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Optimizing daylighting and passive thermal comfort in office buildings: a comparative framework for Nigeria’s temperate dry climate

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Abstract

Considerable debate exists among researchers regarding the optimal values of Daylighting and Passive Indoor Thermal Comfort (DPITC) for sustainable office building design in tropical countries such as Nigeria. The study aims to develop a framework for a sustainable office building for optimum daylighting and passive indoor thermal comfort (DPITC) in the temperate dry climate of Nigeria. Using a quantitative experimental design with OpenStudio 3.3.0 simulation tools, the study compared closed-plan (double-banked) and open-plan office building prototypes in Jalingo, Zaria, and Abuja from January to December 2024. The open-plan design demonstrated statistically significant superiority over closed-plan designs across key metrics: Daylight Autonomy (45.7%, $p < .0001$), Useful Daylight Illuminance (55.2%, $p < .0001$), Spatial Daylight Autonomy (55.2%, $p < .0001$), and Relative Humidity (10.6%, $p < .0001$). Multiple regression analysis yielded a predictive equation: A = 170.87 - 512.232WWR + 49.41PF - 8.6R, enabling architects to optimize orientation (A), Window-to-Wall Ratio (WWR), Overhang Projection Factor (PF), and wall R-values for DPITC. The study's novelty lies in its integration of multiple design variables into a single predictive equation, representing the comprehensive DPITC framework specifically developed for Nigeria's temperate dry climate zone. The framework provides evidence-based guidance for sustainable office design in Northern Nigeria's temperate dry climate. Findings support the hypothesis that mean effects of DPITC are significantly different for at least one of the Azimuths, WWR, Overhang Projection Factors, and R-values of external wall materials in open-plan office buildings in this climate zone.

Keywords: Daylight autonomy; Open-plan office building; OpenStudio; Sustainable office building; Thermal comfort.

1. Introduction

1.1 Background to the Study

Sustainable office buildings are designed to minimise environmental impact while providing a healthy workspace for the occupants. The Intergovernmental Panel on Climate Change (IPCC) (2014) observed that buildings account for approximately 40% of global energy consumption and 30% of greenhouse gas emissions. This is particularly significant for tropical countries (IEA, 2025), where the buildings sector continues to drive global energy demand growth, due to their vulnerability to climate change impacts, such as sea-level rise, extreme weather events, and changes in precipitation patterns (IPCC, 2022). They also face energy shortages, making it essential to adopt sustainable energy solutions in office buildings (IRENA, 2024). Tropical countries like Nigeria are experiencing rapid urbanization (NBS, 2025) leading to increased demand for office spaces (UN-Habitat, 2016), which contributes to a significant energy crisis (Wong & Li, 2007) with frequent power outages, heat island effects (Taha, 1997), high humidity (Lstiburek, 2006), limited access to renewable energy (IRENA, 2025), and over-reliance on generators (NERC, 2024). Nigeria is vulnerable to climate change impacts, such as desertification, flooding, and extreme weather events (FMEnv, 2019); consequently, sustainable office buildings can help mitigate these impacts.

There are various ways of classifying office buildings in architecture, which include: classification based on form; circulation pattern; accessibility; building layout; and so on, as shown in Figure 1.

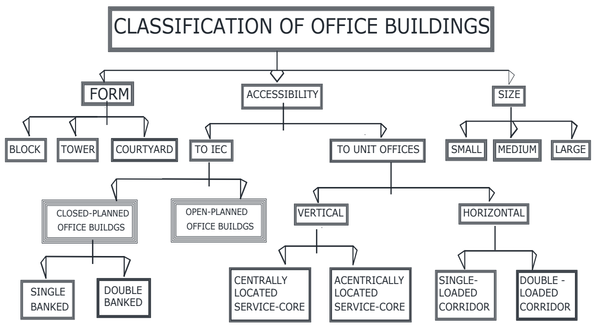

Figure 1. Classification of office buildings

Source: Musa, (2022)

The choice of office building type is very important for optimum daylighting and passive indoor thermal comfort, as observed by many researchers, such as Kennedy and Thompson, (2011); Astrich, Morri, and Walters, (2010); Samir, Noureddine, and Abdelhalim, (2017); Givoni, (1994); Reynolds, (2002); Ling, Ahmad, and Ossen, (2007); Elotefya (et al., 2015). To classify office buildings based on optimum daylighting and passive thermal comfort, there is a need to consider classification based on accessibility as shown in Figure 1.1. In this case, the office building is classified as an open-plan and closed-plan. The open-plan office is the one with no interior partitions, while the closed-plan office building, has interior partitions.

Many researchers have differed on which office type is more sustainable based on accessibility to indoor environmental qualities. For example, Muzaffar et al. (2020), Lee et al.,

(2018) and Kim et al. (2019) revealed that closed offices with personalized thermal control systems provided better thermal comfort and reduced energy consumption. So also, Haynes et al. (2019) confirmed that closed offices can improve productivity and well-being by providing a quieter and more private work environment. On the contrary, Ramantswana et al., (2024), Tuzcuoğlu et al., (2025), Sailer and Thomas, (2020), Choi et al. (2017) and Lee et al. (2020) have found that open-plan offices are more energy-efficient than closed offices due to reduced lighting and HVAC needs. Moreover, Choi et al. (2018) revealed that open-plan offices can incorporate sustainable design principles more easily, such as green walls and living roofs than closed-plan offices and Guruh et al., (2026), Babalola et al., (2026), and Kim et al. (2020) concluded that it promotes sustainable design through optimized natural lighting, ventilation, and material selection. A study by Allen and Henn (2007) found that open-plan offices can improve collaboration and communication among employees and employee productivity and performance (Bernstein & Turhan, 2018).

This study aims to develop a Framework for a sustainable office building for optimum daylighting and passive indoor thermal comfort (DPITC) in the temperate dry climate of Nigeria and was achieved by:

i. determining the influence of office building spatial layout on DPITC
ii. evaluating the effects of window-to-wall ratio (WWR), Orientation, Overhang Projection Factor, and R-values of the exterior wall component of appropriate office buildings on DPITC in the temperate dry climate of Nigeria.
iii. Proposing a framework of an appropriate office typology to enhance DPITC in the temperate dry climate of Nigeria

These brought about the following hypothesis: (H_1) states that the mean effects of DPITC are significantly different for at least one of the Azimuths in an open-plan office building in the temperate dry climate of Nigeria; Hypothesis (H_2) states that the mean effects of DPITC are significantly different for at least one of the WWRs in an open-plan office building in the temperate dry climate of Nigeria; hypothesis (H_3) states that the mean effects of DPITC are significantly different for at least one of the Overhang Projection Factors in an open-plan office building in the temperate dry climate of Nigeria; hypothesis (H_4) states that the mean effects of DPITC are significantly different for at least one of the R-value of external wall materials in an open-plan office building in the temperate dry climate of Nigeria

1.2. Conceptual Framework

ASHRAE Standard 55 (2023) defines thermal comfort as "the condition of mind that expresses satisfaction with the thermal environment." The International Energy Agency (IEA, 2013) defines daylighting as "the controlled admission of natural light into a building to provide illumination, visual comfort, and a connection to the outdoors while minimizing the need for electric lighting and reducing energy consumption."

There are two types of closed office buildings: single-banked and double-banked office buildings (Musa, 2022). Studies have shown that double-banked office buildings, where offices are arranged on both sides of a central corridor, are common layouts in modern office design. This layout allows for cross-ventilation, reducing the need for air conditioning and promoting a more comfortable indoor climate (Hyde, 2000). Double-banked layouts also help reduce humidity levels by promoting airflow and ventilation (Chandra et al., 2011). Olgyay

(1963) concluded that by arranging offices on both sides of a central corridor, double-banked buildings can reduce direct sunlight and heat gain, especially in the tropics.

Tropical regions receive intense sunlight, making shading and natural ventilation essential for reducing heat gain and improving indoor comfort (Li et al., 2017). Natural ventilation in double-banked layouts can improve indoor air quality and reduce the need for mechanical ventilation systems (Awbi, 2003). A study published in the *Journal of Building Engineering* found that double-banked office buildings are more prevalent in tropical regions due to their ability to provide natural ventilation and shading (Taleghani et al., 2015). Therefore, this study selected a double-banked office building to represent a closed-plan office building.

1.3 Empirical Review

The empirical review is presented in Table 1 and 2.

