Thermal Performance Analysis of Residential Buildings in Nigeria: A Case Study of Sokoto State

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Abstract: ***Buildings' thermal functionality and effectiveness depend on the specifics of their designs, climate-responsive design criteria, how they are used on-site, and the specifics of their microclimate type and quality of their fabrics. In this research, four buildings with various system designs were the subject of an examination in the field. Systematically calculated hourly readings of surface and ambient temperatures were used to estimate indoor air. The R-squared value from the regression analysis indicated a very high link between the independent factors (Buildings I–IV) and the dependent factor. The fact that the F-value is substantial at 0.000 suggests that the effect of building types on the ambient temperature is significant. Furthermore, the results indicated that Building I, Building IV, Building III, and Building II had the greatest effects on ambient temperature among the different building types. The impact of Building II on the air temperature was the largest. To improve the thermal comfort of the other mass-content building types, it is advised that plasters be provided for Adobe walls, ceilings, shading, suitable positioning of the buildings, and an increase in the mass contents of the walls. To achieve internal comfort for the occupants, the article suggests that significant care must be paid to effective building construction and appropriate finish operations on walls.***

Keywords: Thermal Performance, Thermal Efficiency, Thermal Comfort, Overheating,

1. Introduction

The research on building thermal comfort has been in existence for over 40 years (Walker et al. 2020). Similarly, a building's thermal behavior is influenced by the degree of thermal controls installed inside the building and the weather outside (Stavrakakis et al. 2012). The human body is a highly adaptable entity. Most individuals can survive under unique environmental circumstances but must use thermo-regulatory mechanisms to adapt to environmental changes to survive up to their full potential (Stavrakakis et al. 2008). Therefore, he needs a setting that is within the limits of his potential for adaptation. When the climate changes in an abnormal way, a response that is beyond its capacity for adaptation is needed, and disease may result. Buildings are used to house people and keep the environment in a state that ensures they can live as comfortable as possible. To create the microclimate necessary for human survival, buildings are used. It establishes areas for all human activity. Buildings are crucial microclimate modifiers, as noted in (Rodriguez, Medina, and Pinzón 2019). The building required proper natural lighting, and insulation to avoid environmental temperature and humidity variations, prevailing winds, and rainfall. Additionally, it has been noted that the discomfort caused by harsh weather conditions can be lessened by the availability of environmental services (Mishra, Loomans, and Hensen 2016). Building design should consider variables like temperature, relative humidity, and sun radiation (Salamone, Belussi, Danza, Galanos, et al. 2016). Thermal comfort controllers such as building thermostats are required to react to occupancy status in the building to OFF/ON HVAC (Heating, Ventilation, and air conditioning) system to manage energy use and preserve thermal comfort for occupants. To enhance thermal comfort, tropical building designs—particularly those in warm, humid climates—should aim to reduce internal heat gain and optimize the building inhabitants' ability to cool down. According to a study by (Park and Rhee 2018) analysis, acceptable indoor comfort requires proper consideration of important parameters such as site selection, building size, shape, and wind direction. These parameters can help the thermostat to ensure occupant comfort is not compromised even if the HVAC system setpoint temperature is set to be lower on the thermostat.

The degree of solar radiation that is blocked from the interior space determines the amount of comfort that can be achieved in buildings (Muhammad S. Aliero et al. 2022). Design elements that affect people's health, comfort, and well-being inside a structure should avoid sun radiation and provide proper lighting. When these elements are not sufficiently considered, a lot of active energy is consumed for air conditioning, ventilation, and lighting to achieve a high level of thermal and visual comfort in buildings. However, designers must aim to consume as little active energy as possible.

An in-depth knowledge of the local climate is necessary for designing with the environment in mind. To prevent overheating of buildings, reduce other heat gains, and improve thermal comfort and efficiency for people, this study investigates the effects of architectural characteristics, thermal performance of buildings, and thermal control in buildings. The field research method is then considered with the previous works' usage of a variety of techniques and systems for the development of a pleasant microclimate with significant thermal efficacy of the buildings resulting in satisfactory thermal comfort of the indoor space (Brager, Zhang, and Arens 2015).

2.Literature Review

2.1 Thermal Performance of Buildings

With climate-responsive architecture, thermal efficiency as well as the performance of buildings should be evaluated. Climate change is an additional possibility for lowering energy consumption or operating HVAC systems at higher capacity which has led to a growing concern. According to a study by (Rostampour and Keviczky 2016), this essentially entails calculating the building's construction cost and running costs throughout its anticipated life.

