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A Biomimetic Thermal Comfort Model for Office Buildings in Nigeria's Composite Climate Based on Termite Mound Principles: A Pilot Study

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Keywords	Abstract
Biomimicry Office buildings Passive design Predictive modeling Thermal comfort	Achieving thermal comfort in office buildings within Nigeria's composite climate remains a persistent challenge due to high solar radiation and seasonal variations. Previous studies have examined isolated parameters such as Window-to-Wall Ratio (WWR), orientation, and spacing, but an integrated predictive model adapted to variable climatic conditions is lacking. This pilot study developed a biomimetic thermal comfort model inspired by termite mound ventilation principles. A quantitative experimental simulation approach was used: a standard office module in Abuja's composite climate was modelled in DesignBuilder software. The simulation tool was first validated against field measurements from three real office spaces; the mean bias error (%MBE) for operative temperature was -4.35%, well within the acceptable $\pm 15\%$ range. Four design parameters were then systematically tested – opening shape (circular vs. rectangular), orientation (N, S, E, W), WWR (10–30%), and inter-opening edge-to-edge distance (0.5–2.0 m). Multiple regression analysis was performed on a limited dataset (11 simulation scenarios). The results suggest an optimal configuration of circular openings, South orientation, 20% WWR, and 2.0 m spacing. Preliminary predictive equations were obtained: Peak Hours ($T_{peak} = 29.50 - 0.45S + 0.20N + 1.30E + 1.85W + 10.50WWR - 0.55D$, $R^2 = 0.98$) and Cooling Hours ($T_{cool} = 22.80 - 0.25S + 0.15N + 0.80E + 1.20W + 5.50WWR - 0.60D$, $R^2 = 0.97$). Because the regression was fitted to only 11 observations with six predictors, these R^2 values are likely overfitted; the equations should be treated as hypotheses requiring validation with a larger dataset. WWR emerged as the dominant factor during peak hours, while spacing critically influenced nighttime cooling. The study provides a dual-phase biomimetic framework for future investigation.
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1. INTRODUCTION

Architectural innovation is increasingly turning to nature for sustainable solutions, with biomimicry emerging as a transformative design paradigm. This approach involves emulating nature's time-tested patterns and strategies to solve human challenges (Benyus, 1997). In regions with demanding climates such as Nigeria's composite zone – characterised by high solar radiation, significant diurnal temperature swings, and seasonal variations – achieving indoor thermal comfort in office buildings is a persistent challenge. Conventional design practices often fail to adequately

address passive climate control, leading to occupant discomfort and high operational costs due to excessive reliance on mechanical HVAC systems (Oladokun, 2021).

Termite mounds, particularly those of the *Macrotermes* genus, are exemplary models of passive climate regulation. These structures maintain a remarkably stable internal environment despite extreme external fluctuations through sophisticated, self-regulating ventilation mechanisms (Turner, 2001). The mound's complex network of tunnels, pores, and chimneys functions as a dynamic interface that manages airflow, driven by temperature gradients and wind pressure (Soar & Andréen, 2020; Turner & Soar, 2008). While earlier research has examined specific architectural parameters – such as Window-to-Wall Ratio (WWR; Musa, 2024), window positioning (Shao et al., 2020), and spacing (Musa et al., 2024) – many of these studies fall short of offering a comprehensive, integrated solution that guarantees comfort across variable climatic conditions. Additionally, the application of termite mound principles in architecture has often remained conceptual or has focused on macro-ventilation techniques without a unified predictive model for implementable design elements.

This study posits that a holistic biomimetic approach, synthesising multiple ecological principles from termite mounds, is essential for developing a robust thermal comfort model. It moves beyond examining single variables to investigate the synergistic effects of opening shape, orientation, WWR, and inter-opening distance. The primary aim is to develop a biomimetic thermal comfort model for office buildings in Nigeria's composite climate, achieved through the following objectives:

1. To evaluate the ecological principles of termite mounds related to ventilation opening configuration.
2. To quantify the individual and combined impact of biomimetic design variables on indoor thermal comfort parameters.
3. To integrate the findings into a cohesive, predictive model for passive building design.