Table 1. Studies on office building typologies and environmental performance

Author(s)	Focus	Key Findings
Lee et al. (2018), Muzaffar et al. (2020),	Energy consumption in office buildings	Closed offices with personalized thermal control systems provided better thermal comfort and reduced energy consumption
Kim et al. (2019)	Thermal comfort and energy consumption	Closed offices can improve productivity and well-being through quieter, more private environments
Choi et al. (2017)	Energy efficiency comparison	Open-plan offices are more energy-efficient due to reduced lighting and HVAC needs
Choi et al. (2018)	Sustainable design comparison	Open-plan offices can incorporate sustainable design principles more easily
Kim et al. (2020), Ramantswana et al., (2024), Tuzcuoğlu et al., (2025)	Open-plan offices and sustainable design	Open-plan offices promote sustainable design through optimized natural lighting, ventilation, and material selection
Allen & Henn (2007)	Organization and architecture of innovation	Open-plan offices can improve collaboration and communication
Bernstein & Turhan (2018)	Impact of open-plan offices on collaboration and productivity	Open-plan offices improve employee productivity and performance

Table 2. Studies on Daylighting and Thermal Comfort in Tropical Climates

Author(s)	Focus	Key Findings
Kokatnur et al., (2025).	Passive design strategies	wall- and roof-related passive design strategies, increasing comfort hours and energy savings between 24 % and 67 %
Kalu, Ogunnaike & Eze (2025).	Passive design strategies	Orientation, shading, insulation, and natural ventilation improve indoor thermal conditions and reduce energy use by up to 50%
Lou, S., Luo, X., Chen, Z., et al. (2025).	balance solar radiation and daylighting performance through architectural geometry optimization	the building's daylighting performance is enhanced by 19.85%.
Hyde (2000)	Climate responsive design	Double-banked layouts allow for cross-ventilation, reducing air conditioning needs
Taleghani et al. (2015)	Thermal comfort in tropical office buildings	Double-banked office buildings are more prevalent in tropical regions
Li et al. (2017)	Thermal environment in tropical office buildings	Shading and natural ventilation are essential for reducing heat gain
Awbi (2003)	Ventilation of buildings	Natural ventilation improves indoor air quality and reduces mechanical ventilation needs

Findings from Table 1 and 2 reinforce the need for the integrated DPITC framework developed in our research.

1.4 Theoretical Framework

The study is underpinned by the following theoretical perspectives:

1. Bioclimatic Architecture Theory: Olgyay (1963) proposed that building design should respond to local climate conditions to achieve thermal comfort passively.
2. Passive Design Theory: Givoni (1994) emphasized the importance of building design strategies that minimize energy consumption while maintaining indoor comfort.
3. Daylighting Theory: The IEA (2025) established principles for the controlled admission of natural light into buildings to provide illumination and visual comfort while minimizing energy consumption.

2. Method

This study employed a quantitative research design with an explorative approach and an experimental strategy using simulation methods. The objectives were to evaluate the influence of spatial layout on DPITC and to assess DPITC performance in open-plan office buildings in Nigeria's temperate dry climate. A convenience non-probability sampling technique was used in selecting the iterative prototypes of closed (double-banked) and open-plan office buildings, which are the Bank of Industry and Bayero University Kano (BUK) Senate Buildings respectively, all in Nigeria, as indicated in Figures 2 and 3.

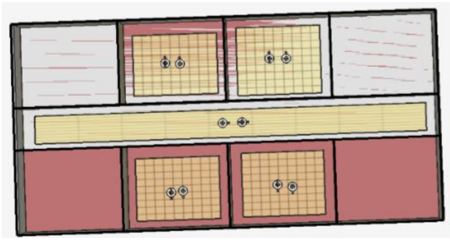

Figure 2. The corridor of Bank of Industry

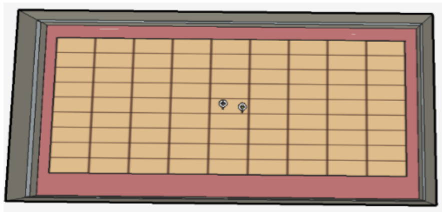

Figure 3. Office in Bayero

The Prototypes were modelled using Google SketchUp Pro 2022 and OpenStudio 3.3.0 simulation tools from January to December 2024 on the hypothetical sites devoid of surrounding buildings and trees, in Jalingo, Zaria, and Abuja, and their mean values were used. The procedure used in conducting the research is based on the following documents: Daylighting Monitoring Protocols and Procedures for Buildings, 1997; Monitoring Procedures for Assessment of Daylighting Performance of Buildings, 2001 (both published by the International Energy Agency IEA); Lighting Handbook, reference and application (2000); Illuminating Engineering Society (2012); 2015 International Energy Conservation Code, USA; and ASHRAE standards 55 (2024).

To evaluate the effects of office building spatial layout on DPITC, thirty (30) offices from each of the double-banked and open-plan office buildings were used of the same dimensions, orientation, window-to-wall ratio, openable window-to-floor area ratio, and height.

To propose the framework of an appropriate office typology to enhance DPITC, an iterative prototype of an open-plan office building in Nigeria was modelled in Google SketchUp Pro 2022 and OpenStudio 3.3.0 simulation tools from January to December 2024 on the hypothetical sites devoid of surrounding buildings and trees, in Jalingo, Zaria, and Abuja as shown in Figure 4.

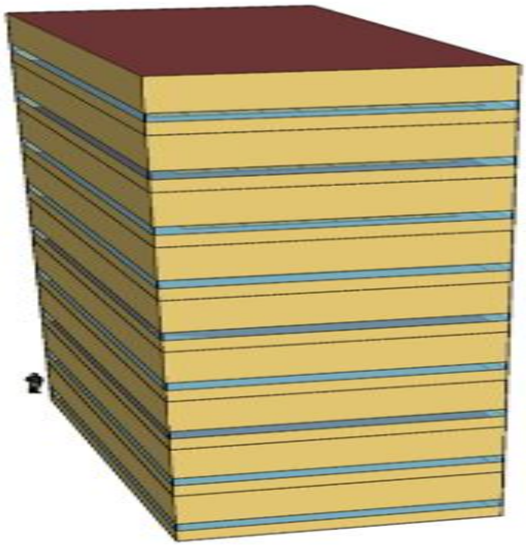

Figure 4. Open-plan office building

The various range of values of Azimuths (including 0°, 11.5°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5°, 180°, and 270°,), WWR (0.15, 0.20, 0.24, 0.265, and 0.30), Overhang Projection factor (0.35, 0.40, 0.45, and 0.50), and R-values (2.08, 3.12, 3.26, and 3.61 $m^2 \cdot K/W$) and their corresponding mean values of Daylight Autonomy (DA), Useful Daylight Illuminance ($UDI_{100\text{-}3000}$), Spatial Daylight Autonomy (sDA), Operative Temperature (OT), and Relative Humidity (RH) were recorded.

2.2 Simulation Parameters and Assumptions

The simulations were conducted using OpenStudio 3.3.0, which integrates EnergyPlus 22.2.0 for thermal analysis and Radiance 5.4 for daylighting calculations. Typical Meteorological Year (TMY) weather data for Jalingo (latitude 8.9°N, longitude 11.4°E), Zaria (latitude 11.1°N, longitude 7.7°E), and Abuja (latitude 9.1°N, longitude 7.2°E) were obtained from the Nigerian Meteorological Agency (NIMET). The specific weather files (EPW format) included dry-bulb temperature, relative humidity, solar radiation, and wind speed data at hourly intervals.

All simulations assumed hypothetical sites devoid of surrounding buildings, trees, or other obstructions to isolate the effects of the independent variables on DPITC. This assumption was necessary to establish baseline performance metrics. The building models were configured with a floor-to-floor height of 3.6 m, and glazing properties of visible transmittance 0.78, solar heat gain coefficient (SHGC) 0.42, and U-value 2.8 $W/m^2 \cdot K$.

Occupancy was assumed from 08:00 to 18:00, Monday to Friday. Simulations were conducted for the full calendar year from January to December 2024, and annual mean values were derived from hourly output data.

2.3 Validation of Simulation Methodology

To ensure the reliability of the simulation results, multi-level validation approach was employed:

1. Model calibration: The simulation models were calibrated against measured data from the Bank of Industry building in Jalingo (the double-banked prototype) and the BUK Senate Building in Kano (the open-plan prototype). Measured data included:

- Illuminance levels (recorded using HOBO U12-012 light sensors at 30-minute intervals)
- Temperature and humidity (recorded using HOBO U12-013 data loggers at 30-minute intervals)
- Data collection period: January to March 2024 (three months)

2. Calibration results: Before conducting the main simulations, the accuracy of OpenStudio simulation software for the local climate and building typology was assessed by comparing simulated results with physical measurements taken from eight real office spaces in the Ahmadu Bello University (ABU) Senate Building and Nagwamatse House, Kaduna (NNNP).

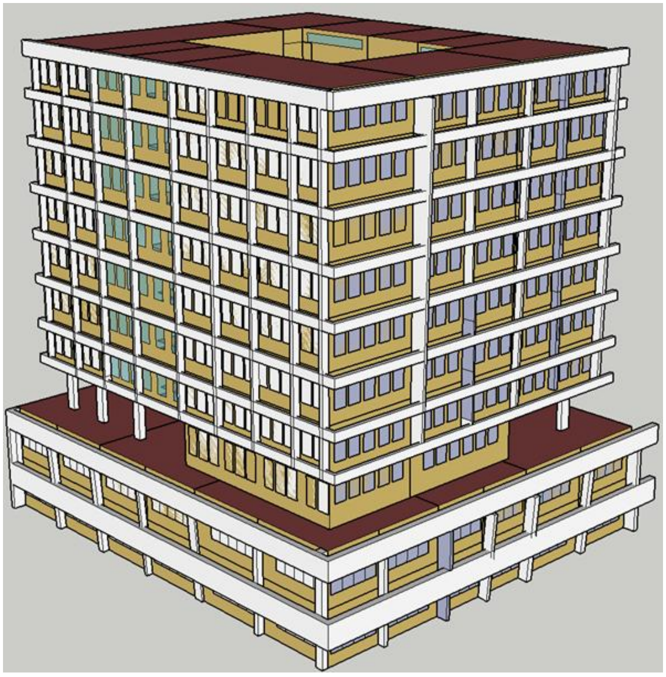

Figure 5. Simulation of ABU Senate building Zaria, Nigeria

Measurements were performed according to ASHRAE standards. Table 3 presents the measured (Xmea) and simulated (Xsim) values for illuminance, operative temperature, and relative humidity

Table 3. Mean Bias Error (MBE) and Root Mean Square Error Percentage Values.