The cost of active energy frequently outweighs the initial investment in a facility. The formation of a comfortable microclimate with optimum thermal comfort in indoor spaces needs the use of numerous tactics as well as a full awareness of the local environment. By utilizing ventilation from the outside via orientation, thermal insulation, opening placement, and layouts, passive design solutions aim to increase the building's thermal efficiency (Salamone, Belussi, Danza, Ghellere, et al. 2016). According to a study by (Ain et al. 2018), the passive design method utilizes the environment's renewable energy, which is accessible to the building via the usage of the microclimate, the architectural shape, and the fabric. In today's environment, higher living standards are expected. To do business or leisure activities without being physically or psychologically distracted, a comfortable atmosphere must be free from discomfort and distraction (Revel, Arnesano, and Pietroni 2014). Temperatures, humidity, air movement, and air purity all contribute to the achievement of acceptable indoor comfort. Our mood and productivity can be affected by a variety of factors, including the behaviors of those who use the place, how indoor spaces are organized, color schemes, and many other things.

Walker et al. 2020; Walker, Brown, and Neven 2016) conducted a study that highlights the significance of consistent and effective temperature and power monitoring in critical environments, including operating rooms, pharmacies, and intensive care units. Moreover, the research endeavors to provide a technique for consistently sending temperature and humidity data over a wireless sensor network to the Internet of Things gateway. The data is then stored in a cloud server for data analytics objectives, making it possible to create many types of reports. By connecting their intelligent terminals—such as mobile phones—to the server, interested medical staff members can use this report to optimize power usage as well as to query and regulate environmental data in real time. Interesting findings from the experimental evaluation were shown, with consistent, accurate data collecting and dependable control.

The energy consumption of smart home appliances can be managed and controlled through an embedded micro-web server that allows for remote access control and the scheduling of which appliances to use based on preferences using an IP connection and a smart mobile application, according to studies by Negendahl and Nielsen (2015) as well as Jiang et al. (2020). Equipment was turned on and off using fuzzy logic depending on values set, which lessens the problem of frequent ON and OFF cycles, which has been shown to shorten the life of these equipment. A drawback of this approach is that information is exchanged on the cloud, making it possible to identify individual occupants and violate their privacy.

A ZigBee-based smart house management system was suggested in a 2015 study by Royapoor and Roskilly to control energy usage in electric home equipment and lessen the impact of inference. The system includes WiFi and sensor nodes that use fuzzy modeling to determine whether to turn on or off the HVAC. In a similar vein, the suggested system is intelligent enough to regulate light by integrating the tone of a room's natural lighting stage. Comparing a functioning station with a relay and pure wireless sensor network, the simulation shows that a working station can save a substantial amount of energy.

Smart socket devices are used in a study by Wang et al. (2017) to get information about energy usage from smart meters that regulate and control smart home appliances. The suggested method may turn off appliances that are only sometimes used and turn on appliances that are commonly used in the house. By turning on appliances that are frequently used, it can save energy by turning them into hibernation mode. To help the occupier determine how much of the monthly quota to buy, the system may also calculate the amount of energy utilized daily before making energy purchases.

To maintain effective energy consumption in smart home equipment and promote occupant thermal comfort, an architecture for smart energy control systems was developed (Dikel et al. 2019). The suggested system is divided into two layers. The first layer controls temperature and humidity. For instance, during the winter, the outside air might fall humidity to less than 30%, which may cause uncomfortable symptoms like excessive thirst and skin drying. Simultaneously, a software package in the form of fuzzy assessed goals,

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constrained by a set of rules as an argument and kept in a database, makes up the lower layer. This software package influences the regulation of how energy should be used in household appliances.
Three perception layer architectures were created by Park and Nagy (2018) to track interior temperature and humidity and adjust energy use without sacrificing occupant comfort. The top layer of the proposed layers is equipped with sensors that collect data about the occupant's living environment; the middle layer is made up of fuzzy rules that control how the system makes decisions based on temperature and humidity data collected; and the bottom layer is made up of a nZEB prototype that provides data among the nodes that would share an update to a cloud server.

2.2 Occupancy Performance on Thermal Comfort

Humans engage in a variety of activities inside enclosed structures. The best performance of these activities is only possible under ideal environmental circumstances. People are impacted by the temperature and climate inside a structure either favorably or unfavorably based on their physiological and psychological responses. The degree of thermal comfort has a big impact on how well people work, both mentally and physically. The degree to which the offered activities are performed will reveal the extent to which the impulses brought on by the various environmental conditions have an impact. Thermal factors will influence degrees of arousal, vigilance, weariness, attention, and boredom, according to (Taleghani et al. 2013).

A study by (Park and Rhee 2018) emphasized the proper use of materials as issues related to thermal comfort in a tropical setting, causing a spike in interest in studies of thermal behavioral patterns in warm, humid climates worldwide. Sokoto residential building thermal performance was examined by Rostampour and Keviczky (2016), while Salamone, Belussi, Danza, Ghellere, et al. (2016) studied the thermal response of an NBRRI model house design created in Kano using the Fourier series.

