose of the simulation was to evaluate the energy performance and thermal behaviour of the building in these distinct climatic conditions. The building materials were used to create the existing energy model for the cooling load analysis. By performing the simulation in three different cities, the analysis aimed to capture the variations in climate and environmental conditions. Each location has its unique climate characteristics, including temperature, humidity, solar radiation, and wind patterns.

3.2.1. Zone I- Maiduguri, Borno State

The existing building's electricity consumption shows higher values throughout the year. The monthly cooling load ranges from 356.03 kWh in January to 1764.83 kWh in May, and the annual total is 12,676.61 kWh as seen in Fig. 12 and Table 2.

Analyzing the energy performance and efficiency of the building in Maiduguri in Table 2, the study observed that introducing insulation in the building fabrics helps reduce the cooling load. With insulation, the cooling load decreases compared to the non-insulated scenario. The monthly cooling load ranges from 371.14 kWh in January to 1297.91 kWh in May, and the annual total is 10,152.92 kWh. Additionally, the inclusion of sun-shading devices further contributes to reducing the cooling load.

With insulation and shading, the cooling load is even lower compared to the previous scenarios. The monthly cooling load ranges from 202.75 kWh in January to 1117.96 kWh in May, and the annual total is 8126.28 kWh. From the data, it is evident that the implementation of insulation and shading devices has a significant impact on reducing the cooling load, resulting in improved energy efficiency and reduced electricity consumption. The reduction in cooling load throughout the year indicates that the building can maintain more comfortable indoor temperatures and rely less on artificial cooling systems.

3.2.2. Zone II – Minna, Niger state

The existing building's electricity consumption shows higher values throughout the year. The monthly cooling load ranges from 790.73 kWh in January to 1556.48 kWh in April, and the annual total is 12,392.59 kWh as seen in Fig. 13 and Table 3.

Analyzing the energy performance and efficiency of the building in Maiduguri in Table 3, the study observed that implementing wall insulation in the building helps to reduce the cooling load. With insulation, the cooling load decreases compared to the non-

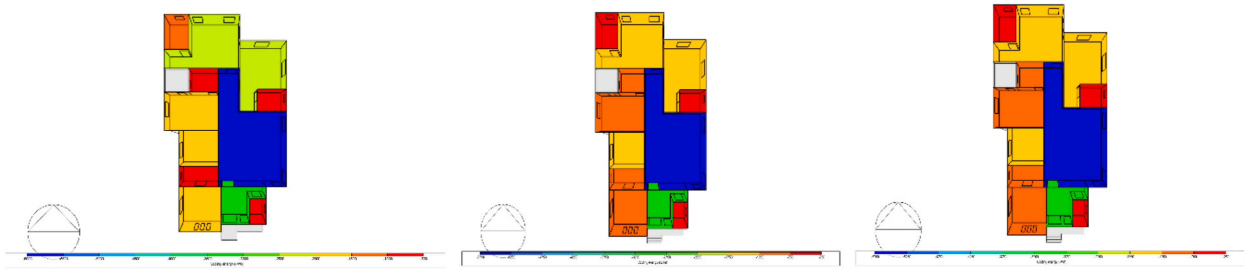

Fig. 12. Building energy consumption graph for existing cooling load, with insulation, and with insulation and window shaders for Maiduguri, Borno State.

Table 2
Energy Consumption for different scenarios in Maiduguri, Borno State.

Month	Exiting Cooling Load (kWh)	With Insulation Cooling load (kWh)	With Insulation and shaders Cooling Load (kWh)
Jan	356.03	371.14	202.75
Feb	596.03	520.75	365.41
Mar	1,138.29	875.08	720.66
Apr	1,566.67	1143.76	987.48
May	1,764.83	1,297.91	1,117.96
Jun	1,547.86	1,196.02	1010.86
Jul	1,192.85	976.91	793.80
Aug	959.67	831.36	673.33
Sep	1,156.29	948.91	796.44
Oct	1,255.19	971.26	804.80
Nov	758.31	622.39	439.23
Dec	384.60	397.44	213.57
Annual	12,676.61	10,152.92	8126.28

insulated scenario. The monthly cooling load ranges from 659.44 kWh in January to 1175.07 kWh in April, and the annual total is 10,100.89 kWh. Additionally, the inclusion of window shaders further contributes to reducing the cooling load. With both insulation and window shaders, the cooling load is further reduced compared to the previous scenarios. The monthly cooling load ranges from 495.29 kWh in January to 1034.20 kWh in April, and the annual total is 8270.08 kWh.

3.2.3. Zone III- Ikeja, Lagos State

The existing building's electricity consumption shows higher values throughout the year. The monthly cooling load ranges from 1111.45 kWh in January to 1350.523 kWh in March, and the annual total is 11,881.06 kWh as seen in Fig. 14 and Table 4.