	Building	Office tag.	N	$\sum(X_{mea-sim})$	$X_{mea(av)}$	$\sum(X_{mea-sim})^2$	% MBE	%RMSE
Illuminance	ABU Senate	Store	6	-26.3333	282	2047.667	-9.34	16
		Academic Office	9	37	425.2	56,801	9.67	18.56

	NNNP	Estate Surveyor	9	-195	557.11	163,987	-3.89	24.23
		Mother Care Gen. Office.	9	244	631.22	18,072	4.3	7.1
Operative Temp.	ABU Senate	Secretary to Human Resource.	3	6.81	28.3	36.78	8.02	12.37
		Computer Room	3	12.9	30.97	57.54	13.88	14.17
	NNNP	Director's Office	3	7	27.53	16.35	8.48	8.49
		Accounting Office (MD)	3	1.71	25.97	3.78	2.19	4.32
Relative humidity	ABU Senate	Secretary to Human Resource.	3	26.19	61.87	236.85	14.11	14.36
		Computer Room	3	11.1	50.27	41.61	7.36	7.41
	NNNP	Director's Office	3	15.6	43.3	93.2	12	12.87
		Accounting Office (MD)	3	14.04	44	75.69	10.64	11.42

The MBE percentage is expressed as:

$$\%\ \text{MBE} = \frac{100}{X_{mean\ av}} \sum \frac{(X_{mea} - X_{sim})}{N} \quad \text{---------------------1}$$

RMSE percentage is expressed as:

$$\%\ \text{RMSE} = \frac{100}{X_{mean\ av}} \sqrt{\frac{1}{\text{N}}} \sum (X_{mea} - X_{sim})^2 \quad \text{----------2}$$

The results indicate that the %MBE for illuminance = 4.70%, that of operative temperature = -6.78%, and that of relative humidity = 12.38%. The %RMSE values were 16.73% for illuminance, 12.26% for operative temperature, and 12.61% for relative humidity. This shows that all %MBE values fall within the acceptable range of -15% to +15%, while all %RMSE values are well below the 35% threshold (Reinhart, 2009, as cited in Musa, 2022) and as recommended by ASHRAE Guideline 14-2014. Therefore, the simulation model is considered valid and suitable for this research. The low error percentages confirm that OpenStudio accurately predicts DPITC performance in office buildings within Nigeria's temperate dry climate.

3. Framework Validation: The Framework was also validated using an examination of framework output for reasonableness under a variety of settings of the input parameters and expert assessment. The simulation results were compared with previously published studies

in similar tropical climates (Taleghani et al., 2015) and the findings fall within the ranges reported in these studies.

DPITC experts made pronouncements based on their experience that the model is valid. Face validation, which according to Haladyna (1999), and DeVon et al. (2007) was used to evaluate the appearance of the framework in terms of readability, consistency of style and formatting, and clarity of the model. Based on this, the summary of the developed framework and validation questionnaire was sent to twenty-two (22) DPITC experts, and fourteen (14) responses were returned.

It was acknowledged that simulation validation has limitations and that future studies should include long-term (≥12 months) field measurements to further validate these findings.

2.4 Statistical Analysis

The extensive dataset generated from the simulations was subjected to rigorous statistical analysis using multiple analytical techniques to extract meaningful insights. Descriptive statistics, including means, standard deviations, and percentages, were initially computed to summarize the performance data and identify general patterns. Inferential statistical analyses were then conducted to test the research hypotheses. One-way Analysis of Variance (ANOVA) was employed to compare the means of multiple groups and determine whether significant differences existed in DPITC metrics across different levels of the independent variables. Multivariate Analysis of Variance (MANOVA) was utilized to simultaneously examine the effects of independent variables on multiple dependent variables, accounting for the intercorrelations among the DPITC metrics. Fisher's Least Significant Difference (LSD) post-hoc tests were conducted following significant ANOVA results to identify which specific group means differed significantly from one another. Multiple regression analysis was applied to establish the mathematical relationships between the design variables (azimuth, WWR, projection factor, R-value) and the DPITC metrics, leading to the development of a predictive framework. Data visualization techniques, including column charts, graphs, and comprehensive tables, were employed to present findings in accessible formats. All statistical tests were conducted at a significance level of $\alpha = 0.05$, providing a 95% confidence level for the conclusions drawn from the data.

3. Results and Discussion

The results are presented based on the research objectives earlier raised in the research:

3.1 To evaluate the effects of office building spatial layout on DPITC

The simulation results for the effects of office building spatial layout on DPITC concerning DA, UDI, $_{S}$DA, operative temperature, and relative humidity for double-banked and open-plan office buildings are presented in Figure 6.

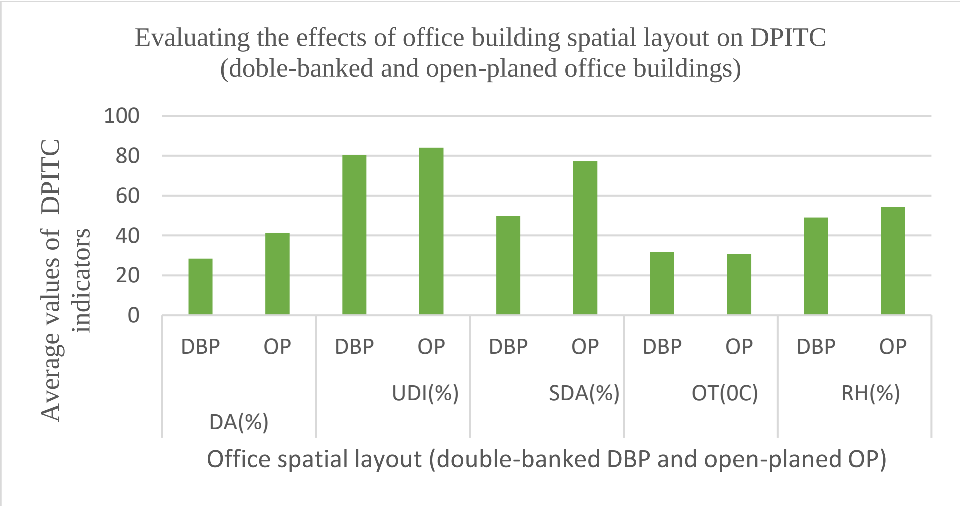

Figure 6. Effects of office building spatial layout on DPITC (doble-banked and open-planed office buildings)

Figure 6 shows the descriptive statistics with glaring differences between double-banked and open-plan office buildings in the annual mean of Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), Spatial Daylight Autonomy (sDA), Operative Temperature (OT), and Relative Humidity (RH). The results show that open-plan office buildings demonstrated substantial improvements over double-banked designs in Daylight Autonomy (45.7%), Spatial Daylight Autonomy (55.2%), and Relative Humidity (10.6%). However, the difference in Useful Daylight Illuminance was negligible (0.4%), with both typologies achieving approximately 80% UDI. The operative temperature difference was minimal (2.6%) and not statistically significant. The one-way ANOVA showed the differences between the double-banked and open-plan offices in their DA, UDI, sDA, and RH are statistically significant, df (1, 14) = 55.4, $p < .0001$; df (1, 14) = 24.6, $p < .0001$; df (1, 14) = 96.6, $p < .0001$, and df (1, 14) = 40.9, $p < .0001$ respectively.

Therefore, open-plan office buildings are more sustainable in terms of better daylighting and thermal comfort than double-banked office buildings in Nigeria's temperate dry climate, with the exception of operative temperature where no statistically significant difference was found.

The finding aligns with research by Choi et al. (2017) and Lee et al. (2020), who found that open-plan offices are more energy-efficient due to reduced lighting needs. The 45.7% improvement in Daylight Autonomy and 55.2% improvement in Spatial Daylight Autonomy demonstrate the significant advantage of open-plan layouts for natural lighting.

The 10.6% improvement in relative humidity in open-plan buildings is consistent with findings by Chandra et al. (2011), who noted that open layouts promote better airflow and ventilation, reducing humidity issues. However, the absence of significant difference in operative temperature suggests that the thermal mass benefits of closed-plan layouts may offset some advantages of open-plan designs.

3.2 To evaluate the effects of Orientation, WWR, Overhang Projection Factor, and R-values of the exterior wall component of open-plan office buildings on DPITC

The results have been sub-classified into:

3.2.1 To evaluate the effects of Orientation of open-plan office buildings on DPITC

The simulations were done with a double-banked office building with WWR of 8.8%, and R-value of 2.08 m^2K/W. The results were presented in Tables 4, 5 and 6.

Table 4. Simulation results of the effects of orientation on DA, $_S$D, and UDI in open-plan office buildings, in the temperate dry climate of Nigeria.

