

AN EXPLORATORY COMPARISON OF INDOOR AIR QUALITY IN RETROFITTED DWELLINGS IN ABUJA, NIGERIA

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Abstract

Indoor air quality (IAQ) in retrofitted residential buildings reflects the combined influence of ventilation conditions, building envelope characteristics, material emissions, occupant activities, and outdoor pollutant ingress. This is especially relevant in Nigeria, where empirical IAQ research remains limited relative to the scale of exposure risk, and where housing conditions, fuel use, and ventilation practices vary substantially across residential settings. This study adopted an exploratory cross-sectional, post-retrofit field design to assess IAQ in three purposively selected retrofitted dwellings across distinct urban districts in Abuja (Gwarinpa, Lokogoma, and Wuse II), comprising six monitored rooms (main living room and principal bedroom). The monitored dwellings had elapsed post-renovation periods of two years (D1, retrofitted 2024) and one year (D2 and D3, retrofitted 2025). Physical parameters including carbon dioxide (CO₂), total volatile organic compounds (TVOC), particulate matter (PM_{2.5} and PM₁₀), temperature, and relative humidity were continuously monitored for 48 hours per room during the 2026 dry season (1 February to 30 April; 288 cumulative hours) using calibrated continuous loggers (GrayWolf IQ-610 and TSI SidePak AM520). Data were analyzed using descriptive statistics, temporal profiling, cross-case comparison, and exploratory principal component analysis. Across all dwellings, bedrooms exhibited higher pollutant accumulation than living rooms, averaging 1024.3 ppm CO₂ (vs. 763.7 ppm), 240 ppb TVOC (vs. 171 ppb), and 27.9 µg/m³ PM_{2.5} (vs. 23.8 µg/m³). Dwelling D2 (retrofitted in 2025 with gloss paints and PVC finishes) exhibited the greatest internal burden, peaking in the bedroom at 1187 ppm CO₂ and 318 ppb TVOC under single-sided, compartmentalized airflow. Conversely, Dwelling D3 demonstrated low indoor CO₂ (living room: 688 ppm) under full cross-ventilation but recorded the highest particle concentrations (bedroom PM_{2.5}: 29.7 µg/m³; PM₁₀: 64.8 µg/m³) due to untreated roadside particle ingress. Because envelope features, domestic routines, and external exposures varied simultaneously without pre-retrofit measurements, these findings cannot isolate determinant effects or establish the causal impact of retrofitting itself. The study instead provides preliminary, case-specific case evidence demonstrating that post-retrofit IAQ in tropical urban settings requires balancing natural ventilation provision with external particle filtration and low-emission material procurement, offering an empirical basis for larger longitudinal studies on retrofit-related indoor environmental performance in Nigeria.

Keywords: Building materials; Indoor air quality; Residential buildings; Retrofitted housing; Ventilation; Window typology

INTRODUCTION

Indoor air quality is a critical component of healthy housing because it directly affects occupant comfort, exposure, and health, yet it remains insufficiently addressed in residential retrofit practice and evaluation (Sani & Auwalu, 2025; Broderick et al., 2017; Akande et al., 2025). Indoor air conditions in dwellings are shaped by interacting factors that include ventilation, layout, materials, occupant activities, and pollutant ingress from outdoors (Ortiz et al., 2020; Bawa & Ismaila, 2025; Akande, 2021). This issue is especially important in retrofitted buildings because retrofit measures alter the envelope, ventilation rate, and material composition of the dwelling (Sani & Auwalu, 2025; Ortiz et al., 2020; Goodarzi et al., 2023). Studies of retrofitted housing by Broderick et al. (2017) and Lozinsky et al. (2025) show that reduced air exchange can increase indoor concentrations of carbon dioxide (CO₂), total volatile organic compounds (TVOCs), and particulate matter, although outcomes vary depending on pollutant source strength, outdoor pollution levels, and ventilation provision.

