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RESEARCH PAPER

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An assessment of the effect of wind flow on the indoor thermal condition of some buildings in Benin City, Nigeria

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ABSTRACT

Natural ventilation plays a critical role in improving indoor thermal comfort and reducing reliance on mechanical cooling in hot-humid tropical environments. However, the influence of wind flow on indoor thermal conditions is strongly affected by building design and surrounding spatial characteristics, which remain insufficiently documented for residential buildings in Benin City, Nigeria. This study assessed the effect of wind flow on the indoor thermal conditions of selected residential buildings in five neighbourhoods of Benin City. A cross-sectional field survey involving 489 completed questionnaires was combined with field measurements of indoor temperature using a thermo-hygrometer and wind speed using a vane anemometer. Descriptive statistics, Pearson's chi-square test, and Pearson's correlation analysis were used to analyse the data. The results showed that 58.3% of buildings were oriented east-west, 63.2% of rooms had only one window, 80.2% of buildings lacked courtyards, and 76.7% were constructed with sand screed solid block walls. Most buildings (70.6%) were separated from neighbouring buildings by 3–6 m, while 56.0% had boundary wall setbacks of only 0.3–1.2 m. Ceiling fans were the predominant cooling method (85.1%), reflecting occupants' dependence on mechanically assisted air movement. Wind speed exhibited a significant positive correlation with indoor temperature ($r= 0.71$, $p = 0.041$), indicating that wind alone did not guarantee improved indoor thermal conditions. The study concludes that indoor thermal comfort is determined by the combined effects of wind flow, building orientation, ventilation openings, spatial configuration, and plot characteristics. Integrating climate-responsive design principles into residential planning can enhance passive cooling, improve indoor thermal comfort, and reduce dependence on mechanical cooling in hot-humid tropical environments.

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INTRODUCTION

Indoor thermal comfort is a fundamental component of healthy, productive, and energy-efficient buildings. It influences occupants' health, well-being, and performance while also affecting building energy consumption, particularly in regions where mechanical cooling is widely used (Awbi, 2021; Lechner, 2021). In hot-humid tropical climates, maintaining acceptable indoor thermal conditions remains a major challenge because high air temperature, humidity, and solar radiation often increase indoor heat accumulation (Xi *et al.*, 2025).

Natural ventilation, particularly wind-driven ventilation, is one of the most effective passive cooling strategies for improving indoor thermal comfort while reducing energy demand. Wind flow creates pressure differences across building openings that facilitate air exchange, enhance convective heat removal, and improve occupants' thermal perception (Aktan, 2014; Awbi, 2021). The effectiveness of this process, however, depends on several interrelated factors, including building orientation, window size and placement, internal layout, surrounding building spacing, and local urban morphology (Lechner, 2021; Li *et al.*, 2024).

Globally, increasing attention has been directed towards climate-responsive building design as a sustainable approach to mitigating rising cooling demands associated with rapid urbanization and climate change. Previous studies have shown that well-designed natural ventilation systems can significantly improve indoor airflow, reduce indoor temperatures, and lower dependence on mechanical cooling (Omrani *et al.*, 2017; Li *et al.*, 2024). Similarly, advances in passive ventilation strategies, including optimized building orientation and opening configuration, have been reported to enhance thermal comfort and building energy performance in both residential and institutional buildings (Mba *et al.*, 2022; Oforji *et al.*, 2023). These findings demonstrate that effective utilization of wind flow remains an essential component of sustainable building design, particularly in hot-humid environments.

In tropical countries such as Nigeria, natural ventilation remains an important means of achieving indoor thermal comfort because high ambient temperatures, persistent humidity, and increasing energy costs limit the widespread use of mechanical cooling systems (Awbi, 2021; Lechner, 2021). However, rapid urbanization and changing residential development patterns have led to increased building density, reduced open spaces, and widespread adoption of construction practices that often overlook climatic considerations. These changes can restrict airflow, increase indoor heat accumulation, and compromise thermal comfort (Akubue, 2023; Mba *et al.*, 2023).

Climate-responsive building design emphasizes passive cooling measures such as appropriate building orientation, effective cross-ventilation, adequate spacing between buildings, optimized window configuration, and suitable building materials to improve indoor environmental quality while reducing cooling energy demand (Lechner, 2021; Li *et al.*, 2024). Previous studies have demonstrated that building orientation and ventilation openings strongly influence airflow and thermal comfort (Mba *et al.*, 2022; Oforji *et al.*, 2023), while building spacing and surrounding urban morphology affect wind penetration and ventilation efficiency (Ahmed and Gregor, 2014; Mohamed, 2023). Similarly, Omrani *et al.* (2017) reported that cross-ventilation consistently provides better indoor airflow and thermal performance than single-sided ventilation.