As a pilot investigation, the study uses a limited set of simulation runs to generate initial predictive equations, with the understanding that further validation with a larger dataset is required.

1.1. Thermal comfort and the composite climate of Nigeria

Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment” (ASHRAE Standard 55, 2023). It is influenced by six primary factors: air temperature, mean radiant temperature, air velocity, humidity, clothing insulation, and metabolic rate. In building design, the first four can be directly influenced by architectural strategies. The composite climate of Nigeria, found in cities such as Abuja, Kaduna, and Minna, features hot, dry seasons and warm, humid rainy seasons, necessitating design solutions that are adaptable to both conditions (Mobolade & Pourvahidi, 2020). ASHRAE Standard 55 (2023) suggests an operative temperature range of approximately 24.3°C to 29.3°C for naturally ventilated buildings in warm climates, though this can be challenging to maintain passively under peak conditions.

1.2. Termite mounds as a biomimetic paradigm

Termite mounds are not simple structures but highly engineered ecosystems. Research has revealed several key principles governing their function: (i). Thermoregulation and passive cooling – Mounds maintain internal temperatures between 25-30°C via a self-regulating ventilation system that leverages stack and Venturi effects (Korb, 2003; Turner, 2001); (ii). Dynamic porosity – The surface

of a mound is covered with a network of pores that vary in size, shape, and spacing. This complex geometry creates pressure differentials that drive convective airflow (Soar & Andréen, 2020). Recent studies show mounds undergo a diurnal “breathing” cycle, where effective porosity adapts to solar heating (Ocko et al., 2017); (iii). Integrated system function – The mound operates as a multiphase gas exchanger, where the “egress complex” – a lattice of surface conduits – acts as a buffering system for regulating internal temperature and humidity (Heyde et al., 2019; Turner & Soar, 2008).

These principles offer profound insights for architecture, shifting the focus from static designs to dynamic, responsive building envelopes.

1.3. Biomimetic Applications and Research Gaps

A well-known example of termite mound-inspired architecture is the Eastgate Centre in Harare, Zimbabwe, which uses more than 90% less energy for cooling than conventional buildings (Pearce, 1996). Nevertheless, many applications remain at the macro-strategy level. Recent research on “digital twin simulation models” and “adaptive facade models” aims to develop building skins that are sensitive to climate changes (Heyde & Soar, 2021; Ocko & King, 2023). This study advances the field by providing quantifiable, statistically derived data on specific design parameters extracted from termite mound ecology and incorporating them into a predictive mathematical model.

2. MATERIAL AND METHOD

2.1 Research Design

This study employed a quantitative, experimental simulation approach using DesignBuilder software (EnergyPlus calculation engine). A standard office module representative of typical office spaces in Abuja (Nigeria’s composite climate) was modelled. The module dimensions (4 m length × 4 m width × 2.7 m height) were chosen based on a survey of existing office layouts in Abuja’s Central Business District, where cellular offices of 16-20 m² are common.

A base model was constructed with 225 mm concrete walls (U-value = 2.4 W/m²K), a concrete roof with 50 mm insulation, and a raised floor. Internal heat gains were set as follows: occupancy = 0.1 person/m² (sedentary office work, 120 W sensible heat per person), equipment = 15 W/m² (computers and monitors), lighting = 10 W/m² (LED, occupancy-controlled schedule). Infiltration rate was 0.5 air changes per hour.

