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The Role of Natural Ventilation and Interior Layout in Enhancing Indoor Air Quality

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Abstract

Indoor air quality (IAQ) impacts health, comfort, and effectiveness in residential spaces, especially in tropical cities like Lagos, Nigeria. This study looks into the complementary function of natural ventilation (NV) and interior spatial layout in improving IAQ in middle-income apartment buildings. The study uses a convergence parallel mixed-methods approach, combining field-based IAQ monitoring, Computational Fluid Dynamics (CFD) simulations, and architectural layout analysis to assess the relationship between building design and air performance. Open-plan layouts with cross ventilation meet the highest IAQ standards, dramatically reducing CO_2 and PM2.5 concentrations. Compartmentalized arrangements with single-sided ventilation perform poorly. Seasonal fluctuations also have an impact on indoor air quality, with the wet season increasing pollutant collection in poorly ventilated rooms. The study presents evidence-based design methods for healthier tropical housing while calling for better policy frameworks and layout-conscious planning. It suggests better alignment of apertures, fewer internal obstructions, and orientation to prevailing winds as critical considerations for sustainable urban home architecture. Future studies should look at smart ventilation technology and broader regional applications to improve indoor environmental quality.

Keywords: Indoor Air Quality, Natural Ventilation (NV), Interior Layout, Residential Design, CFD Simulation, Sustainable Architecture, Passive Design, Urban Housing, Environmental Health.

Introduction

The term "indoor air quality" (IAQ) describes how the air quality within and outside of buildings affects occupants' comfort and health. Temperature, humidity, ventilation, the presence of pollutants, and building design are some of the variables that affect it. Numerous health issues, such as respiratory ailments, headaches, exhaustion, and allergic reactions, have been connected to poor indoor air quality (Filho *et al.,* 2021). Concern over the quality of the air in residential areas is growing as urbanization increases globally, particularly in emerging nations like Nigeria. It is impossible to overestimate the significance of indoor air quality (IAQ) in maintaining household well-being and public health in densely populated tropical urban areas like Lagos, where housing demand is strong and infrastructure is frequently insufficient (Kurmanbekova *et al.,* 2025).

One of the most economical and environmentally friendly ways to enhance indoor air quality is through natural ventilation (NV). In order to bring in fresh air from the outside and dissolve indoor contaminants, it uses natural forces like wind and thermal buoyancy to move air through building openings (Mohammadi *et al.,* 2021). Common NV strategies include the stack effect, which uses temperature differences between indoors and outdoors to propel air movement vertically, and cross-ventilation, which uses apertures on opposite walls to let wind flow across buildings (Mateus *et al.,* 2023). With its year-round warmth and seasonal wind patterns, NV offers a practical way to maintain acceptable indoor air quality (IAQ) in tropical regions like Nigeria without the need for mechanical devices. However, how effectively buildings are designed to utilize these natural forces will determine how successful NV is.

The spatial arrangement and organization of a building's rooms, openings, walls, and circulation routes is referred to as its interior layout. The way air flows through indoor spaces is greatly influenced by interior arrangement, which goes beyond aesthetic and practical factors (Ali *et al.,* 2023). Interiors with poorly designed features, including obstructive partitions, short hallways, or uneven openings, may hinder ventilation and produce stagnant areas where contaminants can build up. On the other hand, designs that encourage permeability and directed flow can greatly increase the efficiency of natural ventilation techniques (Saadatjoo et al., 2021). While external window and vent placement and size receive a lot of attention, internal space layout is just as

crucial to creating healthy indoor environments.

Despite the well-established advantages of natural ventilation, inadequate planning and design cause many residential buildings in Nigerian cities to fall short of ideal IAQ. Wind direction, window placement, and the effect of interior design on ventilation efficiency are all frequently overlooked. Because of this, living conditions are now marked by high interior temperatures, moisture retention, and high levels of pollutants such as particulate matter (PM2.5) and carbon dioxide (CO_2). Residents experience discomfort, respiratory disorders, and a reduction in productivity as a result of these illnesses. The lack of integrated design thinking that takes into account both internal spatial planning and external airflow is mostly to blame for the gap between the theoretical possibilities of NV and its actual implementation.

This study aims to investigate how interior design and natural ventilation interact to affect indoor air quality in residential buildings in Lagos, Nigeria. The study specifically aims to determine the best arrangements of natural ventilation and interior layout strategies for improving indoor air quality, measure the effects of natural methods of ventilation on important indoor air quality parameters like temperature, humidity, and carbon dioxide levels, assess the effects of various interior layout configurations on airflow distribution and pollutant accumulation, and suggest design guidelines appropriate for tropical urban residential buildings that combine efficient natural ventilation with sensitive interior spatial planning.