Although these studies have advanced the understanding of natural ventilation, most have relied on simulation approaches, focused on specific building components, or been conducted outside Benin City. Empirical evidence integrating building orientation, architectural characteristics, surrounding spatial configuration, occupants' adaptive behaviour, and measured wind speed within residential neighbourhoods of Benin City remains limited. This study addresses this knowledge gap by evaluating how wind flow and building design characteristics jointly influence the indoor thermal conditions of selected residential buildings in Benin City, Nigeria.

Recognizing the importance of climate-responsive residential design in tropical environments, this study evaluates the influence of wind flow on indoor thermal conditions within selected neighbourhoods of Benin City. The study provides field-based evidence on how building orientation, architectural characteristics, surrounding spatial configuration, and occupants' adaptive practices interact with wind flow to affect indoor thermal comfort.

The aim of this study was to assess the effect of wind flow on the indoor thermal conditions of selected residential buildings in Benin City, Nigeria. Specifically, the study sought to: (i) evaluate building orientation in relation to natural ventilation; (ii) examine occupants' cooling practices under varying indoor thermal conditions; (iii) assess the influence of building spacing and plot characteristics on airflow; and (iv) determine the relationship between wind speed and indoor temperature.

The findings contribute to the growing body of knowledge on passive cooling and climate-responsive architecture in hot-humid regions. The study also provides evidence that may assist architects, planners, and policymakers in developing residential design strategies that improve natural ventilation, enhance indoor thermal comfort, and reduce dependence on mechanical cooling systems.

The following section describes the study area, research design, data collection procedures, measurement techniques, and statistical methods employed to evaluate the relationship between wind flow and indoor thermal conditions.

MATERIALS AND METHODS

Study area

The study was conducted in Benin City, the administrative headquarters of Edo State, southern Nigeria. Benin City lies approximately between latitudes 6°20′N and 6°58′N and longitudes 5°35′E and 5°41′E, with an average elevation of about 78 m above sea level. The city comprises three Local Government Areas (LGAs): Oredo, Egor, and Ikpoba-Okha, and occupies approximately 607.5 km² (Okhakhu, 2010; Eseigbe, 2011). Owing to its location within the humid tropical climatic zone, Benin City experiences consistently high temperatures and relative humidity throughout most of the year.

The climate is characterized by distinct wet and dry seasons that are governed primarily by the interaction between the tropical maritime and tropical continental air masses. The wet season extends from approximately February to November, while the dry season occurs mainly between December and January and is associated with the Harmattan period. Annual rainfall generally ranges from 2,000 to 2,200 mm, average daily temperatures range from 27 to 36°C, and relative humidity commonly exceeds 75% (Udo, 1978; Iloeje, 1981; Okhakhu, 2010; Eseigbe, 2011). These climatic characteristics make Benin City particularly suitable for investigating the influence of natural ventilation on indoor thermal conditions because wind-driven ventilation represents one of the principal passive cooling mechanisms in hot-humid environments.

Research design

A cross-sectional field survey was adopted to evaluate the influence of wind flow on the indoor thermal conditions of residential buildings. The study combined questionnaire-based data collection with in situ environmental measurements of wind speed and indoor air temperature. This mixed-method approach enabled the integration of occupants' perceptions, building characteristics, and objective microclimatic measurements, thereby providing a comprehensive assessment of factors influencing indoor thermal comfort.

Selection of study neighbourhoods

Five residential neighbourhoods representing different urban development patterns within Benin City were purposively selected. These comprised Ikpoba Hill (Ikpoba-Okha LGA), Government

Reservation Area (G.R.A.) and Ekehuan (Oredo LGA), and Uselu and Ugbowo (Egor LGA). The selected neighbourhoods exhibit variations in building density, architectural characteristics, street layout, and surrounding spatial configuration, making them suitable for comparative assessment of natural ventilation and indoor thermal performance.

Within each neighbourhood, residential buildings were selected based on similarities in general building characteristics and accessibility for field investigation.

Sampling procedure and sample size

A multistage sampling procedure was employed. First, the three LGAs constituting metropolitan Benin City were identified. Second, five representative neighbourhoods were purposively selected. Third, residential streets and households within each neighbourhood were approached using convenience sampling because household participation depended on occupants' availability and willingness to participate during fieldwork.

A total of 550 structured questionnaires (110 per neighbourhood) were distributed. Of these, 489 questionnaires were correctly completed and returned, representing an overall response rate of 88.91%, which is considered adequate for statistical analysis and enhances the reliability of the study findings (Table 1).

Data collection

Primary data were collected using structured questionnaires and direct field observations.