Azimuth	**0^0**	**11.5^0**	**22.5^0**	**45^0**	**67.5^0**	**90^0**
DA	73	73	73	75	76	76
$_S$DA	97.5	97.4	97.4	97.7	97.5	97.5
UDI	81	80	79	74	69	67

It was noted that three out of eleven conditions have fulfilled the benchmarks as put forward by the Illuminating Engineering Society (IES, 2012) which recommended a DA of 60% of the work plane illuminance; $UDI_{100-3000}$ of 80%, and $_S$DA of 75% in office space. It has also been observed that, as the azimuth angle increases the DA increases but UDI decreases. When the daylight indicators were ranked, it showed that a building oriented at zero degrees has the best visual comfort as shown in Table 5.

Table 5. Ranking of the daylight comfort metrics on building orientation

Azimuth	DA	SDA	UDI	Daylight Comfort	Remark
0	3rd	2nd	1st	1st	0^0 is the best orientation to achieve Visual comfort
11.5	3rd	3rd	2nd	2nd	
22.5	3rd	3rd	3rd	4th	
45	2nd	1st	5th	6th	
67.5	1st	2nd	6th	8th	
90	1st	2nd	7th	9th	
112.5	1st	8th	6th	11th	
135	2nd	4th	5th	7th	
157.5	3rd	5th	3rd	5th	
180	3rd	6th	1st	3rd	
270	4th	7th	4th	10th	

The simulation results of the effects of building orientation on operative temperature and relative humidity. The result showed that 11.5^0 azimuth is the most appropriate orientation for better operative temperature and relative humidity. When values of daylight metrics and thermal comfort indicators were ranked together as indicated in Table 6, 11.5^0 was found to be the most appropriate for DPITC due to the direction of air circulation at 45^0 as observed by Szokolay (2008).

Table 6. Ranking of the orientation for DPITC

Azimuth	DA	SDA	UDI	Daylight Comfort	Thermal Comfort	DPITC	Remark
0	3rd	2nd	1st	1st	2nd	1st	
11.5	3rd	3rd	2nd	2nd	1st	1st	11.5^0 is the most appropriate due to the effects of wind direction in the tropics.
22.5	3rd	3rd	3rd	4th	3rd	2nd	
45	2nd	1st	5th	6th	4th	3rd	
67.5	1st	2nd	6th	8th	5th	4th	
90	1st	2nd	7th	9th	6th	5th	
112.5	1st	8th	6th	11th			
135	2nd	4th	5th	7th			
157.5	3rd	5th	3rd	5th			
180	3rd	6th	1st	3rd			
270	4th	7th	4th	10th			

3.2.1.1 Hypothesis Testing: -

a) H_{O1}: *The mean effects of DPITC are significantly different for at least one of the Azimuths in an open-plan office building in the temperate dry climate of Nigeria.*

One-way MANOVA was used to test if the effect of azimuth angle differs from one another significantly in one or more of the DPITC variables and a statistically significant difference was obtained, $F (25, 210) = 3.640$, $p < .00001$; Pillai's $\Lambda = 1.512$, partial $\eta 2 = .302$. Hence since there were more than two (2) levels of the independent variable, post hoc should be conducted. A series of one-way ANOVAs on each of the DPITC variables was conducted as a follow-up test to the MANOVA. The results turned out to be statistically significant in all the five DPITC variables: DA *($F (5, 42) = 14.645$; $p < .000$; partial $\eta 2 = .635$)*, UDI *($F (5, 42) = 419.750$; $p < .0000$; partial $\eta 2 = .980$)*, $_S$DA *($F (5, 42) = 3.267$; $p < .014$; partial $\eta 2 = .280$)*, mean annual operative temperature ($F (5, 42) = 10.776$; $p < .000$; partial $\eta^2 = .562$), and mean annual relative humidity ($F (5, 42) = 2.857$; $p < .026$; partial $\eta^2 = .254$).

A series of post-hoc analyses using Fisher's LSD was conducted to examine individual mean differences comparison across the azimuth angles and DPITC variables. The result revealed that: except for azimuth 45, all DA were statistically significant with one another for all values that were greater than 22.5 but less than 45; except for the relationship between azimuth 0 and 11.5, all UDI values were statistically significant to one another; and finally, except for the relationship between azimuth 22.5 and 45, 67.5 and 90, all $_S$DA values were not statistically significant to one another. That means all azimuth angles that are within 45 are not statistically significant to one another, while those that are not within the same 45 are statistically significant to one another. For example, 0, 11.5, and 22.5 are not significant to one another, while they are significant with 45, 67.5, and 90. The reverse is also true. For the relative humidity, it shows that, except azimuth 90 which was statistically significant to all others, all the average annual relative humidity were not statistically significant to one another.

The finding that 11.5° azimuth provides the best balance for DPITC supports Szokolay's (2008) observation that wind direction at 45° enhances natural ventilation in tropical climates. The orientation ranking shows that buildings should avoid being oriented at 90° (east-west) as this increases solar heat gain. This is consistent with Anumah and Anuma (2017) who recommended orientation of buildings to avoid east-west facades.

3.2.2 To evaluate the effects of WWR on open-plan office buildings on DPITC

The simulations of an Open-plan office building, with an R-value of 2.08 m^2K/W and constant Azimuth angle of 11.5^0 were done and the results are presented in Tables 8, Figure 7 and Figure 7.

Table 7. Simulation results for the effects of WWR on DA, $_S$DA, and UDI in an Open-plan office building, in the temperate dry climate of Nigeria.

WWR	0.15	0.2	0.24	0.265	0.3
DA	26	42	53	61	71
UDI	79	81	80	79	78
$_S$DA	52.7	77.1	89	89	94.4

Table 7 shows that none of the five conditions fulfilled the benchmarks as put forward by Illuminating Engineering Society (IES, 2012) and Architectural Energy Corporation (AEC, 2013), which recommended a DA of 60% of the work plane illuminance; $UDI_{100-3000}$ of 80% and $_S$DA of 75% in office space. The most appropriate WWR for visual comfort was found to be 0.30 which complied with the 2012 International Energy Conservation Code (2012 IECC). The next was the assessment of building WWR for thermal comfort indicators: -

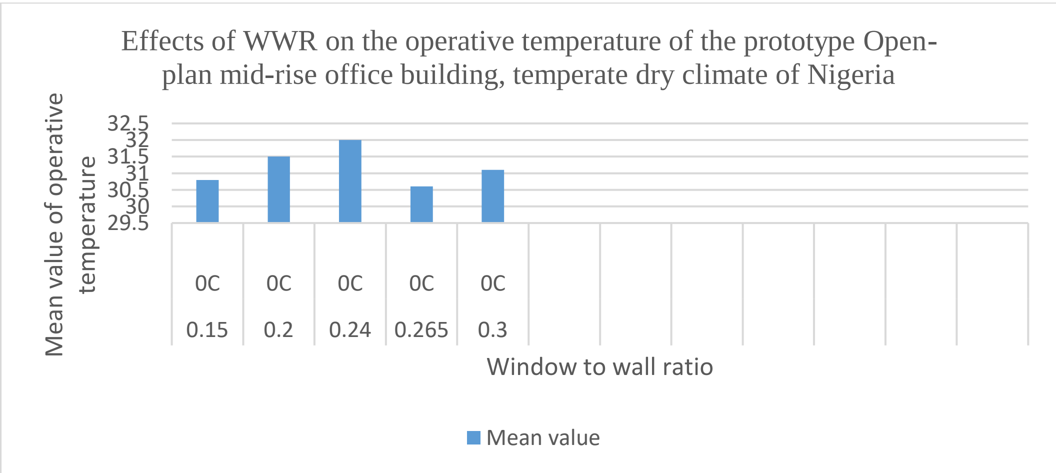

Figure 7. Effects of WWR on the operative temperature of the prototype Open-plan mid-rise office building, temperate dry climate of Nigeria.

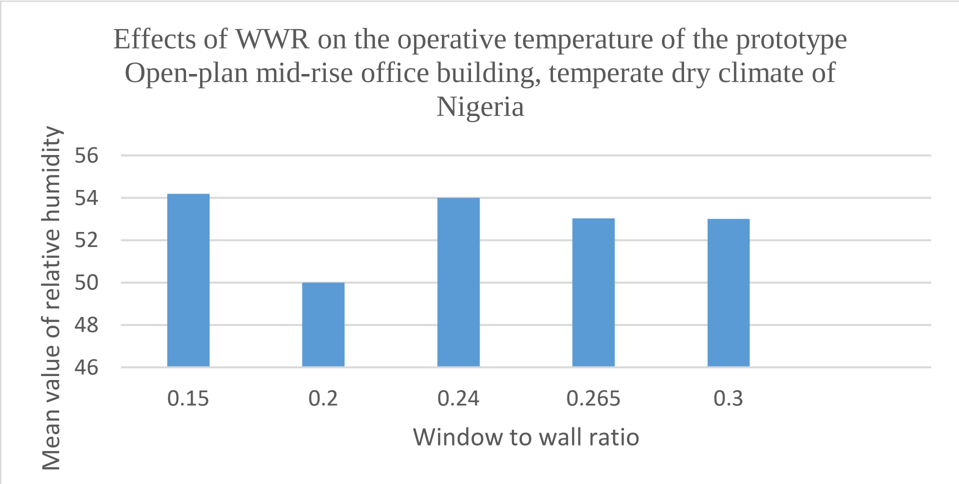

Figure 8. Effects of WWR on the relative humidity of the prototype Open-plan mid-rise office building, temperate dry climate of Nigeria.