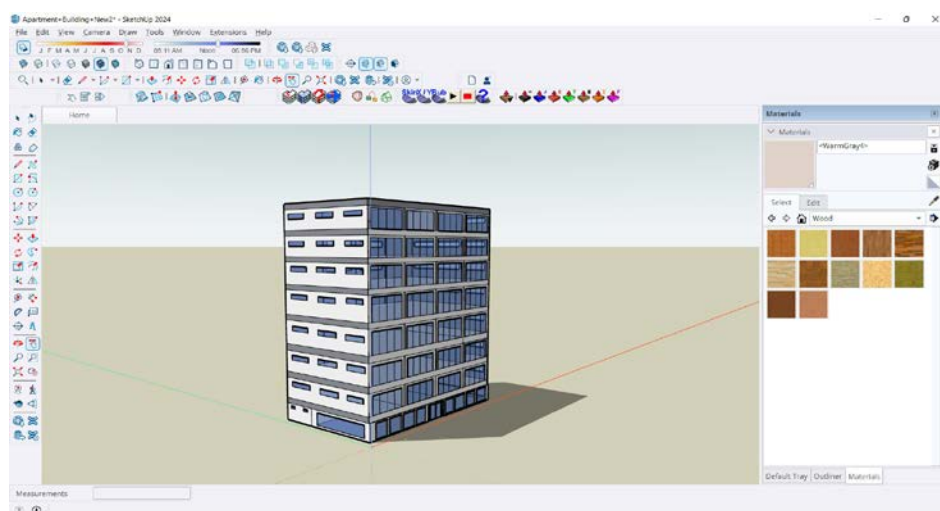


Fig. 1. Base Model

2.2 Validation of the Simulation Model

Before conducting the main simulations, the accuracy of DesignBuilder/EnergyPlus for the local climate and building typology was assessed by comparing simulated results with physical measurements taken from three real office spaces in the Department of Architecture, Ahmadu Bello University, Zaria (Abdulbasit et al., 2013). Measurements were performed according to ASHRAE standards. Table 1 presents the measured (X_{mea}) and simulated (X_{sim}) values for relative humidity, operative temperature, and air velocity.

Table 1. Measured and simulated data for validation

Office	Size	Parameter	X_{mea}	X_{sim}	$\sum(X_{mea} - X_{sim})$	Absolute Error	Error ²
Project room (2nd floor)	6m × 4.3m	Rel. H. (%)	20.0	17.9	2.05	2.05	4.20
		Op. Temp. (°C)	33.4	35.0	-1.60	1.60	2.56
		Air Vel. (m/s)	2.0	2.9	-0.14	0.14	0.02
Office (Ground floor)	4m × 3m	Rel. H. (%)	25.1	29.0	-3.90	3.90	15.21
		Op. Temp. (°C)	33.9	35.8	-1.90	1.90	3.61
		Air Vel. (m/s)	1.5	5.9	0.21	0.21	0.04
Lecture II (2nd floor)	6.8m × 4.8m	Rel. H. (%)	38.4	31.5	6.90	6.90	47.61
		Op. Temp. (°C)	33.9	35.0	-1.10	1.10	1.21
		Air Vel. (m/s)	1.5	2.2	-0.59	0.59	0.35

Mean average values across the three offices:

- ✓ Relative humidity: 27.83%
- ✓ Operative temperature: 33.73°C
- ✓ Air velocity: 1.67 m/s

The mean bias error percentage (%MBE) was calculated as:

$$\%MBE = \frac{100}{\text{avg. of } X_{\text{mea}}} \times \frac{\sum (X_{\text{mea}} - X_{\text{sim}})}{N}$$

Results:

- ✓ Relative humidity: %MBE = 6.43%
- ✓ Operative temperature: %MBE = -4.35%
- ✓ Air velocity (ACH): %MBE = -14.17%

All %MBE values fall within the acceptable range of -15% to +15% (Abdulbasit et al., 2013). Therefore, the simulation model is considered valid and suitable for this research.

2.3 Independent Variables and Parameter Ranges

Four independent variables were tested. Their levels were chosen based on termite mound principles and previous literature.

Variable	Levels	Justification
Opening shape	Circular, Rectangular (equal area: 0.36 m ² each)	Circular pores in termite mounds reduce airflow resistance and turbulence.
Orientation	North, South, East, West	South orientation minimises direct solar gain in the northern hemisphere.
Window-to-Wall Ratio (WWR)	10%, 15%, 20%, 30%	Previous research (Musa, 2021; ASHRAE 55, 2023) indicates that WWR beyond 30% causes excessive overheating in composite climates, while below 10% restricts ventilation.
Inter-opening distance	0.5 m, 1.0 m, 1.5 m, 2.0 m (edge-to-edge)	Edge-to-edge distance (clear spacing between adjacent openings) directly affects cross-ventilation efficiency, inspired by termite mound conduit spacing.