The questionnaire obtained information on:
1. building orientation;
2. number and arrangement of windows;
3. bedroom dimensions;
4. presence or absence of courtyards;
5. wall construction materials;
6. building spacing and setbacks;
7. plot characteristics;
8. cooling and heating practices of occupants; and
9. occupants' perceptions of indoor thermal conditions.

Field observations were conducted simultaneously to verify physical characteristics of the buildings and to minimize reporting bias associated with questionnaire responses.

Measurement of environmental variables

Indoor environmental measurements were conducted to quantify the relationship between wind flow and indoor thermal conditions.

Wind speed was measured using a handheld vane anemometer, while indoor air temperature was measured using a digital thermo-hygrometer. Measurements were taken at approximately 1.5 m above floor level, corresponding to the typical occupied zone recommended for indoor thermal comfort assessment because this height best represents the breathing level of seated and standing occupants and minimizes floor and ceiling thermal influences (ASHRAE Standard 55; ISO 7726).

Measurements were collected under naturally ventilated conditions while doors and windows remained in their normal operating positions during occupancy.

Study variables

The principal dependent variable was indoor thermal condition, represented by indoor air temperature.

Independent variables included:
1. building orientation;
2. number of windows;
3. bedroom dimensions;
4. courtyard provision;
5. wall construction material;
6. distance between neighbouring buildings;
7. boundary setbacks;
8. plot size;
9. percentage plot coverage; and
10. wind speed.

These variables were selected because previous studies have demonstrated their influence on natural ventilation and passive thermal performance in buildings located in hot-humid climates (Awbi, 2021; Lechner, 2021; Li *et al.*, 2024).

Data analysis

Questionnaire responses were coded and analysed using descriptive and inferential statistical techniques. Descriptive statistics, including frequencies, percentages, and summary tables, were used to describe respondents' characteristics, building features, cooling practices, and neighbourhood attributes.

The association between building orientation and neighbourhood location was examined using Pearson's chi-square test. The relationship between wind speed and indoor air temperature was evaluated using Pearson's product-moment correlation coefficient. Statistical significance was assessed at the 5% probability level ($p < 0.05$).

RESULTS

A total of 550 questionnaires were administered across the five selected neighbourhoods, of which 489 were successfully completed and retrieved, giving an overall response rate of 88.91% (Table 1). Uselu recorded the highest retrieval rate (96.36%), followed by Ekehuan (95.45%), Ikpoba Hill (90.91%), Ugbowo (81.82%), and G.R.A. (80.00%) (Table 1).

Table 1. Administered and retrieval of questionnaires

Neighbourhood/ Zones	Administered questionnaires	Completed and retrieved questionnaires	Percentage of retrieved (%)
Ikpoba Hill	110	100	90.91
GRA	110	88	80.00
Uselu	110	106	96.36
Ugbowo	110	90	81.82
Ekehuan	110	105	95.45
Total	550	489	88.91

Table 2. Comparison of building orientation with location

Location	Longer side of building facing sunrise and sunset		Total	Statistics
	Yes	No		
	Frequency (%)	Frequency (%)		
Ikpoba	46 (46.0)	54 (54.0)	100 (100.0)	$X^2 = 35.251$
GRA	46 (52.3)	42 (47.7)	88 (100.0)	df= 4
Uselu	59 (55.7)	47 (44.3)	106 (100.0)	$p < 0.001$
Ugbowo	47 (52.2)	43 (47.8)	90 (100.0)	
Ekehuan	87 (82.9)	18 (17.1)	105 (100.0)	
Total	285 (58.3)	204 (41.7)	489 (100.0)	

Table 3. Building features and space

Number of windows in each room	No. of buildings	Percentage
One	309	63.2
Two	152	31.1
Above two	28	5.7
Minimum size of bedroom (Metre)		
2.4×3.0	58	11.9
3.0×3.0	124	25.4
3.0×3.6	273	55.8
3.6×4.2	29	5.9
4.2×4.8	5	1.0
Building with courtyard		
Courtyard	97	19.8
Not courtyard	392	80.2
Type of wall		
Bricks	39	8.0
Sand screed hollowed block	74	15.1
Sand screed solid block	375	76.7
Earth walls	1	.2

The distribution of building orientation is presented in Table 2. Overall, 285 buildings (58.3%) had their longer sides oriented toward the sunrise and sunset, whereas 204 buildings (41.7%) were oriented otherwise. At the neighbourhood level, the proportion of buildings with the longer side facing the sunrise and sunset was 46.0% in Ikpoba Hill, 52.3% in G.R.A., 55.7% in Uselu, 52.2% in Ugbowo, and 82.9% in Ekehuan. Buildings not oriented in this direction accounted for 54.0%, 47.7%, 44.3%, 47.8%, and 17.1% in Ikpoba Hill, G.R.A., Uselu, Ugbowo, and Ekehuan, respectively. The association between neighbourhood and building orientation was statistically significant ($\chi^2 = 35.251$, df = 4, $p < 0.001$) (Table 2).