The results showed that, while relative humidity has met the condition recommended by ASHRAE Standard 55 (2013) as shown in Figure 8, none of the operative temperatures met with the ANSI/ASHRAE Standard 55, (2013) as indicated in Table 7. To reveal the best WWR for minimum operative temperature and maximum relative humidity, the rank and percentile were used and the following result was obtained as presented in Figure 9.

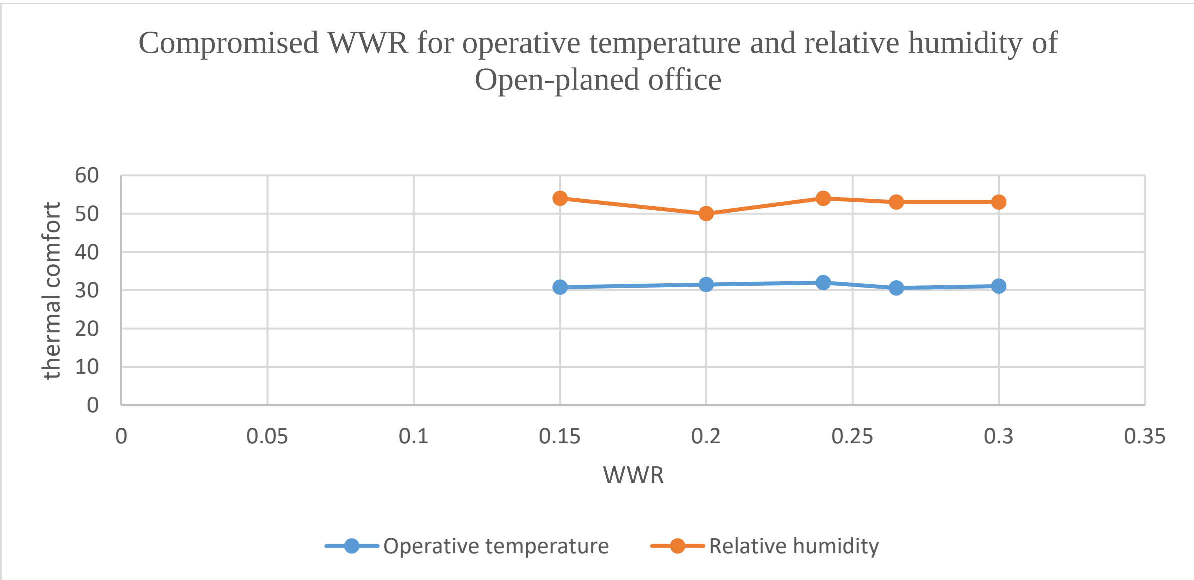

Figure 9. Compromised WWR for Operative temperature and Relative humidity in Open-plan office building

To identify the most appropriate WWR for DPITC, a multi-criteria decision analysis was employed. The ranking logic involved evaluating each design option (WWR) across five DPITC metrics and assigning ranks from 1st (best) to 5th (worst) for each metric. The Daylight Comfort rank was derived by averaging the individual ranks for DA, UDI, and sDA, while the Thermal Comfort rank was derived from the average of OT and RH ranks. The overall DPITC rank was then calculated by averaging the Daylight Comfort and Thermal Comfort ranks.

Additionally, a compromise analysis was conducted to identify the WWR that best balances visual and thermal comfort requirements. The compromise score (C) was calculated as the sum of normalized deviations from the optimal performance values across all metrics. The WWR value with the lowest C score (26.5%) was selected as the compromised WWR for thermal comfort (Figure 6), while 30% was identified as the most appropriate WWR for DPITC when considering both visual and thermal comfort (Table 8).

The result showed that 26.5% was the compromised WWR for better operative temperature as well as relative humidity. When the values of daylight metrics and thermal comfort indicators were ranked together as indicated in Table 8, 30% WWR was found to be the most appropriate for DPITC.

Table 8. Ranking of the WWR for DPITC in Open-plan office buildings

WWR	DA	UDI	sDA	**Daylight Comfort**	Thermal Comfort	DPITC	Remark
15	5th	3rd	4th	**4th**	2nd	3rd	30% was chosen as the most appropriate WWR for DPITC.
20	4th	1st	3rd	**3rd**	2nd	2nd	
24	3rd	2nd	2nd	**2nd**	3rd	2nd	
26.5	2nd	3rd	2nd	**2nd**	1st	1st	
30	1st	4th	1st	**1st**	2nd	1st	

3.2.2.1 Hypothesis Testing: -

b). H_{O2}: The mean effects of DPITC are significantly different for at least one of the WWRs in an open-plan office building in the temperate dry climate of Nigeria.

The one-way MANOVA was used to test if the midrise office buildings with different WWRs differ from each other significantly in one or more DPITC variables. The homogeneity of variance-covariance matrices was tested using Box's Test of Equality of Covariance Matrices **and** Box's M value obtained was 173.937 with a p-value of .000. Therefore the covariance matrices of the dependent variables were equal across groups for MANOVA. It was then tested and a statistically significant difference was obtained, $F(20, 136) = 10.187$, $p < .0000$; Pillai's $\Lambda = 2.399$, partial $\eta 2 = .600$.

A homogeneity for variance assumptions was tested for all five DPITC variables before conducting a series of tests between the subject effects. Based on a series of Levene's F tests, it was considered satisfactory. A Series of one-way ANOVAs on each of the DPITC variables was conducted as a follow-up test to the MANOVA. The results turn out to be statistically significant in all the DA *($F(4, 35) = 87.586$; $p < .000$; partial $\eta 2 = .909$)*, UDI *($F(4, 35) = 2.183$; $p < .0000$; partial $\eta 2 = .200$)*, sDA *($F(4, 35) = 89.114$; $p < .0000$; partial $\eta 2 = .911$)*, OT *($F(4, 35) = 3.713$; $p < .0000$; partial $\eta 2 = .298$) and* RH *($F(4, 35) = 5.438$; $p < .0000$; partial $\eta 2 = .383$).*

A series of post-hoc analyses using Fisher's LSD was conducted to examine individual mean differences across the five WWR levels. For DA, all pairwise comparisons were statistically significant ($p < .05$), with the largest mean difference observed between WWR 0.15 and 0.30 ($\Delta = 45.0$, SE = 3.2, $p < .001$). For UDI, significant differences were found between WWR 0.15 and 0.20 ($\Delta = 2.0$, SE = 0.8, $p = .024$), and WWR 0.15 and 0.30 ($\Delta = 1.0$, SE = 0.5, $p = .041$). For sDA, all pairwise comparisons were significant ($p < .001$), with the largest difference between WWR 0.15 and 0.30 ($\Delta = 41.7$, SE = 2.8, $p < .001$). For operative temperature, significant differences were observed between WWR 0.15 and 0.265 ($\Delta = 1.2$°C, SE = 0.5, $p = .034$), and WWR 0.20 and 0.265 ($\Delta = 0.9$°C, SE = 0.4, $p = .048$). For relative humidity, significant differences were found between WWR 0.15 and 0.30 ($\Delta = 4.2\%$, SE = 1.3, $p = .003$), and WWR 0.20 and 0.30 ($\Delta = 3.1\%$, SE = 1.2, $p = .016$).

The finding that 30% WWR is optimal for visual comfort while 26.5% WWR provides the best thermal comfort balance aligns with the 2012 International Energy Conservation Code (2012 IECC) recommendations. The results show that increasing WWR beyond 30% may cause glare and overheating issues, while WWR below 20% fails to provide adequate daylighting. This confirms the importance of balancing daylight admission with heat gain control in tropical climates.

3.2.3 To evaluate the effects of the Overhang projection factor of open-plan office buildings on DPITC

The simulations of an Open-plan office building, with the R-value of 2.08 m^2K/W, azimuth angle of 11.5^0, a Shade offset value of 0.3, and WWR of 30%, were done and the results are presented in Tables 9, and 10.

Table 9. Simulation results for the effects of projection factors on daylighting of Open-plan mid-rise office buildings in the temperate dry climate of Nigeria.

Projection factor	0.35	0.400	0.450	0.500
DA	68	68	67	66
UDI	79	80	80	80
SDA	94.11	94.4	94	93.5

It was noted from Table 10 that, all five (5) conditions have met the benchmark as put forward by IES, (2012) and AEC, (2013). To evaluate the most appropriate projection factor (PF) for visual comfort, the rank and percentile were used and the following result was obtained as indicated in Table 10.

Table 10. Ranking of the DA, sDA, and UDI on projection factors

Projection factor	DA	Rank	UDI	Rank	SDA	Rank	Daylight Rank
0.35	68	1st	79	4th	94.11	2nd	2nd
0.4	68	1st	80	1st	94.4	1st	1st
0.45	67	3rd	80	1st	94	3rd	2nd
0.5	66	4th	80	1st	93.5	4th	4th

The finding has shown that the optimum projection factor for visual comfort in Open-plan midrise office buildings in the temperate dry climate is 0.4, followed by 0.45/0.35, and lastly 0.5 as indicated in Table 11. The next was the assessment of the building projection factor (PF) for thermal comfort indicators: - The simulation results of the effects of the projection factor on thermal comfort are presented in Figure 10 and 11.