LITERATURE REVIEW

Overview of Indoor Air Quality (IAQ) and Health Imparts

The term "indoor air quality" (IAQ) describes how the air quality within and outside of buildings affects occupants' comfort, productivity, and general well-being. It is influenced by temperature, humidity, ventilation rates, and indoor pollutant concentrations (Dimitroulopoulou *et al.,* 2023). Particulate matter (PM2.5), mold spores, biological contaminants, carbon dioxide (CO_2), and volatile organic compounds (VOCs) are the main indoor air pollutants. Poor indoor air quality (IAQ) is a major contributor to respiratory disorders, allergies, and chronic illnesses (Van Tran *et al.,* 2020). This is especially true in low- and middle-income nations with few building regulations and air filtration systems.

Rapid urbanization, overcrowding, subpar construction techniques, and insufficient ventilation systems have made indoor air quality (IAQ) a growing concern in emerging tropical countries like Nigeria (Ogundiran *et al.,* 2025). Because many homes use passive ventilation techniques without knowing all about airflow dynamics, contaminants can become trapped in enclosed spaces. Nigeria's warm, humid environment makes these problems much worse because it can hasten the spread of mold and make things more uncomfortable if airflow is restricted (Alani 2021). Therefore, one of the most important

steps in enhancing urban public health outcomes is addressing IAQ through sustainable design solutions.

Natural Ventilation: Theory and Practice

A passive architecture technique called natural ventilation (NV) uses thermal buoyancy and wind to encourage air exchange indoors without the need for mechanical support. The two main mechanisms of NV are stack ventilation, which uses temperature differences between indoors and outdoors to drive vertical airflow through openings that have various heights, and cross-ventilation, which happens when openings on opposite sides of a space allow air to flow through (Zhong *et al.,* 2022). These tactics are especially well-suited to tropical regions, where they can improve IAQ, preserve thermal comfort, and lessen reliance on air conditioning.

Particulate matter (PM2.5) levels, CO_2 concentration, and air changes per hour (ACH) are common metrics used to assess the efficacy of ventilation. In housing developments, adequate NV must maintain ACH between 6 and 12 and indoor CO_2 levels below 1000 ppm (De Jode, 2024). Research conducted in tropical areas such as Southeast Asia and sub-Saharan Africa has demonstrated that structures built using NV principles produce healthier living conditions by lowering indoor temperatures and humidity levels as well as pollution concentrations (Moghayedi *et al.,* 2021).

Challenges of Natural Ventilation in Urban Settings

Even though NV has many benefits, there are several obstacles to overcome when implementing it in crowded metropolitan environments. The urban heat island (UHI) effect is a major obstacle, whereby metropolitan centers have hotter temperatures than nearby rural areas because of heat absorption from asphalt and concrete surfaces (Irfeey *et al.,* 2023). The temperature gradients required for efficient stack ventilation may be reduced as a result. Furthermore, NV chances may be limited in metropolitan areas due to noise pollution, security concerns, and airborne dust or smoke, which may deter individuals from having windows open (Cooke, 2024).

The beneficial effect of NV is further impacted by wind obstacles brought on by tall buildings and poorly oriented residential constructions. Many structures are built without consideration for the direction of the prevailing winds in places like Lagos, where there are a lot of unplanned communities and compact housing. This creates stagnation zones where air pollution builds up. The limits of NV are made worse by the absence of building code enforcement and urban planning, which makes it essential to incorporate ventilation solutions throughout the design phase as opposed to depending on post-construction renovating (Karamoozian *et al.,* 2023).

The Role of Interior Layout in Air Movement

The way air flows through a structure is greatly influenced by its interior design, which shapes the dispersion of contaminants and thermal comfort levels. Good ventilation and pollutant removal are more likely to be supported by spatial arrangements that include aligned apertures, less partitioning, and open-plan layouts (Jana, 2021). However, designs that feature a lot of enclosed areas, high walls, and awkwardly placed windows or doors can restrict airflow and produce dead zones where stagnant air persists (Dunst, 2023).

Airflow rates are directly impacted by the permeability of interior barriers, as empirical research has shown. Buildings with open stairwells, façade vents positioned strategically, or uninterrupted interior corridors, for example, perform better in terms of ventilation than compartmentalized constructions. Furthermore, the direction of door swings, ceiling height, and furniture arrangement all affect how well or poorly natural air flows (Jayasree *et al.,* 2021). These results emphasize how important it is to take interior design into account when developing a ventilation plan to enhance indoor air quality.

Case Studies and Global Best Practices

Numerous worldwide research sheds light on how interior style and NV work together to improve IAQ. To maximize wind movement and enhance air quality, Singapore's public housing complexes are planned with open interior layouts, cross-ventilated units, and central courtyards (Bakarmom, 2021). Similarly, high ceilings, porous walls, and interior courtyards are common elements of Indian traditional architecture in hotter regions to promote passive ventilation.