The characteristics of the surveyed buildings are summarized in Table 3. A single window per room was recorded in 309 buildings (63.2%), while 152 buildings (31.1%) had two windows and 28 buildings (5.7%) had more than two windows. Regarding bedroom size, 273 buildings (55.8%) had minimum bedroom dimensions of 3.0 × 3.6 m, followed by 124 buildings (25.4%) with dimensions of 3.0 × 3.0 m, 58 buildings (11.9%) with dimensions of 2.4 × 3.0 m, 29 buildings (5.9%) with dimensions of 3.6 × 4.2 m, and 5 buildings (1.0%) with dimensions of 4.2 × 4.8 m. Courtyards were present in 97 buildings (19.8%), whereas 392 buildings (80.2%) had no courtyard. Sand screed solid block walls were the predominant wall type, occurring in 375 buildings (76.7%), followed by sand screed hollow block walls in 74 buildings (15.1%), brick walls in 39 buildings (8.0%), and earth walls in one building (0.2%) (Table 3).

Table 4. Cooling and heating practices

Variable	Frequency (N= 489)	Percentage
Means of cooling		
Air conditioner (AC)	61	12.5
Ceiling fan	416	85.1
Hand fan	9	1.8
Sit under tree	2	0.4
Sit in verandah	1	0.2
Sit outside to cool self		
Yes	394	80.6
No	95	19.4
Use hand fan to cool self when outside		
Yes	270	55.2
No	219	44.8
Use of hand fan when in verandah		
Yes	312	63.8
No	177	36.2
Method of heating room when weather is cold		
Room heater	12	2.5
Chimney	2	0.4
Don't heat	475	97.1
Hotter time in dry season		
Day time	426	87.1
Night time	63	12.9
Hotter time in wet season		
Day time	70	14.3
Night time	419	85.7

Residents' cooling and heating practices are presented in Table 4. Ceiling fans were the most frequently used cooling method, reported by 416 respondents (85.1%), followed by air conditioners used by 61 respondents (12.5%). Hand fans were used by 9 respondents (1.8%), while sitting under trees and sitting on verandas were reported by 2 (0.4%) and 1 (0.2%) respondents, respectively. A total of 394 respondents (80.6%) reported sitting outside to cool themselves, whereas 95 respondents (19.4%) did not. Hand fans were used outdoors by 270 respondents (55.2%) and not used by 219 respondents (44.8%). While sitting on verandas, 312 respondents (63.8%) reported using hand fans compared with 177 respondents (36.2%) who did not. For heating during cold weather, 475 respondents (97.1%) reported not heating their rooms, whereas 12 respondents (2.5%) used room heaters and 2 respondents (0.4%) used chimneys. During the dry season, 426 respondents (87.1%) identified daytime as the hotter period, while 63 respondents (12.9%) identified nighttime. During the wet season, 419 respondents (85.7%) identified nighttime as the hotter period, whereas 70 respondents (14.3%) identified daytime (Table 4).

Table 5. Surrounding space dimensions of buildings

Space	Frequency (N= 489)	Percentage
Distance of house to neighbour in metre (m)		
3.0 - 6m	345	70.6
6.4 – 7.3m	76	15.5
7.6 – 9m	47	9.6
10.6 – 15m	21	4.3
Distance to wall fence		
0.3 – 1.2m	274	56
1.5 – 1.8m	85	17.4
2.1 – 2.4m	64	13.1
2.7 – 3.0m	33	6.7
Above 3.0m	33	6.7

Table 6. Building design and plot area

Variable	Frequency (N= 489)	Percentage
Zone (Building Design by Architect/Non-Architect)		
Ikpoba Hill	100	20.4/79.6
GRA	88	18.0/82.0
Uselu	106	21.7/78.3
Ugbowo	90	18.4/81.6
Ekehuan	105	21.5/78.5
Plot size of land (Metre)		
15X30	272	55.6
30X30	116	23.7
15X15	67	13.7
30X45	21	4.3
30X60	13	2.7
Percentage of building area per plot area		
30%	35	7.2
40%	122	24.9
50%	204	41.7
Above 50%	128	26.2

The surrounding space dimensions of the buildings are shown in Table 5. The distance between neighbouring buildings ranged from 3.0 to 6.0 m in 345 buildings (70.6%), 6.4 to 7.3 m in 76 buildings (15.5%), 7.6 to 9.0 m in 47 buildings (9.6%), and 10.6 to 15.0 m in 21 buildings (4.3%). With respect to the setback between buildings and perimeter walls, 274 buildings (56.0%) had distances ranging from 0.3 to 1.2 m, 85 buildings (17.4%) had setbacks of 1.5–1.8 m, 64 buildings (13.1%) had setbacks of 2.1–2.4 m, and 33 buildings (6.7%) each had setbacks of 2.7–3.0 m and greater than 3.0 m.