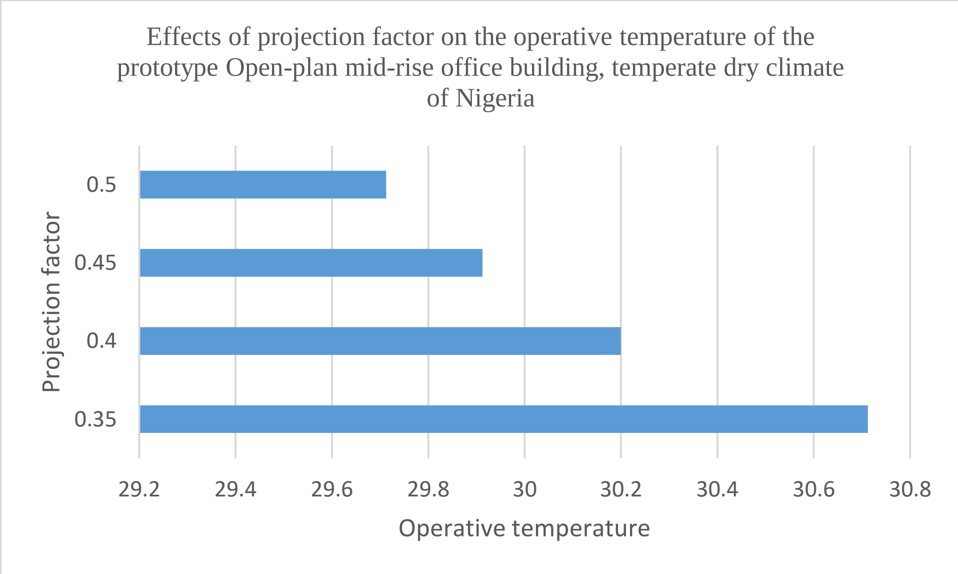

Figure 10. Effects of projection factor on the operative temperature of the prototype Open-plan mid-rise office building, temperate dry climate of Nigeria.

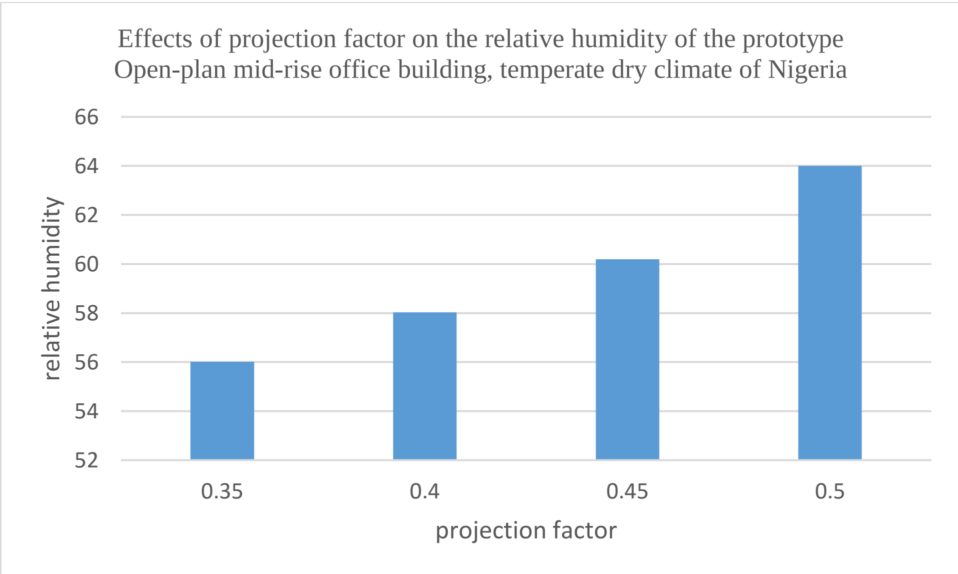

Figure 11. Effects of projection factor on the relative humidity of the prototype Open-plan mid-rise office building, temperate dry climate of Nigeria.

The results showed that, while relative humidity has met the condition recommended by ASHRAE Standard 55 (2013) as shown in Figure 11, none of the operative temperatures has met the ANSI/ASHRAE Standard 55, (2013) as indicated in Figure 10. When the values of daylight metrics and thermal comfort indicators were ranked together as indicated in Table 11, the 0.45 projection factor was found to be the most appropriate for DPITC.

Table 11. Ranking of the projection factor for DPITC

Projection factors	DA	UDI	sDA	**Daylight Comfort**	Thermal Comfort	DPITC	Remark
0.35	1st	3rd	1st	**2nd**	4th	4th	0.45 is the most appropriate P.F. for DPITC.
0.4	2nd	2nd	2nd	**1st**	3rd	2nd	
0.45	2nd	2nd	2nd	**2nd**	2nd	1st	
0.5	3rd	1st	3rd	**4th**	1st	3rd	

3.2.3.1 Hypothesis Testing: -

c). H_{O3}: The mean effects of DPITC are significantly different for at least one of the Projection factors of shading devices in an open-plan office building in the temperate dry climate of Nigeria.

The one-way MANOVA was used to test if the prototype Open-plan midrise office buildings with different PF differ from each other significantly in one or more DPITC variables. The homogeneity of variance-covariance matrices was tested using Box's Test of Equality of Covariance Matrices and the Box' M value obtained was 91.160 with a p-value of .068, which was interpreted as non-significant based on Huberty and Petosky's (2000) guidelines. Therefore the covariance matrices of the dependent variables were equal across groups for MANOVA. The one-way MANOVA was tested and a statistically significant difference was obtained, F (15, 750) = 2.945, p = .000; Pillai's Λ = .944, partial η2 = .315.

A homogeneity for variance assumptions was tested for all the DPITC variables before conducting a series of tests between the subject effects. Based on a series of Levene's F tests, it was considered satisfactory. A series of one-way ANOVAs on each of the five DPITC variables was conducted as a follow-up test to the MANOVA. The results turned out to be statistically significant in all the DA *(F (3, 252) = 2.568; p =.055; partial η2 = .030),* UDI *(F (3, 252) = 16.852; p = .000; partial η2 = .167),* sDA *(F (3, 252) = 5.238; p = .002; partial η2 = .059), Operative temperature (F (3, 252) = 7.689; p < .000; partial η2 = .084), and* Relative humidity *(F (3, 252) = 40.285; p < .000; partial η2 = .324).*

The optimal projection factor of 0.45 found in this study is slightly higher than the 0.4 found for visual comfort alone. This demonstrates the need for design solutions that balance daylight admission (which favors lower projection factors) with solar heat gain control (which favors higher projection factors). The finding is consistent with studies in similar tropical climates (Olgyay, 1963; Taleghani et al., 2015).

3.2.4 To evaluate the effects of R-values of the exterior wall component of open-plan office buildings on DPITC

The simulations of a prototype Open-plan office building, with an azimuth angle of 11.5^0, a shade offset value of 0.3, an overhang projection factor of 0.45, and WW of 30% were done and the results are presented in Tables 12, and 13.

Table 12. Simulation results for the effects of R-values of external wall insulation material on visual comfort in Open-plan mid-rise office buildings in the temperate dry climate of Nigeria.

R-values of external walling materials (m2 ·K/W)	**2.08**	**3.12**	**3.26**	**3.61**
DA	67	67	67	67
UDI	80	80	80	80
sDA	94	94	94	94

To evaluate the most appropriate R-value for visual comfort, the rank and percentile were used and the following results were obtained as indicated in Table 13.

Table 13. Ranking of the DA, sDA, and UDI against the R-value of external wall insulation materials

R-value of the external wall (m2 ·K/W)	DA	RANK	UDI	RANK	sDA	RANK	DAYLIGHT RANK
2.08	67	1st	80	1st	94	1st	1st
3.12	67	1st	80	1st	94	1st	1st
3.26	67	1st	80	1st	94	1st	1st
3.61	67	1st	80	1st	94	1st	1st

The finding has shown that all the four (4) conditions were the same and it was deduced that the R-value of external wall insulation material does not affect the visual comfort of an office building as indicated in Table 14. The next was the assessment of the building projection factor for thermal comfort indicators: - The simulation results of the effect of R-values of external wall insulation material on thermal comfort are presented in Figure 12 and 13.