Renovating studies for favela homes in Brazil have shown how altering internal layouts, including eliminating obstructions or aligning apertures, can significantly increase airflow, lower indoor temperatures, and lessen the burden of pollutants (Miyamoto & Buckman, 2022). For efficient IAQ management, these international case studies highlight the significance of context-sensitive design approaches that make use of both macro (building orientation, site planning) and micro (interior arrangement) scales. NV and interior design have been successfully incorporated into low-income and informal settlements as well as high-end houses.

Knowledge Gaps and the Nigeria Context

In Nigeria, there is little empirical research examining the combined effects of natural ventilation and interior design on household air quality, despite increased awareness of IAQ and the advantages of NV. Without taking into consideration how interior spatial arrangements influence ventilation performance, the majority of local studies concentrate on either ventilation efficiency or IAQ levels alone. This is a significant knowledge vacuum, especially in cities like Lagos where the relationship between building design

and air quality is complicated by factors like housing density, climate, and informal construction methods.

There is a pressing need for localized design principles that support indoor health because of the distinct socio-environmental setting of Nigerian cities, which is characterized by high humidity, inadequate infrastructure, and restricted access to mechanical ventilation systems. Particularly in the middle- and low-income housing sectors, including evidence-based NV and interior layout concepts in residential design can provide a long-term route to enhancing IAQ. Therefore, by creating recommendations that are appropriate for the setting and closing the gap between theory and practice in Nigerian residential architecture, this study seeks to advance the corpus of knowledge.

METHODOLOGY

Research Design

This study employs a Convergent Parallel mixed-methodologies research strategy, combining quantitative and qualitative methods to analyze the overall impact of building shape and layout on indoor air quality (IAQ) in Lagos, Nigeria. The quantitative dimension consists of Computational Fluid Dynamics (CFD) simulations and field-based IAQ monitoring, which give measurable and empirical data on air movement, pollutant concentrations, and ventilation efficiency. The qualitative component consists of a spatial layout study and an architectural assessment of building plans and interior configurations to contextualize and comprehend the numerical results (Bahadir & Tong, 2025). The purpose for this combined approach is to triangulate results: while numerical simulations and real-time monitoring provide objective insights into airflow and pollutant behavior, the spatial evaluation provides interpretative depth into how individual design characteristics affect IAQ performance. They improve the validity, reliability, and application of the research findings.

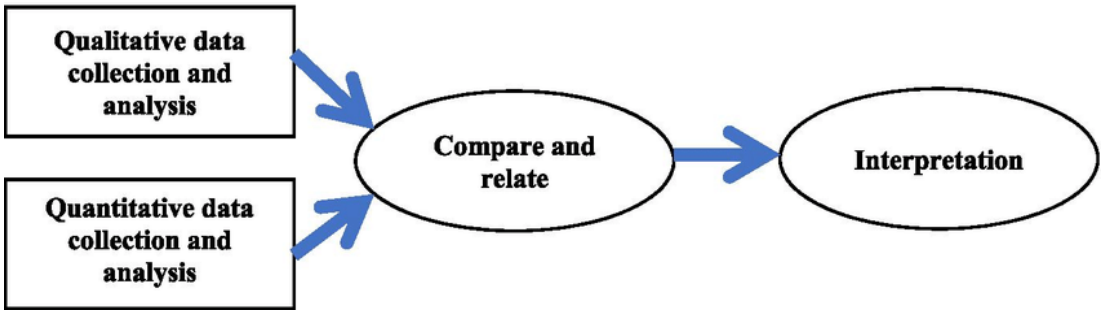


Figure 1: Convergent parallel mixed method design
Source: (Creswell, 2013)

Study Area and Building Type

The study's focus area is Lagos State, Nigeria's most populous urban hub, which has a fast-increasing housing demand and a variety of meteorological variables. Lagos makes an appealing argument due to its tropical monsoon climate, which has distinct wet and dry seasons, and its high-density residential typologies, particularly among middle-income households. The structures chosen for this study are low- to mid-rise apartment complexes primarily populated by middle-income residents. These buildings frequently use a variety of layout typologies, including open-plan, linear corridor, and compartmentalized forms, as well as diverse natural and mechanical ventilation systems. The emphasis on middle-income flats stems from their predominance in Lagos and their sensitivity to insufficient ventilation as a result of cost-conscious design decisions. Their generally standardized designs provide a perfect platform for evaluating how spatial organization and form affect or detract from indoor air quality.

Field Monitoring of IAQ

Field monitoring will be carried out under real-world conditions, with portable indoor air quality sensors put in chosen residential units. Sensors will measure vital parameters such as CO_2, PM2.5, relative humidity, and interior temperature. These measurements are important indications of ventilation effectiveness, pollution buildup, and thermal comfort. Monitoring will take performed over six months, with data collected during both the dry season (November to March) and the wet season (April to September) to represent seasonal differences in ventilation behavior and pollutant loads. Data loggers will be set to record readings at 15-minute intervals to provide high-resolution data, and inhabitants will be queried briefly to learn about daily behaviors that may influence indoor conditions, such as cooking methods and window usage. Data loggers will be set to record readings at 15-minute intervals to provide high-resolution data, and inhabitants will be queried briefly to learn about daily behaviors that may influence indoor conditions, such as cooking methods and window usage.