The distribution of building design characteristics and plot attributes is presented in Table 6. Across the five neighbourhoods, architect-designed buildings accounted for 20.4% in Ikpoba Hill, 18.0% in G.R.A., 21.7% in Uselu, 18.4% in Ugbowo, and 21.5% in Ekehuan, while the corresponding proportions of non-architect-designed buildings were 79.6%, 82.0%, 78.3%, 81.6%, and 78.5%, respectively. Regarding plot size, 272 buildings (55.6%) were situated on 15 × 30 m plots, 116 buildings (23.7%) on 30 × 30 m plots, 67 buildings (13.7%) on 15 × 15 m plots, 21 buildings (4.3%) on 30 × 45 m plots, and 13 buildings (2.7%) on 30 × 60 m plots. Building coverage occupied 30% of the plot area in 35 buildings (7.2%), 40% in 122 buildings (24.9%), 50% in 204 buildings (41.7%), and more than 50% in 128 buildings (26.2%) (Table 6).

Table 7. Relationship between wind speed and indoor temperature

Correlation		Indoor temperature	Wind speed
Indoor temperature	*r*	1	0.71
	p		0.041
Wind speed	*r*	0.71	1
	p	0.041	

The relationship between wind speed and indoor temperature is presented in Table 7. Pearson's correlation analysis showed a correlation coefficient (r) of 0.71 between wind speed and indoor temperature. The relationship was statistically significant ($p = 0.041$).

DISCUSSION

This study demonstrates that the indoor thermal conditions of residential buildings in Benin City are influenced by the combined effects of building orientation, architectural characteristics, and occupants' adaptive behaviours rather than by wind availability alone. Although the study area experiences climatic conditions that are generally favourable for natural ventilation, several design-related factors—including building orientation, limited window provision, the absence of courtyards, and the predominance of solid wall construction—appear to reduce the effectiveness of wind-driven ventilation. Consequently, many occupants compensate through behavioural adaptations such as extensive use of ceiling fans and outdoor cooling practices. This observation supports the widely accepted principle that the effectiveness of natural ventilation depends not only on climatic conditions but also on how buildings are designed to capture, distribute, and exhaust airflow (Awbi, 2021; Lechner, 2021). Recent studies likewise emphasize that building geometry, opening configuration, and surrounding urban morphology collectively determine the performance of passive ventilation systems and indoor thermal comfort (Li *et al.*, 2024).

Building orientation and indoor thermal conditions

Building orientation emerged as one of the most important factors influencing the potential effectiveness of natural ventilation. More than half of the surveyed buildings (58.3%) had their longer façades oriented towards the east and west, with Ekehuan recording the highest proportion (82.9%). Although this orientation is common in many residential developments because of plot subdivision patterns, it is generally less favourable for minimizing solar heat gain in hot-humid climates because the longer façades receive prolonged morning and afternoon solar radiation (Lechner, 2021). Increased solar exposure raises the surface temperature of external walls and subsequently contributes to higher indoor heat gain, particularly where external shading is limited.

The significant variation in orientation among neighbourhoods further suggests that local planning practices and residential development patterns influence the ability of buildings to utilize prevailing winds for natural ventilation. Buildings whose orientation is not aligned with the dominant wind direction are less likely to achieve effective cross-ventilation, thereby reducing the removal of internal heat and increasing dependence on mechanical or behavioural cooling strategies. This finding is consistent with that of Mba *et al.* (2022), who reported that classrooms properly aligned with prevailing wind directions exhibited better natural ventilation and improved thermal comfort than buildings with less favourable orientation. Similarly, Lechner (2021) identified building orientation as one of the primary passive design strategies for simultaneously reducing solar heat gain and enhancing wind-driven ventilation. More recently, Li *et al.* (2024) demonstrated that orientation remains one of the most influential design variables affecting natural ventilation performance across different climatic regions.

The present findings therefore indicate that building orientation should be considered during both neighbourhood planning and individual building design.

In rapidly urbanizing tropical cities, residential layouts are often determined primarily by land subdivision patterns and plot geometry, with limited consideration of local climatic conditions. Integrating prevailing wind direction into planning regulations and architectural design could substantially improve natural ventilation, reduce indoor heat accumulation, and decrease reliance on mechanical cooling systems (Lechner, 2021; Li *et al*., 2024).