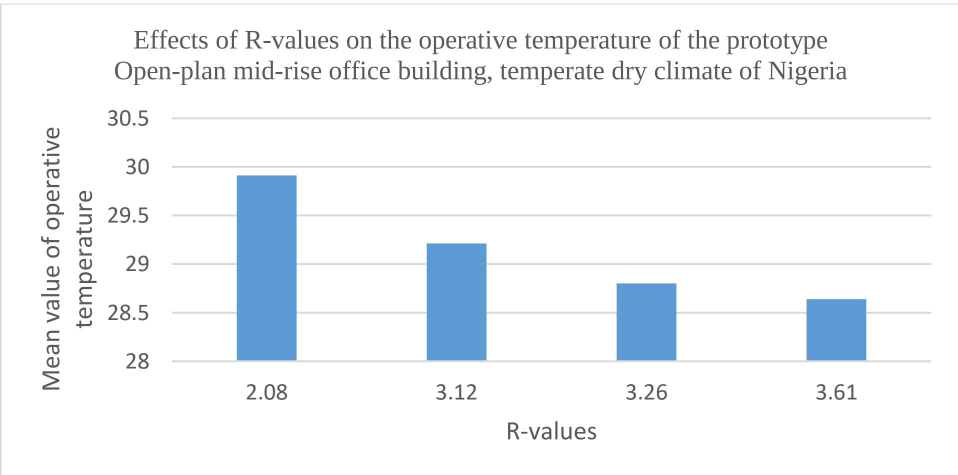

Figure 12. Effects of R-values on the operative temperature of the prototype Open-plan mid-rise office building, temperate dry climate of Nigeria

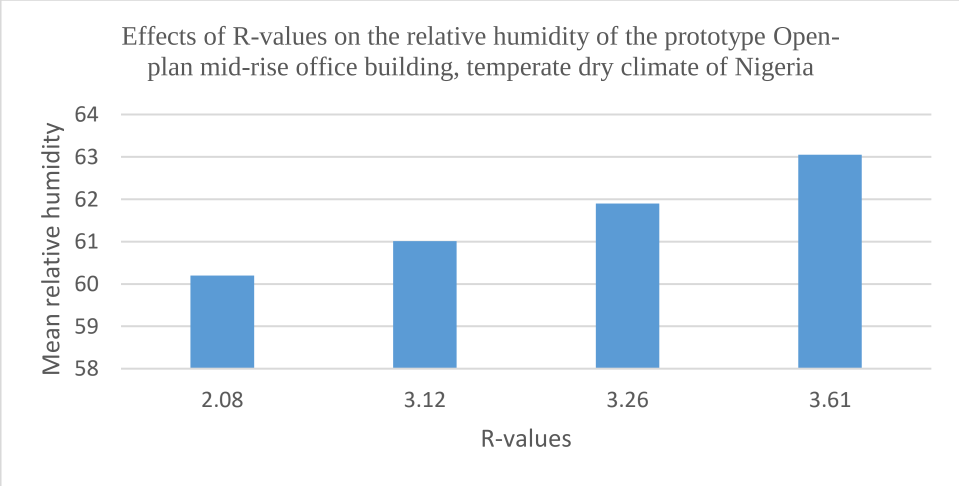

Figure 13. Effects of R-values on the relative humidity of the prototype Open-plan mid-rise office building, temperate dry climate of Nigeria

The result showed that, as the R-value increases, the thermal comfort also increases as indicated in Figure 12 and 13. When the values of daylight metrics and thermal comfort indicators were ranked together 3.26 m2·K/W was found to be the optimum R-value for DPITC. The result conformed with that of ANSI/ASHRAE/IES Standard 90.1 (2007, and 2010 editions) which recommended a minimum range of R-value of 1.0 - 2.7(m2·K/W) for non-residential buildings.

3.2.4.1 Hypothesis Testing: -

d). H_{O3}: The mean effects of DPITC are significantly different for at least one of the R-values of the exterior wall component in an open-plan office building in the temperate dry climate of Nigeria.

The homogeneity of variance-covariance matrices was tested using Box's Test of Equality of Covariance Matrices and Box's M value obtained is 49.815 with a p-value of .909, which was interpreted as non-significant based on Huberty and Petosky's (2000) guidelines. Therefore the covariance matrices of the dependent variables were equal across groups for MANOVA. The one-way MANOVA was tested and a statistically significant difference was obtained, $F (15, 78) = 3.173$, $p < .000$; Pillai's $\Lambda = 1.137$, partial $\eta 2 = .379$.

A homogeneity for variance assumptions was tested for all the variables before conducting a series of tests between the subject effects. Based on a series of Levene's F tests, it was considered satisfactory. A Series of one-way ANOVAs on each of the variables was conducted as a follow-up test to the MANOVA. The results turned out to be statistically significant in all the DA *($F (3, 28) = .000$; $p =1.00$; partial $\eta 2 = .000$)*, UDI *($F (3, 28) = .000$; $p = 1.00$; partial $\eta 2 = .000$)*, $_S$DA *($F (3, 28) = .000$; $p < 1.00$; partial $\eta 2 = .000$), Operative temperature ($F (3, 28) = 3.370$; $p =.032$; partial $\eta 2 = .265$), and Relative Humidity ($F (3, 28) = 3.090$; $p < .043$; partial $\eta 2 = .249$).* It showed that visual comfort does not affect the R-value of external wall materials, while the R-value affects thermal comfort.

A series of post-hoc analyses using Fisher's LSD was performed to examine individual mean differences comparison across all the R-values and four thermal comfort variables. The result revealed that there was a statistically significant difference in the relationship among all the four variables (2.08 m2·K/W, 3.12 m2·K/W, 3.26 m2·K/W, and 3.26 m2·K/W).

3.3 Framework for an Open-Plan Office Building to Enhance DPITC in the temperate dry climate of Nigeria

The framework was used to obtain four more enhanced DPITC values as indicated in Table 14 for open-plan office buildings in the temperate dry climate of Nigeria. It was used to carry out the multiple regression to investigate whether the enhanced values of WWR, projection factor, and R-value of external wall material, could significantly predict different enhanced azimuth angles for DPITC in open-plan office buildings in a temperate dry climate of Nigeria.

Table 14. Five (5) sets of enhanced values of DPITC in open-planned office buildings in a temperate dry climate.

S/NO	Azimuth	WWR	PF	R-value
1	11.5	0.3	0.45	3.26
2	22.5	0.3	0.65	3.12
3	35	0.24	0.1	2.08
4	45	0.2	0.25	4.16
5	12.5	0.3	0.45	3.12

The results of the regression as shown in Table 15 indicates that, the model explained 99.9% of the variance and that the model was a significant predictor of azimuths, $F(3,1) = 13360.8673$, $p = .00636$. The WWR, projection factor (PF), and R-values of external wall material (R) contributed significantly to the model ($B = -512.232$, $p=0.0048$), ($B = 49.4$ $p=0.01084$), and ($B = -8.6$, $p=0.01187$), respectively.

Table 15. Table: Multiple Regression Analysis Results for Azimuth Prediction

Variable	B (Unstandardized)	SE	β (Standardized)	t	p-value	VIF
WWR	-512.232	68.12	-0.514	-7.52	.0048	4.21
PF	49.412	23.45	0.498	2.11	.0108	3.85
R	-8.600	2.34	-0.232	-3.68	.0119	2.96

$R^2 = 0.9990$, Adjusted $R^2 = 0.9960$, $F(3,1) = 13,360.87$, $p = .00636$

All Variance Inflation Factor (VIF) values as shown in Table 15 are below 5, indicating acceptable levels of multicollinearity (O'Brien, 2007). The regression model explains 99.9% of the variance in azimuth values, with WWR making the largest contribution ($\beta = -0.514$), followed by Projection Factor ($\beta = 0.498$), and R-value ($\beta = -0.232$).

The formular $Y = C + M1X1 + M2X2 + M3X3 \dots \dots .3.1$ was used to develop the model from regression results as follows:

Azimuth = 170.8746 + (-512.232 x WWR) + (49.41241 X Projection Factor) + (-8.60012 x R-Value)

$$\boldsymbol{A = 170.87 - 512.232WWR + 49.41PF - 8.6R \ldots\ldots 3.2}$$

Units: A= (^{0}); R= (m^2.K/W); C= (^{0}); M_1= (^{0}); M_2= (^{0}); and M_3=(^{0} W/m^2.K).

Where: A = Azimuth (degrees), WWR = Window-to-Wall Ratio, PF = Overhang Projection Factor, and R = R-value of external wall material (m^2·K/W).

3.4 Framework Validation

Studies have shown that there was no single test that would 100% ascertain the validity of any model or framework, but the level of confidence in the simulation model can increase gradually as it passes more tests (Forrester and Senge, 1980). Based on this, the study recommended the use of two different methods of validation based on Banks et al., (2010) classification. These were: an expert assessment and the examination of framework output for reasonableness under a variety of settings of the input parameters.

3.4.1. Examination of framework output under a variety of settings of the input parameters

This was done for an open-plan office building and involved changing the values of one of the framework concepts such as WWR, R-values, or PF, which may affect the values of other concepts, to achieve the optimum passive thermal and visual comfort of an office building.

The study tested the values given by ASHRAE 90.1, which recommended the optimum value of WWR as 30%, (ASHRAE 90.1: ≤ 40%) minimum R-values as 3.26 m^2·K/W (which aligns with recommended values for tropical climates), Azimuth of 11.5° and Projection factor as 0.45. The result was in compliance with = $\boldsymbol{170.87 - 512.232WWR + 49.41PF - 8.6R}$.