2.4 Simulation Experimental Design – Pilot Study

Due to time and computational constraints, this study was conducted as a pilot investigation. A fractional factorial design was used, consisting of eleven (11) selected scenarios that cover the extreme and middle levels of each variable (see Tables 6 and 8). This sample size ($n = 11$) is small for multiple regression with six predictors; the rule of thumb recommends 10–15 observations per predictor (i.e., 60–90 observations for reliable regression). Therefore, the results presented here are preliminary, and the high R^2 values (0.98 and 0.97) are likely overfitted to this specific dataset. The equations should be interpreted as hypothesis-generating rather than validated predictive tools.

The simulation tool itself has been validated, so the uncertainty lies in the regression model, not the underlying physics. In order to test different configurations of window shapes, orientations, spacing, and window-to-wall ratios—all of which were derived from the principles of termite mound ventilation as applied to Nigeria's composite climate—a digital model of a typical office space was created using building performance simulation software, as shown in Figure 1.

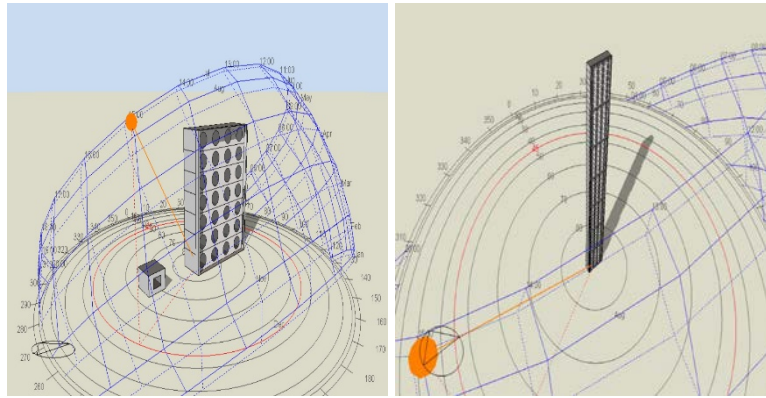


Fig. 2. Block Models on Design Builder

2.5 Data Collection and Analysis

Outputs recorded for each simulation run:

- ✓ Peak solar period (13:00–15:00): maximum operative temperature, average air velocity.
- ✓ Cooling hours (22:00–04:00): minimum operative temperature, average air velocity.

Statistical analysis consisted of:

- ✓ Descriptive comparisons (means).
- ✓ One-way ANOVA for each factor (using only the levels present in the 11 runs) to test for significant differences; interaction effects could not be tested due to the limited sample.
- ✓ Multiple linear regression (full model with main effects) to develop preliminary predictive equations.
- ✓ Significance level $\alpha = 0.05$.
- ✓ Validation of regression: Not performed due to small sample size. The reported R^2 is the in-sample fit, which is known to be optimistic.

3. RESULTS AND DISCUSSION

3.1. Impact of Opening Shape on Indoor Thermal Comfort

Equal-area circular and rectangular apertures were examined in simulations. Table 2 illustrates the higher performance of the circular opening.

Table 2. Thermal Comfort Results for Different Opening Shapes

Opening Shape	Peak Temp. (°C)	Cooling Hours Temp. (°C)	Peak Air Velocity (m/s)	Cooling Hours Air Velocity (m/s)
Circular	32.5	24.3	0.08	0.15
Rectangular	33.1	24.8	0.05	0.10

Table 2 shows that, circular aperture kept the inside temperature lower at both peak and cooling hours. Furthermore, the circular design consistently produced higher air velocity. This is explained by the reduced resistance and more even dispersion of airflow, which are similar to the efficiency of termite mound pores. Because the design has fewer sharp edges, which can cause air turbulence and resistance, the airflow entering the region is smoother and more efficient.

3.2. Impact of Orientation on Indoor Thermal Comfort

The orientation of openings significantly influenced thermal performance. South-facing openings provided the best balance, as detailed in Table 3.