Analyzing the energy performance and efficiency of the building in Ikeja Lagos in Table 4, the study observed that introducing insulation in the building fabric helps to reduce the cooling load. The cooling load decreases compared to the non-insulated scenario. The monthly cooling load ranges from 912.29 kWh in January to 1135.16 kWh in March, and the annual total is 10,336.80 kWh. Furthermore, the inclusion of shaders in addition to Rockwool insulation contributes to a further reduction in the cooling load. With both Rockwool insulation and shaders, the cooling load is lower compared to the previous scenarios. The monthly cooling load ranges from 746.19 kWh in January to 988.60 kWh in March, and the annual total is 8600.15 kWh.

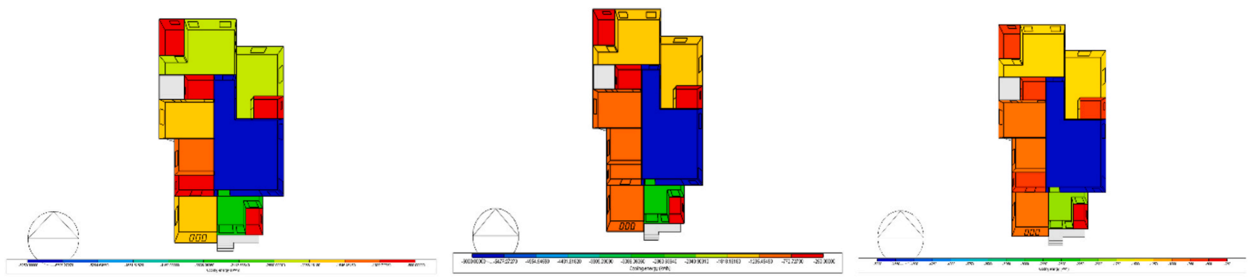

Fig. 13. Building energy consumption graph for existing cooling load, with insulation, and with insulation and window shaders for Minna, Niger State.

Table 3
Energy Consumption for different scenarios in Minna, Niger State.

Month	Exiting Cooling Load (kWh)	With Insulation Cooling load (kWh)	With Insulation and shaders Cooling Load (kWh)
Jan	790.73	659.44	495.29
Feb	1,105.94	820.57	688.66
Mar	1,490.73	1,152.58	1,010.95
Apr	1,556.48	1,175.07	1,034.20
May	1,366.39	1,107.73	947.05
Jun	1,004.72	848.84	696
Jul	835.92	723.03	570.26
Aug	612.58	601	458.97
Sep	748.82	681.38	543.20
Oct	979.56	831.02	665.43
Nov	1,001.58	780.03	614.79
Dec	899.15	720.20	545.30
Annual	12,392.59	10,100.89	8,270.08

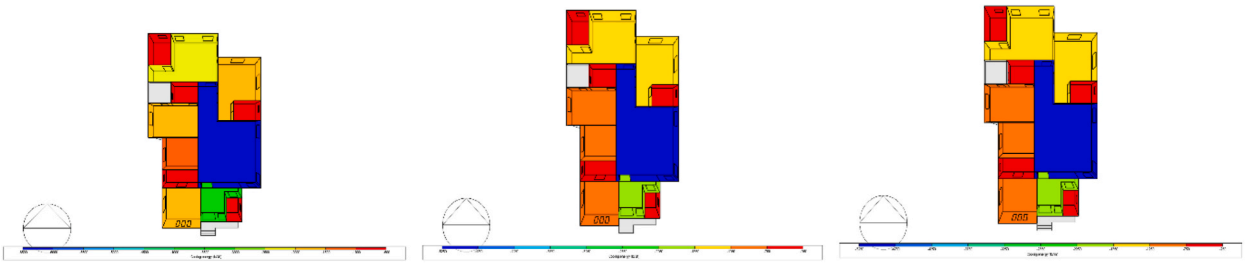

Fig. 14. Building energy consumption graph for existing cooling load, with insulation, and with insulation and window shaders for Ikeja, Lagos State.

Table 4
Energy Consumption for different scenarios in Ikeja, Lagos State.

Month	Exiting Cooling Load (kWh)	With Insulation Cooling load (kWh)	With Insulation and shaders Cooling Load (kWh)
Jan	1,111.45	912.29	746.19
Feb	1,144.48	941.20	805.06
Mar	1,350.53	1,135.16	988.60
Apr	1,311.59	1,122.40	980.10
May	1,028.74	909.27	763.54
Jun	766.33	711.83	563.58
Jul	727.07	678.90	535.04
Aug	667.99	640.73	508.36
Sep	697.99	649.87	524.97
Oct	817.16	742.69	612.24
Nov	1,027.74	890.42	741.24
Dec	1,230	1,002.04	831.24
Annual	11,881.06	10,336.80	8,600.15

3.2.4. Comparative analysis of energy consumption in Maiduguri, Minna, and Lagos

Comparing the result from Table 2, Tables 3 and 4 represented in Fig. 15, the energy consumption improved greatly by 19.91% for Maiduguri when insulation was introduced and 37.9% percentage when insulation and shaders were used compared to previous energy consumption. There was also a significant improvement for Minna by 18.5% when insulation was used and 33.4% when insulation and shaders were used compared to previous energy consumption. Furthermore, Ikeja Lagos State experienced significant energy improvement by 13% when insulation was used and 27.6%when insulation and shaders were used compared to previous energy consumption. The data indicates that the implementation of insulation in the building fabrics and window shaders has a significant impact on reducing the cooling load, leading to improved energy efficiency and reduced electricity consumption. The energy reduction in cooling load throughout the year demonstrates the building's improved ability to maintain comfortable indoor temperatures and decrease reliance on artificial cooling systems. The aforementioned analysis also agrees with the study of [49,50] with respect to the energy efficiency of buildings determined by the choice of materials.

