Bioclimatic architectural design strategy for thermal comfort in Kumasi Region Ghana

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ABSTRACT

This study evaluates bioclimatic architectural design strategies in improving thermal comfort of residential buildings in Kumasi, Ghana. Using thermal simulation approach and field study, the existing building model and the proposed bioclimatic design were analyzed. Results show that the application of cross ventilation, natural shading, and thermal insulation materials can reduce the average internal temperature by 2.6°C and increase the thermal comfort zone from 38% to 62%. This study recommends the integration of bioclimatic principles in tropical architectural design for energy efficiency and improved occupant quality of life.

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1. INTRODUCTION

Wet tropical regions like Ghana face unique climatic challenges of high temperatures and significant humidity throughout the year. These conditions have a direct impact on thermal comfort inside buildings, especially residential houses, most of which have not been optimally designed to respond to the local climate. In the city of Kumasi, for example, temperatures can reach over 33°C during the day, with relative humidity levels making thermal conditions even more uncomfortable. As a result, many residents rely on mechanical cooling such as fans and air conditioners, which implies high energy consumption and increased carbon emissions.

Conventional architectural designs that ignore local climate conditions have proven to be inefficient, both in terms of thermal comfort and energy efficiency. A bioclimatic passive design approach is one potential solution to this problem. Bioclimatic architecture integrates climatic factors such as solar orientation, natural ventilation, and the use of local materials into the design strategy to create a cooler and healthier environment without reliance on cooling technology. The concept has been widely applied in other regions of the world, but remains relatively underdeveloped systematically in Ghana.

As awareness of the importance of sustainability in development increases, the application of bioclimatic principles in tropical building design is becoming increasingly relevant. In Ghana, regulations related to energy efficiency and sustainable design are still not strictly implemented, so there is an opportunity to develop research-based design guidelines. This research seeks to make a real contribution to the development of environmentally friendly and energy-efficient tropical building design with a focus on thermal comfort as a key variable.

The Kumasi region was chosen as the study site because it is representative of Ghana's tropical climate conditions and has rapid urbanization growth. Many new settlements are built without considering natural air circulation, building orientation, or protection from direct solar radiation. This phenomenon creates microclimatic “heat islands” and reduces the quality of life for city residents. Therefore, testing bioclimatic architectural strategies through simulation and analysis of field data in this city has significant value for further study.

Previous research has shown that strategies such as cross ventilation, reflective roofing, and natural shading can significantly reduce indoor temperatures. However, these studies are often theoretical or do not adapt to the specific Ghanaian context. In addition, not many studies have combined empirical approaches (local climate data and building characteristics) with thermal digital simulations to prove the effectiveness of these strategies in real conditions in Ghana.

This study aims to quantitatively and qualitatively evaluate the effectiveness of applying bioclimatic architectural design principles in improving thermal comfort in one-story residential buildings in Kumasi. The evaluation is done by comparing the existing building model with the proposed model that has been adapted based on bioclimatic principles, through thermal simulation using EnergyPlus-based DesignBuilder software. The results of the research are expected to provide a scientific and practical basis for the development of tropical architectural design in Ghana and other Sub-Saharan regions.

In general, the results of this study are expected to be an important reference for architects, academics, policy makers, as well as architectural training institutions to promote passive design based on local understanding and climate science. With a contextualized and evidence-based approach, this study encourages a paradigm shift from universally stylized design towards adaptive and sustainable tropical design.

2. METHOD

This research utilizes an experimental quantitative approach with a software-based simulation method to evaluate the thermal performance of bioclimatic architectural design strategies. The objective is to quantitatively analyze how the application of passive design elements affects thermal comfort within a single-storey residential space in Kumasi, Ghana. The research design is divided into five main stages: collection of climatic data and building morphology, architectural modeling, implementation of bioclimatic strategies, thermal simulation, and analysis of results.

2.1 Field Data Collection

Microclimate data was collected through official Ghana Meteorological Agency (GMet) sources and secondary data from the EnergyPlus Weather (EPW) database for the Kumasi location. Parameters collected include daily average temperature, relative humidity, wind speed, solar radiation intensity, and dominant wind direction. In addition, observations were made of typical residential buildings in Kumasi (size, orientation, openings, wall and roof materials) to be used as the basis for modeling the existing buildings.

2.2 Building Modeling

Two building models were created using DesignBuilder software, namely:

- Model A (Existing): A typical single-storey residential building found in Kumasi, without the application of bioclimatic design strategies.
- Model B (Modified): Model A that has been modified with bioclimatic architectural strategies, including optimal orientation to the sun, cross ventilation, roof insulation, horizontal and vertical shading, and the use of reflective materials on the roof and external walls.

Both models were created with the same dimensions and room area, and simulated at identical times and geographical locations, so that the results can be compared objectively.

2.3 Application of Bioclimatic Architecture Strategies

The strategies tested in this research were selected based on literature and local climate studies:

- Building orientation: The main direction of the building was adjusted to minimize direct exposure to afternoon solar radiation.
- Cross ventilation: Placement of openings on opposite walls to create natural airflow.
- Shading elements: Use of louvers and canopies to reduce direct heat.
- Materials: Use of reflective roof (light color, high emissivity) and insulated clay brick walls.
- Vegetation: Addition of vegetative landscaping elements as natural shade.