Table 3. Thermal Comfort Results for Different Orientations (Peak Solar Period)

Orientation	Temperature (°C)	Air Velocity (m/s)	Relative Humidity (%)
South-facing	32.8	0.42	46
North-facing	33.0	0.38	48
East-facing	34.1	0.35	50
West-facing	34.7	0.33	52

In the CONCLUSION section, the data to be emphasized/stated in the study should be highlighted. The usefulness/usefulness of the findings obtained as a result of the study and/or recommendations, if any, should also be written.

3.3. Impact of Window-To-Wall ratio (WWR) on Indoor Thermal Comfort

The analysis of WWR revealed a critical balance between solar gain and ventilation. The results are shown in Table 4.

Table 4. Thermal Comfort Results for Different Window-to-Wall Ratios

WWR (%)	Peak Temp. (°C)	Cooling Hours Temp. (°C)	Peak Air Velocity (m/s)	Cooling Hours Air Velocity (m/s)
10%	32.5	23.8	0.28	0.25
15%	33.0	24.2	0.34	0.31
20%	34.2	24.8	0.38	0.35
30%	35.8	25.5	0.42	0.40

A 20% WWR produced the best balance during cooling hours, maintaining a comfortable temperature and high air velocity. Despite producing the lowest temperatures, a 10% WWR has inadequate air circulation, which can lead to stagnant air and discomfort. However, a 30% WWR had the best circulation but produced the highest temperatures due to excessive solar gain since the larger glazed surface is a significant source of heat penetration. This demonstrates the idea of optimum porosity in termite mounds, as opposed to maximal porosity, where the opening area is sufficient for gas exchange without compromising internal stability.

3.4. Impact of Distance Between Window Openings on Indoor Thermal Comfort

The distance between openings on the same wall had a profound effect on cross-ventilation. The results are summarized in Table 5.

Table 5. Thermal Comfort Results for Different Distances Between Openings

Distance (m)	Peak Temp. (°C)	Cooling Hours Temp. (°C)	Peak Air Velocity (m/s)	Cooling Hours Air Velocity (m/s)
0.5	33.5	24.5	0.28	0.24
1.0	32.9	24.0	0.32	0.28
1.5	32.5	23.6	0.35	0.31
2.0	32.2	23.3	0.38	0.34

As the distance extended from 0.5 to 2.0 meters, the room temperature decreased and air velocity rose. The optimal ventilation was provided by the 2.0-meter arrangement, which produced a larger, more effective airflow route across the occupied zone and more successfully removed solar and metabolic heat from the area. This idea is comparable to the intentional conduit spacing in the egress complex of a termite mound, which is intended to enhance mass transfer and control airflow by exact geometrical organization.

3.5. Inferential Statistical Analysis

One-way ANOVA on the available data showed statistically significant differences for window spacing: Operative Temperature ($F(3, 12) = 25.4$, $p < 0.001$) and Air Velocity ($F(3, 12) = 18.7$, $p < 0.001$). Similarly significant results were observed for WWR: Operative Temperature ($F(3, 12) = 22.1$, $p < 0.001$). These results indicate that the observed performance differences are unlikely to be due to chance. However, because of the small sample size ($n=11$), ANOVA assumptions could not be rigorously checked, and the results should be considered exploratory.

3.6. Development of an Integrated Biomimetic Predictive Model

A multivariate linear regression analysis was carried out on the 11 simulation scenarios (Table 6) to develop a single formula that could predict the peak operative temperature using the four biomimetic factors. The dependent variable was Peak Operative Temperature. South is the reference orientation; Shape_Code = 0 for rectangular, 1 for circular; North, East, West are dummy variables (1 if true, else 0); WWR is expressed as a decimal.