Building characteristics and indoor thermal conditions

The architectural characteristics observed in this study indicate that many residential buildings possess features that are unlikely to maximize natural ventilation. Nearly two-thirds of the surveyed buildings contained only one window per room, four out of every five buildings lacked courtyards, and more than three-quarters were constructed with sand screed solid block walls. Collectively, these characteristics are likely to reduce indoor air movement and limit passive heat removal.

Window configuration is a fundamental determinant of natural ventilation because it governs both air entry and air exit. Rooms containing only one window generally rely on single-sided ventilation, which typically produces lower ventilation rates than cross-ventilation. Experimental investigations by Omrani *et al*. (2017) demonstrated that cross-ventilation provides substantially greater airflow distribution, higher ventilation efficiency, and improved thermal comfort than single-sided ventilation under comparable environmental conditions. Similarly, Awbi (2021) explained that effective natural ventilation depends on the appropriate location, size, and arrangement of openings to facilitate continuous airflow through occupied spaces.

The low occurrence of courtyards observed in the present study may further reduce the effectiveness of passive ventilation. Courtyards function as natural ventilation modifiers by promoting pressure differences, encouraging air circulation, and enhancing convective heat removal. Their role in improving indoor thermal conditions has been widely recognized in climate-responsive architecture, particularly in warm and humid environments (Lechner, 2021).

Wall construction materials may also have contributed to the observed thermal conditions. The predominance of sand screed solid block walls suggests relatively high thermal mass, allowing substantial solar heat absorption during daytime and gradual release of stored heat into indoor spaces after sunset. In hot-humid climates, where night-time cooling is frequently limited by high humidity, this delayed heat release can prolong indoor discomfort unless sufficient night ventilation is available to dissipate the accumulated heat (Awbi, 2021; Lechner, 2021). However, thermal mass itself should not necessarily be regarded as detrimental because its effectiveness depends largely on adequate ventilation and appropriate climatic conditions.

Overall, these findings agree with established principles of building science, which emphasize that natural ventilation performance results from the interaction among building openings, internal spatial organization, and envelope characteristics rather than from any single design feature (Awbi, 2021). Likewise, Li *et al*. (2024) reported that building configuration and opening design remain among the most influential factors governing ventilation effectiveness and indoor thermal performance.

From a practical perspective, many of these limitations could be addressed through relatively simple architectural interventions. Increasing the number of operable windows, improving their placement to facilitate cross-ventilation, incorporating shaded ventilation openings, and introducing courtyards or semi-open internal spaces where feasible would enhance airflow and improve indoor thermal comfort without substantially increasing construction costs (Lechner, 2021; Li *et al*., 2024).

Occupants' cooling behaviour and adaptive responses

The cooling practices reported by respondents provide valuable insight into how occupants adapt to prevailing indoor thermal conditions. The overwhelming reliance on ceiling fans (85.1%) indicates that increasing air movement remains the principal strategy for improving thermal comfort within residences. Unlike air conditioners, ceiling fans do not reduce indoor air temperature but instead increase air velocity around occupants, thereby enhancing convective and evaporative heat loss from the human body. Their widespread use therefore suggests that naturally induced indoor airflow may be insufficient to provide acceptable thermal comfort.

Behavioural adaptation was also evident in the large proportion of respondents who reported sitting outdoors during periods of thermal discomfort. Outdoor environments generally experience greater air movement than enclosed indoor spaces, particularly where surrounding buildings and boundary walls restrict indoor ventilation. Likewise, the frequent use of hand fans outdoors and on verandas indicates that occupants actively compensate for inadequate natural airflow through localized enhancement of air movement.

Seasonal perceptions of heat also reflected the prevailing climatic conditions of the study area. Most respondents identified daytime as the hottest period during the dry season, whereas nighttime was more frequently reported as hotter during the wet season. High nocturnal humidity combined with reduced night-time cooling may explain this seasonal pattern because elevated humidity restricts evaporative heat loss from the human body and reduces thermal comfort despite lower air temperatures.

These adaptive responses are consistent with the adaptive thermal comfort theory, which proposes that occupants continuously modify their behaviour, clothing, activity, and use of environmental controls to maintain acceptable comfort under naturally ventilated conditions (ASHRAE Standard 55). Furthermore, adequate natural ventilation is essential not only for thermal comfort but also for maintaining acceptable indoor environmental quality through improved dilution of indoor-generated contaminants, including carbon dioxide (Mendell *et al.*, 2024).

Building spacing, setbacks and indoor thermal conditions

The findings indicate that the spatial arrangement of buildings may substantially influence the effectiveness of natural ventilation in the study area. More than two-thirds of the surveyed buildings were separated from neighbouring buildings by only 3–6 m, while approximately three-quarters had boundary wall setbacks of less than 1.8 m. Such compact spatial configurations are likely to restrict air movement around buildings by creating aerodynamic obstructions that reduce wind penetration and weaken cross-ventilation. In densely developed residential environments, closely spaced buildings and perimeter walls modify local airflow patterns, producing zones of reduced wind velocity that limit the exchange of indoor and outdoor air (Awbi, 2021).