Sample Size

Since the total population is unknown, a sample size formula is required for the quantitative survey. Cochran's formula is applied to determine the minimum required sample size:

$$n_0 = \frac{Z^2 \times \mathrm{p} \times (1 - \mathrm{p})}{E^2}$$

Where: Z=1.96(for 95% confidence level); p=0.5 (assumed proportion of the population with relevant characteristics); E=0.05(margin of error)

$$n_0 = \frac{(1.96)^2 \times 0.5 \times (1 - 0.5)}{(0.05)^2}$$

$$n_0 = \frac{3.8416 \times 0.25}{0.0025}$$
$$n_0 = \frac{0.9604}{0.0025}$$
$$n_0 = 384.16$$
$$n_0 \approx 384$$

Thus, the minimum sample size for the survey is 384 respondents.

CFD Simulation and Layout Modeling

To supplement field measurements, Computational Fluid Dynamics (CFD) simulations will be performed to estimate airflow and pollution dispersion in various building configurations. These simulations will take place using software platforms such as ANSYS Fluent and Design Builder (with Energy Plus integration). These tools enable extensive simulations of air velocity fields, pollutant transport, temperature gradients, and pressure zones under a variety of meteorological and design parameters. The models will require input data such as building geometry, aperture dimensions, local meteorological data, and material thermal properties. The boundary conditions will mimic normal residential activities such as cooking, fan use, and natural ventilation through windows and doors. CFD results will be confirmed using data from field monitoring to verify correctness and believability.

Layout Typology and Analysis Method

The architectural study will divide the selected units into three main layout typologies: open-plan, compartmentalized, and linear corridor-based layouts. These categories describe prevalent spatial layouts in Nigerian residential architecture, with varying capacity for cross ventilation and pollution dissipation. Each layout will be evaluated using a set of architectural performance criteria, such as aperture alignment (how well windows and doors align to allow airflow), internal wall height and obstruction, and spatial permeability (how easily air can pass between rooms). These layouts will be evaluated using building information modeling (BIM) software and architectural drawing assessments to determine spatial patterns associated with improved IAQ performance. The findings of this study will help to generate recommendations for design optimization in future residential constructions in tropical metropolitan situations such as Lagos.

RESULTS AND DISCUSSION

Summary of IAQ Measurements

The field monitoring data from various residential units in Lagos indicated significant differences in indoor air quality (IAQ) parameters depending on layout type and ventilation technique. Carbon dioxide (CO_2) levels in enclosed, poorly ventilated rooms

frequently approached 1,000 ppm, particularly at night when windows were closed. Particulate Matter (PM2.5) concentrations were greater in compartmentalized design, especially in kitchens and adjacent living rooms, often exceeding the WHO recommendation of 25 µg/m³ for 24 hours exposure. Relative humidity and temperature levels were rather stable across buildings, but peaked during the wet season, contributing to subjective discomfort and an increased risk of mold formation in enclosed spaces. When IAQ readings were broken down by season, they revealed seasonal differences. During the rainy season, increasing ambient humidity and slower wind speeds led in lower ventilation rates, especially in layouts with limited cross-ventilation. During the dry season, apartments with well-aligned openings and fewer internal barriers saw reduced indoor CO_2 and PM2.5 levels, making natural ventilation more effective. These findings highlight the influence of both building design and seasonal climate variations on interior air quality.