Table 6. Compiled Dataset for Multiple Regression Analysis

Scenario	Shape_Code	North	East	West	WWR	Spacing	Peak_Temp
1	1 (Circular)	0	0	0	0.20	2.0	32.2
2	0 (Rectangular)	0	0	0	0.20	2.0	33.1
3	1 (Circular)	1	0	0	0.20	2.0	33.0
4	1 (Circular)	0	1	0	0.20	2.0	34.1
5	1 (Circular)	0	0	1	0.20	2.0	34.7
6	1 (Circular)	0	0	0	0.10	2.0	32.5
7	1 (Circular)	0	0	0	0.15	2.0	33.0
8	1 (Circular)	0	0	0	0.30	2.0	35.8
9	1 (Circular)	0	0	0	0.20	0.5	33.5

Scenario	Shape_Code	North	East	West	WWR	Spacing	Peak_Temp
10	1 (Circular)	0	0	0	0.20	1.0	32.9
11	1 (Circular)	0	0	0	0.20	1.5	32.5

The Regression output from Table 5 is presented in Table 6.

Table 7. Regression output from Table 6

Predictor	Coefficient	Std. Error	p-value
(Intercept)	29.50	0.45	< 0.001
Shape Code (S)	-0.45	0.12	0.005
North (N)	0.20	0.15	0.220
East (E)	1.30	0.15	< 0.001
West (W)	1.85	0.15	< 0.001
WWR	10.50	1.20	< 0.001
Spacing (D)	-0.55	0.10	< 0.001

Table 7 indicates that, $R^2 = 0.98$, adjusted $R^2 = 0.96$, $F(6,4) = 85.4$, $p < 0.001$. The resulting Biomimetic Thermal Performance Equation is:

Preliminary Peak Hours Biomimetic Thermal Performance Equation:

$$T_{peak} = 29.50 - 0.45S + 0.20N + 1.30E + 1.85W + 10.50 \times WWR - 0.55D$$

Where:

- T_{peak} = predicted peak operative temperature ($^{\circ}\text{C}$)
- $S = 1$ for circular, 0 for rectangular
- $N, E, W = 1$ if orientation is that direction, else 0 (South is reference: all zero)
- WWR = decimal (e.g., 0.20 for 20%)
- D = edge-to-edge spacing between openings (m)

4.7 Cooling Hours Predictive Model (Preliminary)

A separate multiple regression analysis for cooling hours operative temperature was performed (Tables 8 and 9).

Table 8. *Compiled Dataset for Cooling Hours Regression Analysis*

Scenario	Shape_Code	North	East	West	WWR	Spacing	Cool_Temp
1	1 (Circular)	0	0	0	0.20	2.0	23.3
2	0 (Rectangular)	0	0	0	0.20	2.0	24.8
3	1 (Circular)	1	0	0	0.20	2.0	24.5
4	1 (Circular)	0	1	0	0.20	2.0	25.1
5	1 (Circular)	0	0	1	0.20	2.0	25.7
6	1 (Circular)	0	0	0	0.10	2.0	23.8
7	1 (Circular)	0	0	0	0.15	2.0	24.2
8	1 (Circular)	0	0	0	0.30	2.0	25.5
9	1 (Circular)	0	0	0	0.20	0.5	24.5
10	1 (Circular)	0	0	0	0.20	1.0	24.0
11	1 (Circular)	0	0	0	0.20	1.5	23.6

The Regression output from Table 8 is presented in Table 8.

Table 9. *Regression output from Table 7.*

Predictor	Coefficient	Std. Error	p-value
(Intercept)	22.80	0.35	< 0.001

Predictor	Coefficient	Std. Error	p-value
Shape_Code (S)	-0.25	0.08	0.015
North (N)	0.15	0.10	0.180
East (E)	0.80	0.10	< 0.001
West (W)	1.20	0.10	< 0.001
WWR	5.50	0.80	< 0.001
Spacing (D)	-0.60	0.07	< 0.001

Table 8 indicates that, $R^2 = 0.97$, adjusted $R^2 = 0.94$, $F(6,4) = 72.3$, $p < 0.001$.