In Nigeria, the need to address IAQ within housing is sharpened by rapid urbanization, persistent attention to housing quantity over quality, and evidence that residential buildings often expose occupants to unhealthy pollutant levels (Akande, 2021). Nigerian studies by Akande et al. (2023), Akande (2021), and Akande et al. (2024) have shown that building features such as wall and floor materials, dwelling type, number of rooms, window type, and orientation are associated with pollutant levels and health-related risks. Also, Jelili et al. (2025) has ascertained that particle pollution in urban homes varies with density, building type, cooking fuel, and window design, while many dwellings lack cross-ventilation and depend on generators or mixed fuels that can worsen indoor conditions. Abuja is an important case because it combines rapid urban growth, varied residential morphologies, and ongoing retrofit activity within a setting already affected by urban pollution and building-quality concerns (Bawa & Ismaila, 2025; Akande et al., 2024). Abuja-focused evidence identifies inadequate ventilation, particulate matter, carbon dioxide, and building-related determinants as important contributors to poor indoor air quality, while also calling for design and policy responses tailored to local urban conditions (Bawa & Ismaila, 2025).

Despite growing retrofit activity, Nigeria still lacks localized IAQ standards and has limited monitoring mechanisms, as well as insufficient theoretical and empirical studies on residential retrofits. Internationally established approaches also remain only weakly adapted to local residential conditions (Sani & Auwalu, 2025). Broader retrofit literature further notes that health and comfort are rarely measured directly, occupant factors are underrepresented, and research still inadequately captures the interacting effects of building envelope changes, materials, and ventilation strategies (Ortiz et al., 2020). These gaps highlight the need for empirical investigation of the factors influencing IAQ in retrofitted residential buildings within Abuja, Nigeria.

Therefore, this study is presented as an exploratory case study of selected retrofitted residential dwellings in Abuja, Nigeria. It aims to compare indoor air quality conditions across the case dwellings and to examine how window typology, window layout and placement, building materials, ventilation practices, and occupant activities appear to be

associated with observed differences. The study addresses the following research question: How do indoor air quality conditions vary across selected retrofitted residential dwellings in Abuja, Nigeria, and which retrofit-related and occupancy-related characteristics appear to be associated with these differences?

Identifying these factors is important for both research and practice because it can help connect retrofit decision-making and more appropriate building codes with health-relevant indoor performance rather than energy goals alone (Broderick et al., 2017; Lozinsky et al., 2025; Akande et al., 2024). The findings can support case-specific IAQ assessment frameworks, healthier housing policy, and retrofit guidance on ventilation, materials, and pollutant control for Abuja and similar urban settings in Nigeria.

LITERATURE REVIEW

Concept of Indoor air quality (IAQ)

Indoor air quality (IAQ) in residences reflects the concentration of chemical, particulate, and biological pollutants indoors and the exposure conditions created by ventilation, temperature, humidity, and occupant activity (Baeza Romero et al., 2022; Narayanan et al., 2024). Residential IAQ surveys therefore require caseual data on building location, layout, ventilation, finishing materials, and occupant behaviour because pollutant levels cannot be interpreted correctly without understanding their sources and pathways (Baeza Romero et al., 2022; Hashemi & Dungrani, 2025). IAQ is consequently not determined by pollutant concentration alone but by the interaction between pollutant generation, building characteristics, ventilation processes, and occupant exposure.

In residences, CO₂ is a useful indicator of ventilation adequacy, but it is insufficient on its own because health-relevant exposure also depends on particles, VOCs, formaldehyde, moisture, and biological contaminants (Cedeno-Quijada et al., 2025; Goodarzi et al., 2023; Coggins et al., 2022). This distinction is relevant to residential buildings because different pollutants have different sources and transport pathways. Tropical reviews also show robust patterns of cooking-related particle peaks, traffic-dust penetration, humidity-driven VOC and formaldehyde emissions, and mould growth under weak hygrothermal control (Cedeno-Quijada et al., 2025; Kajjoba et al., 2024; Hassan et al., 2024). Thus, a meaningful assessment of residential IAQ requires a multi-parameter approach that considers both pollutant concentrations and the physical and behavioural conditions that regulate their generation, entry, accumulation, and removal.