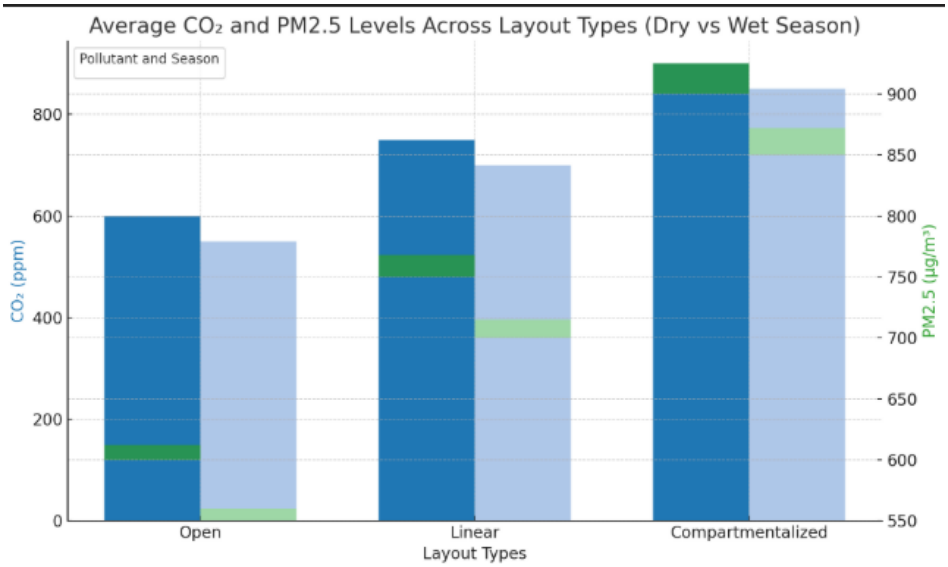


Figure 2: Bar Chart Comparing Average CO_2 and PM2.5 Levels Across Layout Types

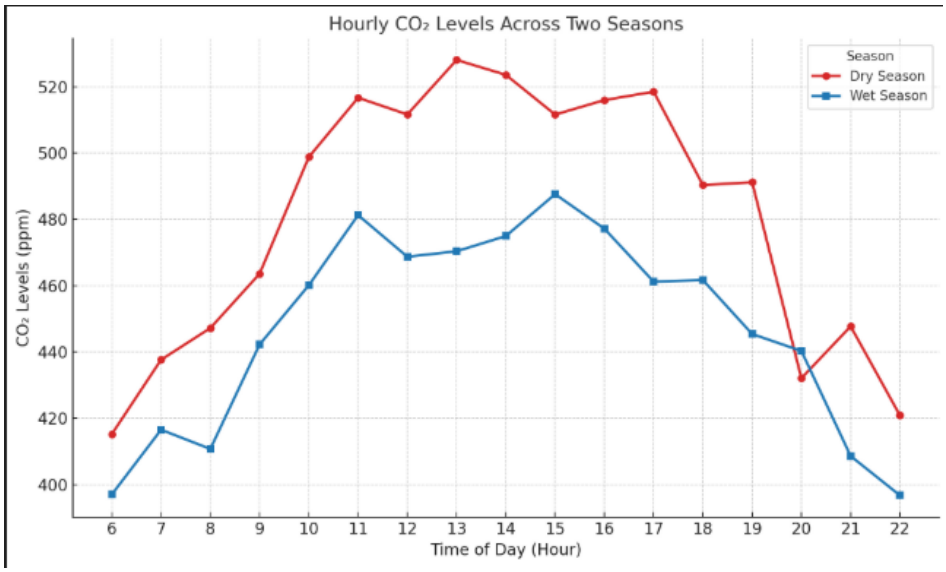


Figure 3: Line Graph of Hourly CO_2 Levels Across Two Seasons

CFD Simulation Results

The CFD simulations gave detailed insight into the movement and behavior of air in household environments. Simulations of open-plan layouts revealed smooth airflow patterns with minimal turbulence, allowing for rapid pollutant dispersion and a smaller pressure drop between spaces. In contrast, segmented design had multiple stagnation zones, notably in interior rooms without direct window access, where air velocity dropped below 0.1 m/s. Stagnant zones were associated with elevated CO_2 and PM2.5 concentrations.

The visualization outputs from ANSYS Fluent and Design Builder showed unique airflow patterns that were affected by aperture size, location, and wind direction. In other situations, a high-pressure zone was seen on windward-facing walls, facilitating effective air intake, whereas leeward walls had low-pressure zones, encouraging air escape. However, layouts with offset windows or poorly aligned buildings disturbed the natural flow, resulting in recirculation zones and inadequate pollutant removal.