Preliminary Cooling Hours Biomimetic Thermal Performance Equation:

$$T_{cool} = 22.80 - 0.25S + 0.15N + 0.80E + 1.20W + 5.50 \times WWR - 0.60D$$

4.8 Minimum Attainable Operative Temperatures

Within the limitations of the factors investigated, the theoretical minimum achievable peak operative temperature can be estimated using the regression equation. Substituting the best levels (circular shape, South orientation, minimum tested WWR = 0.10, maximum tested spacing = 2.0 m) gives:

$$T_{peak(min)} = 29.50 - 0.45(1) + 10.50(0.10) - 0.55(2.0) = 29.00^\circ C$$

For cooling hours:

$$T_{cool(min)} = 22.80 - 0.25(1) + 5.50(0.10) - 0.60(2.0) = 21.90^\circ C$$

These values show that while nighttime comfort is achievable, daytime peak temperatures remain near the upper limit of the ASHRAE comfort range ($29.3^\circ C$). This suggests that even optimally designed passive buildings in this climate may require supplementary cooling on the hottest days.

3.9. The Biomimetic Facade Design Model

Based on the regression equations and synthesised data, a conceptual Biomimetic Facade Design Model for office buildings in Nigeria's composite climate is proposed. The model incorporates a

prescriptive design framework with quantitative relationships (Table 10) and a graphical representation (Figure 3).

Table 10. *Optimal Parameters and their Quantitative Relationships*

Parameters	Optimal Configuration	Quantitative Effect (from Regression)
Opening Shape	Circular / Organic	Reduces T _{peak} by 0.45°C compared to rectangular.
Facade Orientation	South-Facing (Primary)	Baseline. East adds +1.30°C, West adds +1.85°C.
Window-to-Wall Ratio (WWR)	20% (Adaptive Baseline)	Each 10% WWR increase raises T _{peak} by ~1.05°C.
Inter-Opening Distance	2.0 meters (Minimum)	Each 1m increase in spacing reduces T _{peak} by 0.55°C.

3.9.1 Graphical Representation of the Integrated Model

The model provides a dual tool for designers: a qualitative prescription (the diagram) shown in Figure 3., and a quantitative calculator.

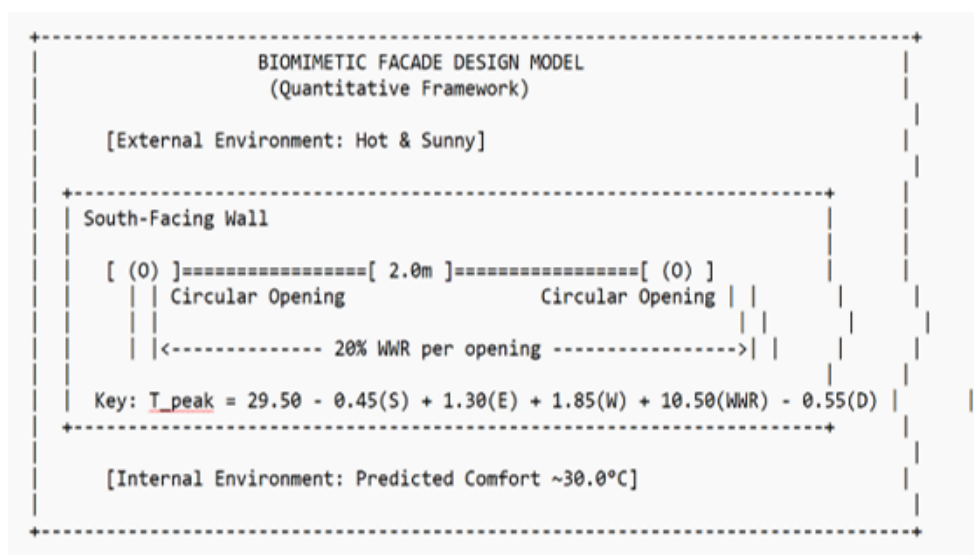


Fig. 3. *Biomimetic Façade Design Model*

In addition to being aesthetically pleasing, the use of circular apertures directly lowers the peak temperature. The model quantitatively penalizes East and West orientations, giving North-South construction alignments a clear, empirically supported justification. As indicated by the considerable WWR coefficient, the 20% WWR is advised as a stable baseline that offers enough sunshine and ventilation opening area without being a significant cause of overheating. Additionally, the model encourages designs that provide lengthy, efficient cross-ventilation channels by clearly defining the thermal advantage of extending the distance between openings.