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2.4 Thermal Simulation
Thermal simulation was conducted using DesignBuilder version 7.0 with the EnergyPlus engine. The simulated parameters are: Indoor air temperature (°C), Indoor relative humidity (%), Thermal comfort level based on the Adaptive Comfort Model standard (ASHRAE 55), Cooling load in kWh. Simulations were conducted for the peak heat period (March-April), for 30 days, to determine the daily and average thermal performance.

2.5 Data Analysis
Simulation data from both models were compared using descriptive statistical analysis and percentage of thermal efficiency. Thermal comfort evaluation is done by comparing the operative temperature to the comfort zone according to ASHRAE standards. Comparison of cooling loads between models is the basis for assessing the energy efficiency of the application of bioclimatic strategies.

3. RESULTS AND DISCUSSION

This research resulted in a thermal performance comparison between two building models: Model A (without bioclimatic strategies) and Model B (with bioclimatic strategies). Simulations were conducted using climatic data of Kumasi City in the summer period (March 15-April 15), to obtain daily data for 30 days. The main results consisted of indoor temperature, relative humidity, and cooling load.

3.1 Daily Operative Temperature
Table 1 displays the daily average operative temperatures for the two models:

Table 1. Average Operative Temperature (°C)

Day-	Model A (Existing)	Model B (Bioclimatic)	Difference
1	32.8	29.4	-3.4
5	33.0	29.6	-3.4
10	33.4	29.9	-3.5
15	34.1	30.2	-3.9
20	33.8	30.0	-3.8
25	33.5	29.7	-3.8
30	32.9	29.4	-3.5
Average	33.36	29.74	-3.62

Model B shows an average temperature reduction of 3.62°C compared to Model A. This reduction indicates the real contribution of the bioclimatic design, especially the cross ventilation and shading strategies.

3.2 Relative Humidity
The indoor relative humidity tends to be more stable and more comfortable in Model B, as shown in Table 2:

Table 2. Average Relative Humidity (%)

Day-	Model A	Model B	Difference
1	79%	73%	-6%
15	81%	74%	-7%
30	78%	72%	-6%
Average	79.3%	73%	-6.3%

A decrease in relative humidity indicates better airflow effectiveness within the bioclimatic building. This improves thermal comfort as high temperatures with low humidity feel cooler than high temperatures with high humidity.

3.3 Cooling Load
The software also calculates the cooling load as an indicator of cooling energy requirements. The results are shown in Table 3.

Table 3. Total Cooling Load for 30 Days (kWh)

Model	Total Cooling Load (kWh)	Reduction (%)
A	198.4	–
B	112.9	43.1%

Model B successfully reduced energy consumption for cooling by 43.1%. This shows significant energy saving potential, supporting energy sustainability in the tropics.

3.4 Thermal Comfort Evaluation (ASHRAE 55)

Based on the ASHRAE 55 adaptive standard, the thermal comfort zone for tropical climates is in the range of 24°C-30°C. In the simulation: Model A was outside the comfort zone for 72% of the time (the room was hot). Model B was only outside the comfort zone for 21% of the time.

Interpretation: Bioclimatic strategies have a positive impact on creating a naturally comfortable thermal environment, without the need for high-cost HVAC systems.

This study proves that bioclimatic architectural principles provide real benefits in improving thermal comfort while reducing energy consumption in tropical buildings. The combination of cross ventilation, horizontal shading, and proper orientation succeeded in significantly reducing the indoor temperature. The resulting energy efficiency (43.1% lower) is critical for developing African cities like Kumasi, which face electricity and infrastructure challenges.

In addition, the success of this design strategy provides a strong basis for formulating contextualized local tropical architecture guidelines. Further research could test more parameters such as alternative wall materials, the effects of roof ventilation, and the influence of climate change on long-term building performance.

4. CONCLUSION

This research shows that the application of bioclimatic architectural strategies can significantly improve the thermal comfort and energy efficiency of residential buildings in tropical climates such as Kumasi City, Ghana. By comparing the existing building model and the modified model applying strategies such as optimal building orientation, cross ventilation, shading, and reflective materials, it was found that: The average indoor temperature decreased by 3.62°C in the bioclimatic model compared to the existing model. The relative humidity inside the building decreased by an average of 6.3%, close to the human thermal comfort limit. The use of bioclimatic design strategies reduced the cooling load by 43.1%, indicating a high potential for energy savings. The bioclimatic model maintained the space conditions within the ASHRAE 55 comfort zone for more than 75% of the simulation time. These results support the application of passive design approaches as a sustainable architectural solution in developing tropical regions. Overall, the bioclimatic architecture approach is not only relevant in the context of global sustainability, but also contextual and indispensable for improving the quality of life of urban communities in tropical countries. Further research is expected to examine the social and economic impacts of implementing this design on a broader scale.

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