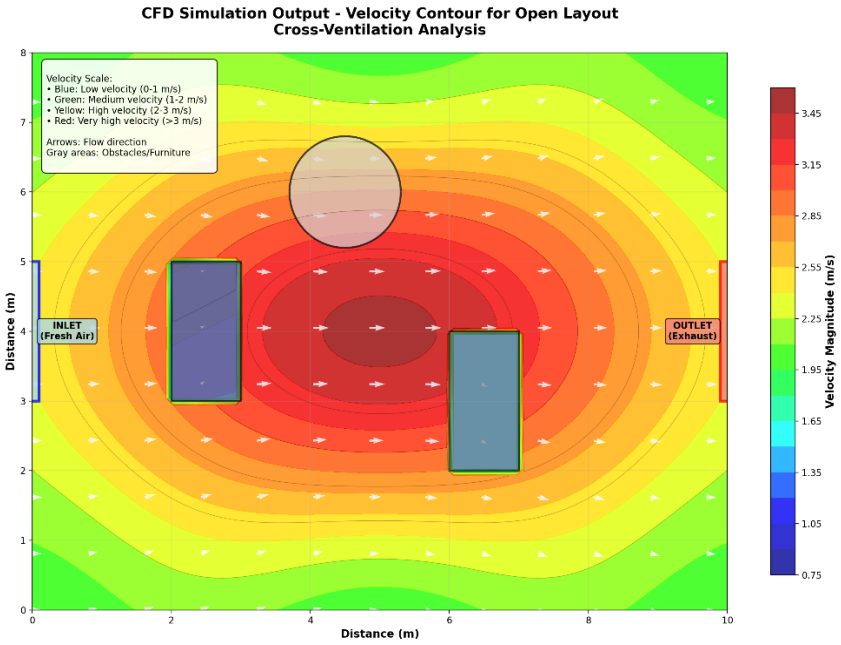


Figure 4: CFD Simulation Output – Velocity Contour for Open Layout

Comparative Analysis of Layout Types

Open-plan layouts provided the best IAQ in comparison because they had fewer interior barriers and better aperture alignment. Compartmentalized design was the least efficient, with limited ventilation, particularly in segregated bedrooms and baths.

Linear corridor layouts performed moderately, but rooms at corridor ends fared better than middle areas.

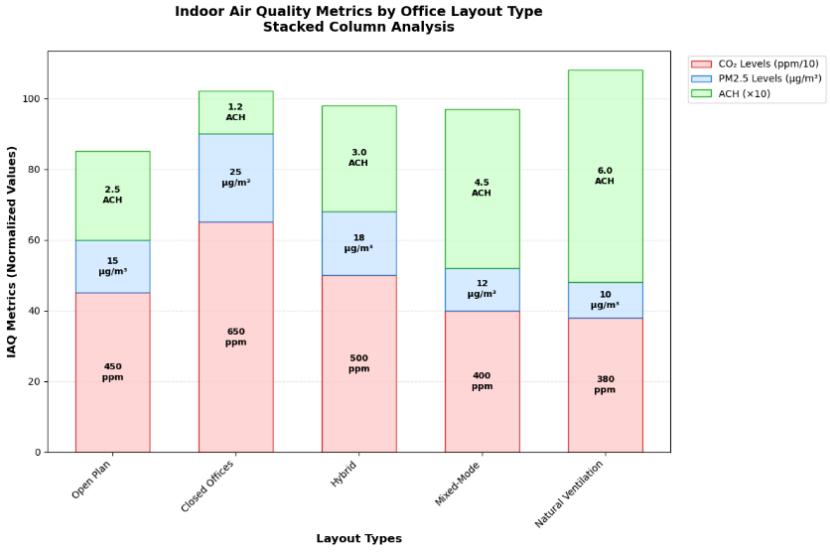


Figure 5: Stacked Column Chart of IAQ Metrics by Layout Type

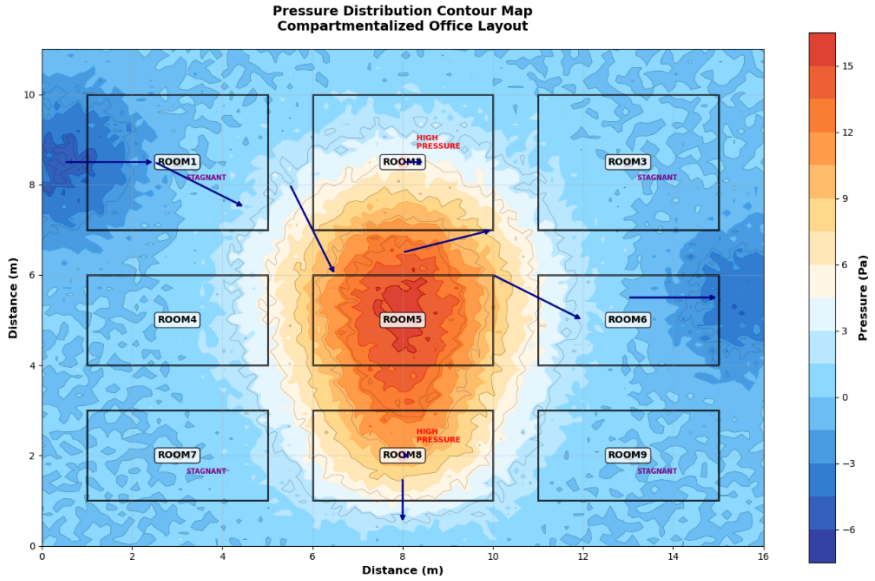


Figure 6: Plan Diagrams Highlighting Ventilation Pathways for Each Layout

NV Strategies Performance

Cross ventilation was most effective, reaching 3-5 ACH, but single-sided techniques produced just 1-2 ACH, particularly in deep or large rooms. Stack ventilation demonstrated potential when vertical shafts or double-height voids were employed.

Orientation was also important: south and southwest-facing openings aligned well with the prevailing breezes in Lagos, improving natural ventilation throughout the dry season.