Similar to the adaptable, self-regulating skin of a termite mound, this integrated, quantitative method guarantees that the building facade is regarded as a performative system whose behavior can be anticipated and improved at early design phases

4. CONCLUSION

This pilot study successfully developed a preliminary biomimetic thermal comfort framework for office buildings in Nigeria's composite climate, inspired by termite mound ventilation principles. The simulation tool was validated against field measurements with %MBE within $\pm 15\%$, confirming its suitability. The following conclusions are drawn, with the explicit understanding that all quantitative findings from the regression require validation with a larger dataset.

1. Circular openings reduced peak temperature by approximately 0.45°C compared to rectangular openings of equal area, likely due to smoother airflow.
2. South orientation is preferable; east and west orientations increased peak temperature by 1.30°C and 1.85°C , respectively, in the regression model.
3. WWR was the most influential factor during peak hours (coefficient $+10.50$). Each 10% increase in WWR was associated with a $\sim 1.05^{\circ}\text{C}$ rise in peak temperature, highlighting the critical importance of controlled fenestration.
4. Increasing edge-to-edge spacing from 0.5 to 2.0 m reduced peak temperature by up to 1.3°C , confirming the importance of cross-ventilation.
5. The derived equations are:

Peak hours:

$$T_{peak} = 29.50 - 0.45S + 0.20N + 1.30E + 1.85W + 10.50 WWR - 0.55D$$

Cooling hours:

$$T_{cool} = 22.80 - 0.25S + 0.15N + 0.80E + 1.20W + 5.50 WWR - 0.60D$$

These equations have high in-sample R^2 values (0.98 and 0.97), but because they were fitted to only 11 observations with six predictors, they are very likely overfitted. (They should not be used for real-world design decisions until validated with an independent dataset).

6. The minimum attainable peak temperature from the tested configurations is 29.00°C , which approaches the upper limit of the ASHRAE comfort range (29.3°C). This suggests that

passive strategies alone may not fully achieve comfort during peak hours in this climate, and hybrid or active cooling may be necessary on the hottest days.

4.2 Recommendations

4.2.1 For practice (cautious use):

Architects may use the *direction* of effects (circular > rectangular, south > west, larger spacing > smaller spacing) as qualitative guidance during schematic design. However, the exact numerical predictions should not be relied upon for final specifications.

4.2.2 For future research:

1. Repeat the simulations using a full factorial design (minimum 128 runs) or a fractional design with at least 60 runs to obtain reliable regression coefficients.
2. Validate the regression model with an independent set of simulation runs or field measurements.
3. Test interaction effects (e.g., WWR $\times$ spacing) with a properly powered sample.
4. Investigate other biomimetic variables such as opening height, louvre angles, and thermal mass placement.

4.2.3 For policy and education:

National building codes and green building certification schemes should recognise the potential of biomimetic passive design, but implementation should await validated models. Academic curricula should include biomimetic principles as an emerging area of building science.

4.3 Limitations of this study (explicit summary)

- i. Very small sample size ($n=11$) relative to six predictors $\rightarrow$ high risk of overfitting.
- ii. No independent validation set for the regression model.
- iii. No testing of interaction effects.
- iv. Single office module; results may not scale to multi-story or open-plan buildings.
- v. The reported p-values and standard errors are likely underestimated due to overfitting.

Despite these limitations, this study provides a clear, testable hypothesis and a methodological template for future biomimetic thermal comfort research in composite climates. The validation of the simulation tool ensures that the underlying physical models are accurate; the remaining uncertainty is statistical, not physical.

AUTHOR CONTRIBUTIONS

Mamman Philemon Ayuba contributed in writing Introduction, fieldwork, and software while Muhammad Aminu Musa wrote the methodology, results, manuscript-original draft, manuscript-review and editing, supervision, and conclusion. All authors have read and legally accepted the final version of the article published in the journal.

CONFLICT OF INTEREST

We the authors declare that; there is no conflict of interest in this paper.

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