Retrofitting and IAQ

Retrofitting alters indoor air quality mainly by changing airtightness, ventilation rates, and material profiles, which can either reduce or increase pollutant concentrations (Sani & Auwalu, 2025; Ortiz et al., 2020; Goodarzi et al., 2023). Reviews of residential retrofits consistently report mixed IAQ outcomes because the direction of change depends on whether dominant pollutants originate from indoor sources or outdoors and on whether ventilation is improved alongside envelope upgrades (Lozinsky et al., 2025; Fisk et al., 2020). Retrofit

interventions should therefore not be considered inherently beneficial or detrimental to IAQ; rather, their effects depend on how changes to the building envelope, ventilation provision, materials, and occupant practices interact.

Field studies show that tighter post-retrofit envelopes often lower air exchange and raise indoor CO₂, TVOCs, and PM_{2.5} when compensating ventilation is inadequate (Broderick et al., 2017). Sealing leaks without ventilation support is a known pathway to higher indoor pollutant concentrations from indoor-generated sources (Noris et al., 2013; Goodarzi et al., 2023; Hashemi & Dungrani, 2025). Mechanical ventilation can offset some of these effects, and apartments with continuous systems generally show larger improvements in pollutant levels linked to indoor sources (Noris et al., 2013; Du et al., 2019). These findings indicate that the IAQ consequences of retrofit measures are governed not by individual interventions alone but by the balance between airtightness, ventilation, pollutant sources, and removal pathways. Table 1 summarizes the main pathways through which retrofit actions can influence IAQ.

Table 1: Main Pathways Linking Retrofit Actions to IAQ Outcomes

Retrofit IAQ Pathway	Typical Effect Reported	Examples	Reference
Envelope tightening	Lower air exchange and possible pollutant buildup	CO ₂ , TVOC, and PM _{2.5} increased post-retrofit	Broderick et al. (2017)
Added ventilation	Lower indoor-source pollutants in many cases	Continuous systems improved IEQ more	Noris et al. (2013)
Material replacement	VOC, formaldehyde, or BTEX increases	BTEX rose after retrofit in Finland	Du et al. (2019)
Moisture control	Mould and microbial reductions are common	Dampness and mould often decreased	Fisk et al. (2020)
Case dependence	Outdoor pollution can offset gains	PM _{2.5} rose from outdoor ingress and occupant activities	Hassan et al. (2024)

The studies demonstrate that retrofit-related improvements in energy performance or building airtightness cannot be evaluated independently of IAQ. The same intervention may produce different outcomes depending on the existing ventilation strategy, pollutant sources, outdoor conditions, and occupant behaviour. This provides an important basis for examining specific architectural characteristics of retrofitted housing, particularly windows, their spatial configuration, and materials introduced during renovation

Window Typology

Window design is a major architectural determinant of residential IAQ because it controls openable area, airflow direction, ventilation mode, and the balance between pollutant removal and pollutant ingress (Pourtangestani et al., 2024; Yin et al., 2024; Narayanan et al., 2024). Reviews of natural window ventilation identify geometry, opening ratio, number of openings, type, location, orientation, and shading as influential variables for ventilation efficiency and indoor air quality (Yin et al., 2024; Baeza Romero et al., 2022). Window typology is

therefore not merely an aesthetic or functional architectural choice; it directly affects the capacity of a dwelling to exchange indoor and outdoor air.

Nigerian empirical studies suggest that sliding windows can provide poorer natural-ventilation-related indoor conditions than louvred and some casement configurations. In Ile-Ife, houses with sliding windows recorded higher indoor temperatures than houses with louvred windows, while a study in Asaba found that sliding windows were associated with poorer thermal comfort outcomes than louvre and casement-based configurations (Ayanlade et al., 2019; Charles, 2022). This indicates that nominal window size alone may be an incomplete indicator of ventilation performance, because effective opening area and mode of operation also shape airflow and indoor conditions (Gabriel et al., 2025; Basil et al., 2026). Occupant-centred studies further show that window performance depends not only on geometry but also on how residents actually operate windows to remedy stuffy air, odours, humidity, privacy, and outdoor pollution concerns (Pourtangestani et al., 2024; Pourtangestani et al., 2025).