3. Methodology

One of Nigeria's 36 states, Sokoto State is situated in the far northwest of the nation. the states of Zamfara and Kebbi, which are partially separated by the Ka River, to the east, and the Republic of the Niger to the north and west for 363 km (226 miles). Sokoto, the country's largest city, serves as its capital. The Sokoto River and the Rima River meet close to where Sokoto is situated. Its estimated population in 2005 was about 4.2 million (Vabi et al. 2019)

However, this work presents the findings of a field assessment of the thermal performance of four residential building types with various design systems in Sokoto State, Nigeria, which is situated between latitudes 7o201 and Longitudes 7o401. Building responses to temperature are estimated hourly values of surface temperature, indoor air temperature, and external temperature. To help, the distribution of solar insulation has been shown on an hourly basis for the entire day.

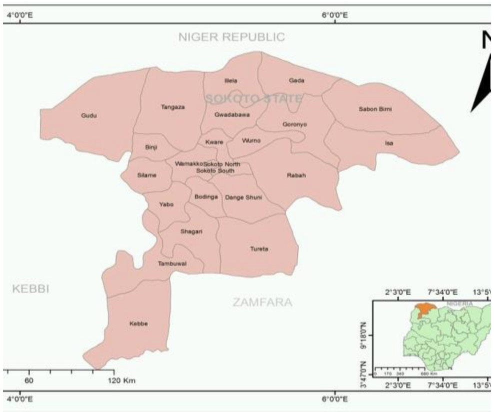

Figure 1: Map of Sokoto state showing.
Source**:** (Ibrahim Dankani 2018)

3.1 Experimental Apparatus

The traditional structures known as "Mud houses" (Building I) have ceilings covered in galvanized rusting sheets without plaster; "adobe mud bricks unplastered houses" (Building II) have a floor rendered by cement sand and a roof covered in corrugated iron sheets; and "adobe mud bricks plastered houses" (Building III) (Building III). This study was approached as a quantitative experimental study. A study by (Muhammad S. Aliero et al. 2022) argues that environmental sensors produced precise and accurate readings compared to other data collection approaches. The author's experiment indicates solid prediction. For this reason, this study utilized a DHT11 sensor to measure temperature, and SX2596 to measure sun insulation.

3.2 Data Collection

To choose the building arrangement that provides the best thermal comfort, field research was conducted on the four different types of residential structures that are in the same location. Based on this goal, hourly measurements of the temperatures of the exposed surfaces, solar isolation, and interior environment areas of each of the buildings were made. On August 19, 2023, measurements of these temperatures were made continuously throughout the whole day to aid in the investigation of the structures' thermal performance.

4. Result and Discussion

4.1 Building Temperature

The relationship between the ambient temperature and solar insolation is that the ambient surface temperature increases as solar insolation increases. For the various types of buildings under study, Table 1 depicts the variance in sun radiation, ambient temperature within, and outdoor temperature. The average highest temperature of the day was 31.6C at 2:00 PM. Table 1 shows that the semi-traditional building (Building II), semi-modern building (Building III), and modern building (Building IV) all had inside temperatures below ambient between 12:00 A.M. AND 2:00 P.M., whereas the traditional building (Building I) had indoor temperatures below ambient between 11 A.M. and 2:30 P.M., 10:00 A.M and 6:00 A.M., and 12:00 A.M. and 4:00 A.M. As opposed to the study in Aliero et al. (2022) that observed higher ambient temperature and indoor temperature from 12:30 A.M to 4:20 P.M in three different rooms of the same building when air conditioning is not operating.

Table 3.1: Ambient temperature and Indoor Temperature of the Buildings (Abuhussain et al. 2023)

S/ No	Ambient Temp (oC)	Building I (oC)	Building II (oC)	Building III (oC)	Building IV (oC)
1.	27.0	23.2	27.7	31.2	27.4
2.	27.4	21.0	27.6	31.0	27.9
3.	27.9	21.0	27.9	31.0	27.1
4.	27.1	21.2	27.5	31.2.	27.7
5.	27.7	21.2	27.8	31.2	27.6
6.	27.6	21.0	27.0	31.0	27.9
7.	27.9	21.0	27.4	31.0	27.5
8.	27.5	31.0	34.0	31.0	27.8
9.	27.8	21.0	34.4	31.0	27.0
10.	27.0	27.1	34.6	31.0	27.4
11.	27.4	27.0	34.3	33.0	27.4
12.	34.0	24.5	34.0	27.8	27.9
13.	34.4	23.3	33.2	28.0	34.6
14.	34.6	23.0	33.3	28.2	34.3
15.	34.3	21.8	33.0	33.0	34.0
16.	34.0	21.5	31.8	31.8	24.6
17.	24.6	21.0	31.5	31.5	28.1
18.	28.1	21.0	31.0	31.0	28.2
19.	28.2	21.8	31.0	31.0	28.5
20.	28.5	32.4	31.8	31.8	26.0
21.	26.0	32.9	32.4	32.4	27.3
22.	27.3	32.0	32.9	32.9	26.8
23.	26.8	32.0	32.0	32.0	27.3
24.	27.3	31.6	32.0	32.0	34.6