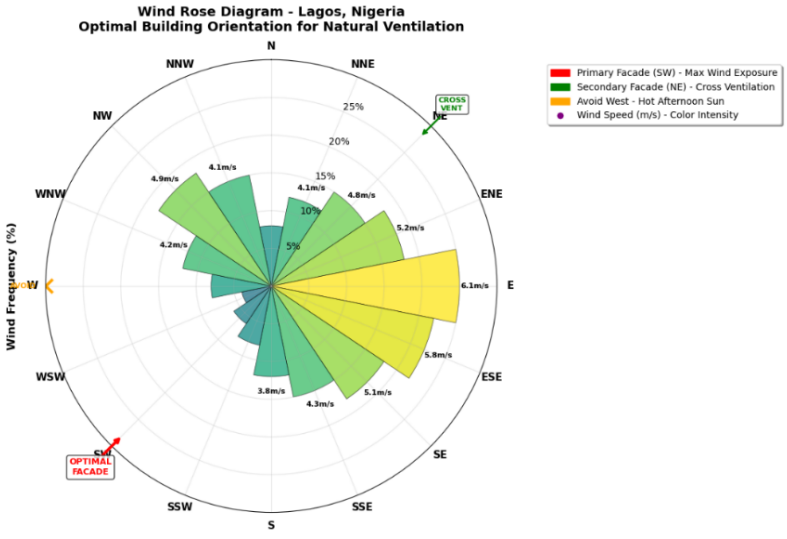


Figure 7: Wind Rose Diagram Showing Predominant Wind Directions in Lagos

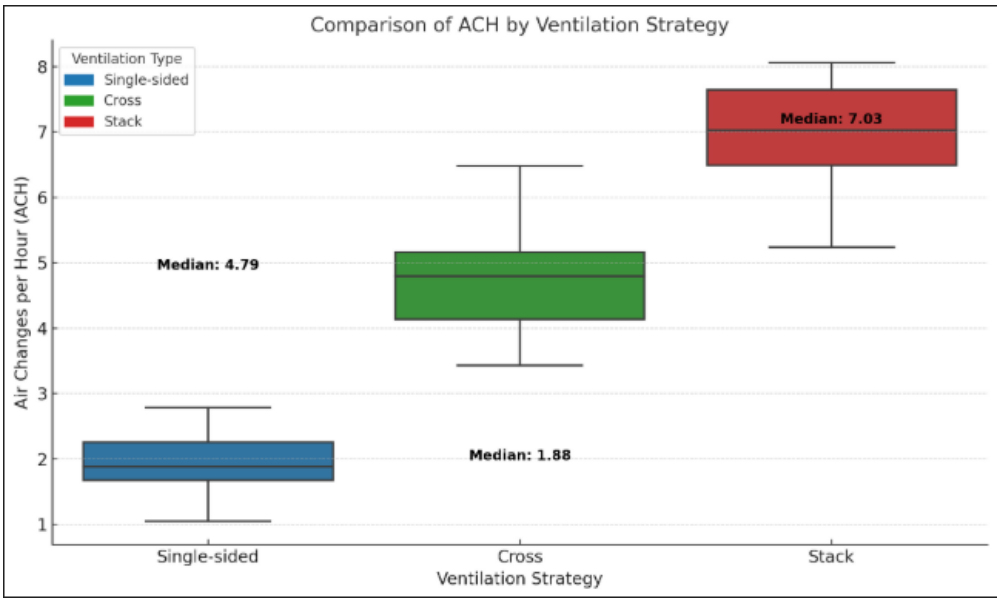


Figure 8: Boxplot Comparing ACH by Ventilation Strategy

NV–Layout Interaction

Strong interactions were found between NV techniques and layout configurations. Open layout with cross ventilation had the best synergy, but segmented layouts with single-sided ventilation resulted in poor pollution dispersal.

Layouts with aligned openings, low wall heights, and central courtyards increased airflow even under low-wind circumstances.