The present findings are consistent with previous studies demonstrating that urban morphology strongly affects natural ventilation. Ahmed and Gregor (2014) reported that airflow around groups of buildings decreases as building spacing becomes narrower because adjacent structures alter wind direction and generate wake effects that reduce ventilation efficiency. Similarly, Mohamed (2023) showed through computational fluid dynamics (CFD) simulations that closely spaced residential buildings experience reduced indoor airflow compared with layouts that provide greater separation distances. More recently, Linghu *et al.* (2025) identified building spacing and surrounding urban geometry as important determinants of ventilation performance and cooling loads in complex building environments.

Restricted spacing may also influence indoor thermal conditions indirectly by reducing the capacity of buildings to dissipate accumulated heat through natural ventilation during both daytime and nighttime. In hot-humid climates, where wind-driven ventilation represents one of the primary passive cooling mechanisms, limited air circulation around buildings may increase indoor heat retention and prolong periods of thermal discomfort. Consequently, the compact development pattern observed in many of the surveyed neighbourhoods may partly explain the extensive reliance on mechanical air movement reported by occupants.

These findings emphasize that adequate building setbacks should not be viewed solely as planning requirements for access and safety but also as important climatic design measures. Providing sufficient separation between neighbouring buildings and maintaining appropriate distances from boundary walls can improve airflow around building envelopes, enhance cross-ventilation, and contribute to better indoor thermal performance (Lechner, 2021; Awbi, 2021).

Plot characteristics, building design and indoor thermal conditions

The predominance of relatively small plot sizes and high building coverage observed in this study further illustrates how residential development patterns may influence indoor thermal conditions. More than half of the surveyed buildings were constructed on 15 × 30 m plots, while approximately two-thirds occupied 50% or more of the available plot area. High site coverage reduces the amount of open space available for air circulation and limits opportunities for landscape elements that can enhance local microclimatic conditions. As a result, buildings are more likely to experience reduced wind penetration and greater heat accumulation.

Another notable finding is that fewer than one-quarter of the surveyed buildings were designed by architects, whereas the majority were designed without professional architectural input. Although this study did not directly evaluate design quality, professionally designed buildings are generally more likely to incorporate climate-responsive principles such as appropriate orientation, window placement, shading devices, and cross-ventilation strategies (Lechner, 2021). Consequently, the predominance of non-professional designs may contribute to reduced natural ventilation efficiency and poorer indoor thermal performance.

The observed relationship between plot characteristics and ventilation agrees with previous research on residential design in tropical climates. Akubue (2023) reported that housing layouts characterized by high density and limited open space significantly reduced natural airflow in residential developments in southeastern Nigeria. Similarly, Oforji *et al.* (2023) demonstrated that the configuration of building openings and overall building layout substantially influence airflow patterns in low-rise residential buildings. Recent work by Li *et al.* (2024) also concluded that building form, spatial arrangement, and opening configuration should be integrated during the early design stage to optimize natural ventilation under different climatic conditions.

These findings highlight the importance of considering urban planning and building design simultaneously. Improving indoor thermal conditions requires more than modifying individual buildings; neighbourhood layout, plot utilization, and building density should also be planned to facilitate adequate airflow throughout residential communities. Such integrated planning approaches are increasingly recommended as part of climate-responsive urban development strategies aimed at reducing cooling energy demand while improving occupant comfort (Lechner, 2021; Li *et al.*, 2024).

Relationship between wind speed and indoor temperature

The correlation analysis revealed a statistically significant positive relationship between wind speed and indoor temperature. Although increased wind speed is generally expected to improve thermal comfort through enhanced convective cooling, the observed positive association indicates that higher outdoor wind speed did not necessarily correspond to lower indoor temperatures in the surveyed buildings. This finding suggests that the cooling effectiveness of wind depends not only on its magnitude but also on the ability of buildings to capture, distribute, and exhaust airflow effectively.

One plausible explanation is that incoming air may already possess relatively high temperatures during periods of intense solar radiation, particularly in hot-humid tropical climates. Under such conditions, increased wind speed alone may not substantially reduce indoor air temperature if the incoming air is warm. Furthermore, buildings with limited openings, poor orientation, inadequate cross-ventilation, or restricted surrounding airflow may fail to utilize available wind effectively. Consequently, warm outdoor air may enter the building without producing sufficient ventilation to remove accumulated internal heat.