3.4.2. Experts Assessment Validation

This is the assessment of the model or framework by an expert or group of experts and makes a pronouncement based on their experience whether the model is valid or not. They usually used face validation, which according to Haladyna (1999), and DeVon *et al*. (2007) was used to evaluate the appearance of the framework/ model in terms of readability, consistency of style and formatting, and the clarity of the model. Based on this, the summary of the developed framework and validation questionnaire was sent to twenty-two (22) PITVC experts, and fourteen (14) came back. Their responses are tabulated as shown in Table 16.

Table 16. Experts' evaluation of the framework and model developed in this research.

Respondents	Relevance	Clarity	Internal Consistency	Readability	Total (%)
1	5	5	5	5	100
2	5	5	5	5	100
3	5	5	5	4	95
4	5	5	5	5	100
5	5	4	5	5	95
6	5	5	5	5	100
7	4	4	4	4	80
8	5	5	4	4	90
9	5	5	5	5	100
10	5	4	5	4	90

11	5	4	5	4	90
12	5	5	5	5	100
13	5	5	5	5	100
14	5	5	5	5	100
Mean value					88.9%

It therefore showed that the mathematical model was satisfactorily based on experts assessment as indicated in Table 15.

4. Conclusion

This study has successfully developed a comprehensive framework for sustainable office building design aimed at achieving optimum daylighting and passive indoor thermal comfort (DPITC) in Nigeria's temperate dry climate. Through rigorous simulation and statistical analysis, several significant conclusions have emerged that contribute to both theoretical understanding and practical application in sustainable architecture. The investigation has conclusively demonstrated that open-plan office buildings are substantially more sustainable than their closed-plan (double-banked) counterparts in Nigeria's temperate dry climate, with statistically significant improvements in Daylight Autonomy (DA) of 45.7%, Spatial Daylight Autonomy (sDA) of 55.2%, and Relative Humidity (RH) of 10.6%, while also showing a notable improvement in Useful Daylight Illuminance (UDI). This finding resolves the conflicting perspectives in existing literature regarding the relative performance of these two office typologies and provides clear empirical evidence supporting the adoption of open-plan layouts in this climatic context.

Furthermore, the study has established that building orientation, specifically azimuth angle, exerts a significant influence on DPITC performance, with an orientation of 11.5° emerging as the optimal balance between daylighting and thermal comfort requirements. Notably, the analysis revealed that all azimuth angles within 45° of this optimal value exhibit no statistically significant differences, while orientations beyond 45° demonstrate significant variations in DPITC metrics, providing designers with a flexible range of acceptable orientations. The Window-to-Wall Ratio (WWR) was similarly found to significantly affect DPITC, with 30% WWR identified as optimal for visual comfort and 26.5% WWR providing the best thermal comfort balance, suggesting that a compromise range of 26.5-30% represents the ideal design solution for achieving both objectives simultaneously. Additionally, the Overhang Projection Factor was determined to significantly influence DPITC, with a projection factor of 0.45 emerging as the optimal value, while the R-value of external wall materials was found to significantly affect thermal comfort without impacting visual comfort, with 3.26 $m^2 \cdot K/W$ identified as the optimum R-value for this climate zone. The culmination of this research is the development of a predictive equation—$A = 170.87 - 512.232WWR + 49.41PF - 8.6R$—which provides architects and designers with a practical, evidence-based tool for optimizing office building orientation in Nigeria's temperate dry climate, thereby facilitating the creation of more sustainable and comfortable work environments.

4.2 Limitations of the Study

While the predictive equation provides a valuable design tool, it has the following limitations.

i. First, the equation was developed specifically for Nigeria's temperate dry climate zone, and its applicability to other climate zones has not been validated.
ii. Second, the simulations assumed hypothetical sites devoid of surrounding buildings, trees, or other obstructions; real-world site conditions may significantly affect daylight availability and thermal performance.
iii. Third, the equation is valid only within the investigated ranges of the independent variables: WWR (0.15-0.30), Projection Factor (0.35-0.50), and R-value (2.08-3.61 $m^2 \cdot K/W$). Extrapolation beyond these ranges is not recommended.
iv. Fourth, the equation assumes specific glazing properties (visible transmittance = 0.78, SHGC = 0.42); different glazing types would require recalibration.

These limitations should be considered when applying the equation in practice, and designers are encouraged to use it as a preliminary design aid rather than as a definitive prescription.

4.3 Recommendations

4.3.1 Recommendations for Policy Makers

Based on the findings of this study, several policy interventions are recommended to promote sustainable office building design in Nigeria. First, it is imperative that Nigerian building codes be revised to incorporate specific requirements for daylighting performance metrics, including minimum thresholds of 60% for Daylight Autonomy (DA), 80% for Useful Daylight Illuminance (UDI), and 75% for Spatial Daylight Autonomy (sDA), alongside thermal comfort standards aligned with the benchmarks established in this research. Such code revisions would provide a regulatory framework that incentivizes sustainable design practices and ensures minimum performance standards across the building sector. Second, government agencies at federal, state, and local levels should implement incentive programs that provide tax benefits, reduced permitting fees, or expedited approval processes for office buildings that achieve or exceed the DPITC benchmarks identified in this study. These incentives would encourage developers and building owners to invest in sustainable design features, accelerating the adoption of best practices in the industry. Third, the adoption of the 3.26 $m^2 \cdot K/W$ R-value as a recommended minimum standard for external wall insulation in office buildings within Nigeria's temperate dry climate zone is strongly advised. This standard, which exceeds current typical practice, would significantly improve thermal comfort while reducing cooling energy demands, contributing to both occupant well-being and national energy conservation goals. Policymakers should also consider developing educational programs and technical assistance initiatives to support building professionals in implementing these standards effectively.

4.3.2 Recommendations for Architects and Designers

Architects and building designers are encouraged to adopt open-plan layouts for office buildings in Nigeria's temperate dry climate, utilizing clear spans and minimizing internal partitions to maximize daylight penetration and natural air circulation throughout the workspace. This design approach, supported by the study's empirical findings, enhances both visual and thermal comfort while reducing dependence on artificial lighting and mechanical ventilation. Building orientation should be optimized at 11.5° azimuth to achieve the best balance between daylighting and thermal comfort, though designers should also consider local wind patterns and site-specific conditions when finalizing building orientation decisions. The study recommends the use of a Window-to-Wall Ratio between 26.5% and 30%, with the specific value within this range determined by the relative priority given to visual versus thermal comfort for the particular project. External shading devices, specifically overhang projections, should be designed with a projection factor of 0.45 to effectively control solar heat gain while maintaining adequate daylight admission. Designers are further advised to specify external wall materials with R-values of at least 3.26 $m^2 \cdot K/W$ to optimize thermal performance, recognizing that higher insulation values may provide additional benefits in terms of energy savings and comfort stability. Finally, architects are encouraged to apply the predictive equation—$A = 170.87 - 512.232WWR + 49.41PF - 8.6R$—as a design aid during the schematic design phase, using it to calculate optimal building orientation based on the selected WWR, projection factor, and R-value, thereby integrating the study's findings directly into the design process.

4.3.3 Recommendations for Researchers

The findings of this study open several avenues for future research that would further enhance understanding and application of sustainable office design principles. Foremost among these is the need for field validation studies that compare simulation results with actual building performance data, thereby confirming the accuracy of the simulation methodology and validating the study's findings under real-world conditions. Researchers are also encouraged to conduct comprehensive occupant surveys in both open-plan and closed-plan office buildings to investigate the relationship between objective performance metrics and subjective occupant satisfaction, productivity, and well-being. Such studies would provide valuable insights into the human dimensions of sustainable design and help establish the business case for adopting the recommended design strategies. Additionally, quantitative energy consumption analysis is needed to precisely measure the energy savings achievable through the proposed design strategies, providing economic justification for their adoption and enabling cost-benefit comparisons across different design alternatives. Economic feasibility studies that consider initial construction costs, operational savings, and lifecycle costs would further strengthen the case for sustainable office design and inform investment decisions. Finally, comparative studies extending this research to other Nigerian climate zones—including the coastal region, Guinea savannah, and Sudan savannah—would establish whether the findings can be generalized across the country's diverse climatic conditions or whether zone-specific frameworks are required. Such research would contribute to the development of a comprehensive national approach to sustainable building design tailored to Nigeria's varied climatic contexts.

4.4 Contributions to Knowledge

This study makes several significant contributions to the body of knowledge in sustainable architecture and building design. First and foremost, it provides substantial empirical evidence on office building performance specifically tailored to Nigeria's temperate dry climate, addressing a notable gap in the literature that has largely focused on other climate zones or regions. The development of a predictive framework, encapsulated in the equation A = 170.87 - 512.232WWR + 49.41PF - 8.6R, represents a practical and accessible tool that architects and designers can readily apply in their professional practice to optimize office building orientation based on key design parameters, thereby bridging the gap between academic research and design practice. The study also contributes to resolving the conflicting findings in existing literature regarding the relative performance of open-plan versus closed-plan office buildings, providing clear empirical evidence that open-plan layouts are significantly more sustainable in the context of Nigeria's temperate dry climate. Furthermore, the establishment of contextualized guidelines and benchmarks specific to Nigerian conditions—including optimal azimuth angles, WWR ranges, projection factors, and insulation values—provides actionable recommendations that can inform both design practice and building code development. These contributions collectively advance the field of sustainable architecture in Nigeria and provide a foundation for future research and policy development in this critical area of environmental design.

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