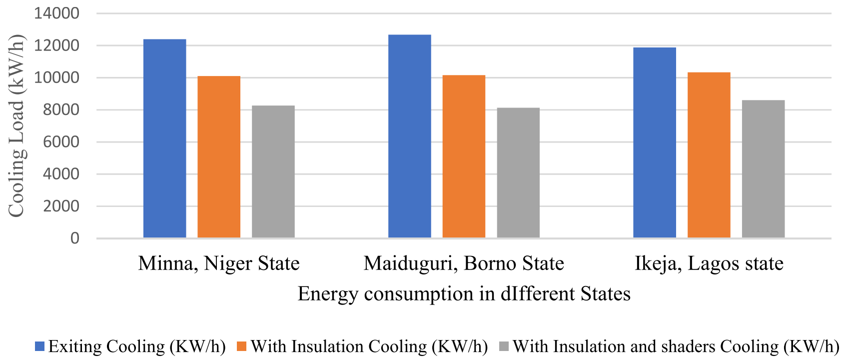

Fig. 15. Comparison of energy consumption in Maiduguri, Minna, and Lagos. PLEASE MOVE THIS TO THE END OF SECTION 3.2.4

4. Conclusions and recommendations

In conclusion, this research focused on examining the influence of building materials on the energy efficiency and interior cooling of Nigerian homes. Through the utilization of literature reviews, a case study, simulations and energy performance analysis, a thorough analysis were conducted, encompassing various elements such as walls, doors, windows, roof ceilings, and floors that comprise the building fabric. The research objectives were successfully achieved, leading to valuable insights and findings. The conclusion aligns with the literature review's recommendation for optimizing energy performance and enhancing thermal comfort, emphasizing the significance of considering local climatic conditions in building design and emphasizing the importance of building materials in enhancing energy efficiency and indoor cooling in Nigerian homes. By implementing the insights and recommendations derived from the study, such as the use of energy-efficient building materials and effective design strategies, substantial energy savings can be achieved. Also, the study's analysis of three distinct climatic zones in Nigeria further supports this notion, as it demonstrates the influence of climatic factors on interior cooling requirements and the effectiveness of building materials in mitigating heat gain. Furthermore, the study's evaluation of different building materials and their impact on energy performance supports the existing literature, highlighting the role of insulation, shading, and effective design strategies in reducing cooling load and electricity consumption.

The analysis of energy consumption data in the cities of Maiduguri, Minna, and Lagos highlighted the significant potential for energy savings through the implementation of insulation and shading strategies. The results consistently demonstrated that the introduction of insulation alone led to substantial reductions in cooling load ranging from approximately 79.9%–86.8% across the three cities. When shading devices were combined with insulation, further energy savings were achieved, ranging from approximately 61.9%–72.3%. These findings support the importance of incorporating insulation and shading devices in building designs to enhance energy efficiency and interior comfort. The utilization of energy analysis tools such as DesignBuilder proved instrumental in evaluating the energy performance of buildings and guiding design decisions. This highlights the significance of leveraging advanced technologies and software in the design and construction industry to optimize energy consumption and improve thermal comfort. Based on the research findings, several recommendations are put forward to enhance the energy efficiency and interior cooling of Nigerian homes. These include the promotion of energy-efficient building materials, the integration of insulation and shading strategies, the encouragement of natural ventilation techniques, the provision of design tools and guidelines, the need for awareness and education, and the call for further research in localized climatic zones. Implementing these recommendations will have substantial benefits, including reduced energy consumption, cost savings, improved indoor comfort, and environmental sustainability. It is crucial to raise awareness among stakeholders, including homeowners, builders, and policymakers, about the importance of energy-efficient building practices and the potential long-term advantages they offer.

The research recognizes certain limitations such as occupant behaviour and building management practices, were not extensively explored. Future studies could consider a broader range of variables to provide a more comprehensive understanding of energy performance in residential buildings. The study focused on a specific building in three climatic zones in Nigeria. While these locations provide valuable insights, the findings may not be generalizable to all regions in the country. Further research with a larger sample size and broader geographic coverage may enhance the study's applicability. In conclusion, this research contributes to the body of knowledge on building energy efficiency and provides practical insights for the Nigerian construction industry. By adopting the recommendations and embracing energy-efficient building practices, Nigerian homes can contribute to a more sustainable and comfortable built environment while reducing their environmental impact and energy costs.

Author contribution statement

Donatus Ebere Okonta: Conceived and designed the experiments; Performed the experiments; Analysed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data included in article/supp. Material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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