These findings support previous research indicating that wind speed alone is not a sufficient predictor of indoor thermal performance. Omrani *et al.* (2017) demonstrated that ventilation effectiveness depends on the interaction between external wind conditions and building configuration, with cross-ventilation consistently outperforming single-sided ventilation. Likewise, Awbi (2021) emphasized that airflow patterns inside buildings are governed by pressure differences, opening geometry, and internal spatial organization rather than external wind speed alone. More recently, Li *et al.* (2024) reported that natural ventilation performance results from the combined effects of climatic conditions and building design, highlighting the importance of integrating these factors during architectural planning.

The present findings therefore reinforce the concept that wind should be considered as one component of a broader passive cooling strategy rather than as an independent solution for achieving thermal comfort. Effective climate-responsive architecture requires simultaneous consideration of building orientation, opening design, building spacing, and surrounding urban morphology to maximize the cooling benefits of naturally available wind.

PRACTICAL IMPLICATIONS

The findings of this study have important implications for residential building design and urban planning in hot-humid tropical environments. First, the predominance of buildings with limited ventilation features suggests that substantial improvements in indoor thermal comfort could be achieved through relatively simple passive design interventions. Increasing the number of operable windows, improving cross-ventilation pathways, incorporating courtyards or semi-open spaces, and maintaining adequate setbacks between buildings would enhance natural airflow while reducing dependence on mechanical cooling systems.

Second, the results emphasize the need for stronger integration of climate-responsive principles into planning regulations and residential development practices. Building orientation, neighbourhood layout, and plot coverage should be considered alongside structural and functional requirements during the design process. Such approaches would contribute to reduced building energy consumption, improved occupant comfort, and greater resilience to increasing urban temperatures associated with climate change (Lechner, 2021; Awbi, 2021).

Finally, these findings may assist architects, planners, housing developers, and policy makers in revising residential design guidelines to better reflect the climatic characteristics of tropical cities. Incorporating passive ventilation strategies into building regulations has the potential to improve indoor environmental quality while supporting sustainable urban development.

STUDY LIMITATIONS

Several limitations should be considered when interpreting the findings of this study. First, the investigation was limited to selected residential neighbourhoods within Benin City; therefore, the results may not fully represent other climatic regions or urban settings in Nigeria. Second, environmental measurements were based primarily on wind speed and indoor air temperature. Other environmental variables known to influence thermal comfort, including relative humidity, mean radiant temperature, solar radiation, and air exchange rate, were not simultaneously evaluated. Third, the cross-sectional design captured conditions during the survey period and therefore did not account for seasonal or long-term variations in microclimatic conditions. Future studies should incorporate continuous environmental monitoring, computational airflow modelling, and seasonal observations to provide a more comprehensive understanding of natural ventilation performance in tropical residential buildings.

CONCLUSION

This study demonstrates that indoor thermal conditions in residential buildings in Benin City are influenced by the combined effects of building orientation, architectural design, surrounding spacing, and wind flow. The predominance of east–west building orientation, limited window provision, absence of courtyards, extensive use of solid block walls, narrow setbacks, and high plot coverage collectively reduced the effectiveness of natural ventilation.

The widespread reliance on ceiling fans and outdoor cooling practices indicates that natural ventilation alone was insufficient to maintain acceptable indoor thermal conditions. Although wind speed showed a significant positive relationship with indoor temperature, the findings suggest that wind contributes to thermal comfort only when supported by appropriate building design and spatial planning.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

1. Incorporate climate-responsive building orientation. Residential buildings should be oriented to optimize prevailing wind direction while minimizing excessive solar heat gain. Site planning should consider local wind patterns during the early design stage to improve natural ventilation.
2. Improve natural ventilation through building design. Buildings should incorporate adequately sized and strategically positioned openings on opposite façades to facilitate effective cross-ventilation. Where feasible, courtyards and semi-open spaces should be integrated into residential layouts to enhance indoor airflow.
3. Maintain adequate building spacing and setbacks. Planning authorities should enforce minimum distances between adjacent buildings and boundary walls to reduce airflow obstruction and improve wind penetration within residential neighbourhoods.
4. Promote climate-responsive building regulations. Building approval processes should encourage compliance with passive design principles, including orientation, window configuration, building spacing, and appropriate plot coverage, particularly for residential developments in hot-humid climates.
5. Strengthen professional involvement in residential design. Greater participation of qualified architects and urban planners should be encouraged to ensure that residential buildings incorporate scientifically established passive cooling strategies that improve indoor thermal comfort and energy efficiency.
6. Undertake further research. Future studies should include seasonal measurements of wind speed, indoor temperature, relative humidity, and mean radiant temperature, together with computational airflow modelling and building energy simulations, to provide a more comprehensive evaluation of natural ventilation and indoor thermal performance under tropical climatic conditions.

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