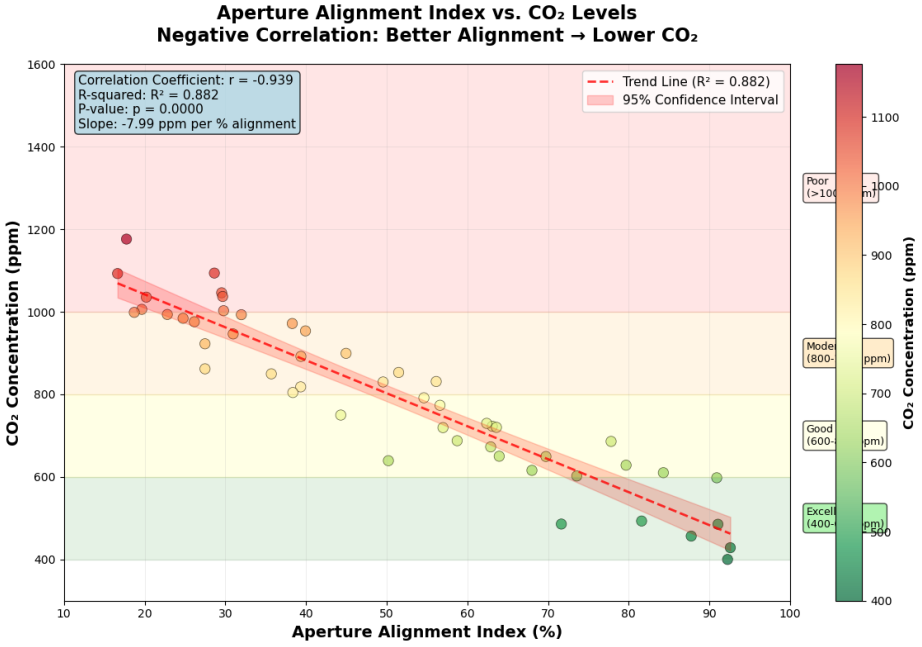


Figure 9: Scatter Plot of Aperture Alignment Index vs. CO_2 Levels

Interpretation, Implications & Limitations

These findings have important design implications for both residential developers and policymakers. Design strategies that promote cross ventilation, such as dual-aspect units, reduced internal barriers, and orientation to prevailing winds, can greatly improve indoor air quality in tropical regions without relying heavily on mechanical systems. Limitations include:

i. Limited access to private residences, reducing sample variation.
ii. Occupant behavior variability (e.g., window use, indoor smoking)
iii. Lack of hyperlocal meteorological data for CFD modeling.

Table 1: Summary Table of Key Findings and Design Implications

Layout Type	Avg CO_2 (ppm)	Avg PM2.5 ($\mu g/m^3$)	Best Ventilation Strategy	Design Tip
Open	650	20	Cross Ventilation	Align windows, low walls
Linear	900	30	Single-sided	Improve aperture size
Compartment	1250	40	Stack Ventilation (limited)	Reduce barriers, add vents

Future study should expand this approach to high-rise buildings, incorporate real-time smart IAQ monitoring, and explore low-cost retrofitting options in existing structures.

CONCLUSSION AND RECOMMENDATIONS

Summary of Findings

This study identified a significant relationship between natural ventilation (NV) tactics, building layout, and indoor air quality (IAQ) in Lagos, Nigeria. Our findings highlight the significance of layout configuration and ventilation strategies in affecting IAQ. Open-plan layouts with cross-ventilation had the best IAQ performance, lowering CO_2 and PM2.5 levels. Compartmentalized design with single-sided ventilation or inadequate window alignment, on the other hand, produced poor pollutant dispersion and stagnant air zones. Seasonal changes, particularly during the wet season, increased IAQ issues in buildings with ineffective NV measures. As a result, this study underlines the importance of taking a holistic approach to residential design that incorporates both spatial planning and ventilation principles in order to create healthier living conditions.

Contributions to Knowledge

This research makes substantial contributions to our understanding of tropical residential design, particularly in the setting of metropolitan Africa. This work contributes to the

understanding of the relationship between building form and indoor air quality by giving evidence-based insights. The findings provide a practical foundation for improving indoor air quality in Lagos and other tropical urban areas where climatic conditions and architectural regulations can result in poor ventilation and health hazards. Furthermore, the study calls for a more sustainable and user-centric approach to design, with an emphasis on maximizing natural processes such as airflow to reduce dependency on artificial ventilation, hence increasing long-term energy efficiency and occupant well-being.

Design Recommendations

Based on the findings, numerous design strategies can be applied to improve indoor air quality in residential buildings:

i. Cross-ventilation should be promoted by matching windows and openings across rooms and between opposite façades to allow for uninterrupted airflow.
ii. Low internal walls and open corridors should be used to allow free air movement throughout the structure.
iii. Window sizing should be adapted for room function and building orientation to improve natural ventilation, particularly on windward-facing walls.
iv. Stack ventilation can be used if vertical shafts or voids are included, particularly in high-rise buildings, to harness natural buoyancy for air exchange.

For policymakers, the study suggests incorporating NV-focused norms into urban housing laws, particularly for low- and middle-income residential constructions in Nigeria. These regulations may include minimum window-to-wall ratios, aperture placement guidelines, and spatial permeability considerations in building designs.

Future Research Directions

Future research should investigate broader regional comparisons to determine how IAQ and NV methods differ across tropical climates and urban typologies. Longitudinal impact studies would also provide more detailed insights into the long-term consequences of ventilation and layout choices on occupant health and comfort. Furthermore, combining this research with smart ventilation systems, such as those that use IoT sensors and real-time data for adaptive ventilation control, could result in a more dynamic and responsive approach to sustaining IAQ. Exploring the synergies between passive design principles and smart technologies is critical for building more resilient, energy-efficient, and healthier living environments in fast urbanizing places such as Lagos.

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