4. 2 Building Thermal Behaviour

While heat absorption capacity is related to the quality of the material declarations, all four building types were able to absorb solar radiation between 8 and 10 hours, when the display temperature was at its highest. Table 2 displays how the wall, roof, and floor together make up a structure's exterior envelope. The quantity of heat that can enter a building relies on the reflectivity, absorptivity, and emissivity of the materials used to construct the walls, roofs, and floors. The amount of solar radiation that was kept from entering the interior of the building determines how comfortable its occupants are physiologically. Building III, a semi-modern structure, has a combination of mud bricks coated with cement sand making floor, corrugated iron sheets for the roof, and asbestos sheets for the ceiling. Building IV, a modern structure, has hollow sand-create walls with low material content and low absorptive capacity, which emit more heat to the interior spaces between the hours of 11:00 and 17:00. This study employed statistical analysis for weather prediction and thermal comfort analysis. Unlike studies in (Muhammad Saidu Aliero et al. 2022; Muhammad S. Aliero et al. 2022) that used a machine learning approach for their prediction. Regression results from statistical analysis tend to produce less accurate results compared to machine learning when predicting uncertain activities, such as occupant response to thermal comfort or behavior.

Table 3.2: Building Thermal Properties

SURFACES	REFLECTIVITIES	ABSORPTIVITY	EMMISSIVITIES
Asbestos Cement, New	0.03	0.02	0.30
Brass and Cooper, Dull	0.06	0.60	0.60
Concrete, Uncoloured	0.67	0.70	0.60
Cement, white Portland	0.56	0.60	0.50
Paint Black	0.03	0.30	0.50
Paper White	0.06	0.60	0.60
Paint, brown, red, green	0.60	0.60	0.60
Tiles, red clay	0.60	0.60	0.60
Tiles, red clay	0.60	0.60	.0.70
Brick, red rough	0.60	0.60	0.55
Slate, dark	0.60	0.60	0.60
Tiles, black concrete	0.65	0.60	0.50
Steel, galvanized, new	0.40	0.40	0.40
Tiles, uncoloured concrete	0.70	0.70	0.70
Glass	0.60	0.60	0.60
Paint, white	0.70	0.70	0.70
Plant aluminum	0.60	0.60	0.50
Brick, light buff	0.80	0.80	0.40
Marble white	0.30	0.30	0.30
Brass and Cooper polished	0.60	0.60	0.40
Aluminum, Bright	0.60	0.60	0.50
Asbestos cement, aged	0.60	0.60	0.60

1.1 Regression Analysis

The study uses regression analysis to find the squared value from the regression analysis. The finding indicated a very high link between the independent components (Building I–IV) and the dependent factor (ambient temperature). The reliability index's F-value, which is 0.000, is noteworthy (see Table 3). This suggests that the impact of building types on the surrounding temperature is significant. The outcome also indicated that I, IV, III, and II had the greatest effects on ambient temperature among the different building types. The impact of Building II on the air temperature was the largest.

Thus, y = -27 + 0.43x1 + 1.027x2 + 0.66x3 + 0.108x4 is the regression equation.

Where y is the outside temperature and x1 to x4 are the different building kinds.

Table 3.3: Regression Analysis

Model	*Frequency*	*Mean Square*	*Sum Square*
Residual	-	1.67	29
Regression	28.1	43.2	183.6
Total	28.1	44.87	212.6

2 CONCLUSION

The results of this study have demonstrated the significant contributions that material choice, apertures, orientation, and the presence of vegetation around buildings make to the thermal comfort of residents in Sokoto. The examined buildings' thermal comforts are arranged in the following order: (Building IV), (Building III), (Building II), (Building I). Additionally, it has been demonstrated that adding a ceiling and providing shading can improve thermal comfort by reducing the amount of solar heat gain. Based on the findings of this study, it is advised that buildings in Sokoto land with the climatic conditions utilize adobe mud bricks plastered dwellings, cement sand rendering floor, corrugated iron sheets as roof covering, and asbestos sheets as ceiling materials. The most often statistical approach adopted in this study produced ambiguous data naturally which has ga reater impact on model performance when different datasets are used. Even though this represents the initial results of our study in the future, the machine learning prediction approach should be explored.

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