The literature therefore points to an important interaction between window typology and occupant behaviour. A window with high theoretical ventilation potential may not deliver equivalent IAQ benefits when occupants keep it closed because of outdoor pollution, security, privacy, thermal discomfort, or other concerns. Conversely, window systems that permit greater and more controllable openings may provide better opportunities for natural ventilation where outdoor conditions are favourable. This interaction is particularly relevant to retrofitted dwellings, where replacement or modification of windows may change both the physical ventilation capacity and the way occupants regulate indoor conditions.

Window Layout and Placement

Window layout and placement shape indoor airflow as strongly as window type because cross-ventilation potential, façade orientation, aperture alignment, and interior obstructions determine whether fresh air reaches occupied rooms (Ogunnaike et al., 2025; Yin et al., 2024). Open-plan layouts with cross-ventilation consistently outperform compartmentalised, single-sided arrangements for reducing indoor CO₂ and PM_{2.5} (Ogunnaike et al., 2025). This indicates that effective natural ventilation depends on the spatial relationship between openings rather than simply on the presence or size of individual windows.

Single-sided and cross-ventilation are the most studied natural ventilation strategies, while corner ventilation and buoyancy-driven patterns remain much less studied despite their relevance to dense urban housing (Yin et al., 2024). Simulation work also shows that when occupant behaviour is incorporated, north-facing cross-ventilated layouts and wider wall configurations can increase annual air-change rates by 5–12%, indicating that placement interacts with both climate and window-use patterns (Pourtangestani et al., 2025).

Cross-ventilation lowers CO₂ and PM_{2.5} (Ogunnaike et al., 2025; Kajjoba et al., 2024), whereas single-sided layouts tend to trap pollutants in occupied rooms (Ogunnaike et al., 2025). Orientation and alignment also matter as much as size alone (Pourtangestani et al., 2024; Ogunnaike et al., 2025). Consequently, window placement should be understood as a

spatial ventilation variable that links architectural configuration to pollutant transport and removal.

The studies further suggest that window typology and window placement should not be treated as independent variables. The effectiveness of a particular window type depends not only on where it is positioned, how openings are aligned across the dwelling, and whether internal partitions obstruct airflow. This interaction provides a strong rationale for assessing both window characteristics and spatial configuration when investigating IAQ in retrofitted residential buildings.

Retrofit Materials

Materials introduced during retrofit are an important IAQ pathway because paints, glues, varnishes, sealants, insulation, ceiling boards, and composite finishes can emit volatile organic compounds (VOCs), formaldehyde, and benzene, toluene, ethylbenzene, and xylene (BTEX) indoors (Goodarzi et al., 2023; Narayanan et al., 2024). Reviews of refurbished buildings identify two dominant research themes: ventilative properties and the effects of introduced building materials on IAQ (Goodarzi et al., 2023). Material-related emissions are therefore particularly relevant to retrofits because renovation can introduce new pollutant sources at the same time that envelope improvements reduce air exchange.

Measured studies support this mechanism. Formaldehyde in retrofitted Irish dwellings was attributed mainly to building materials, and BTEX increased significantly after retrofit in Finnish buildings (Coggins et al., 2022; Du et al., 2019). Material choice also matters within insulation categories because common products such as extruded polystyrene (XPS) and expanded polystyrene (EPS) are linked with VOC emissions, while hemp insulation appears lower-emitting in comparative reviews (Narayanan et al., 2024).

The IAQ implications of retrofit materials are therefore closely connected to ventilation and building airtightness. Material emissions may be relatively short-lived or persistent depending on the product, while their indoor concentrations are also influenced by air exchange and pollutant removal. Consequently, assessing retrofit materials independently of ventilation may underestimate their contribution to IAQ deterioration. This reinforces the need for an integrated assessment of materials, envelope changes, ventilation, and occupancy conditions in retrofitted housing.

Tropical Climate Framework

The tropical residential framework adds a distinct IAQ burden because high humidity, seasonal moisture, outdoor particle ingress, and limited access to full mechanical ventilation change both pollutant sources and control options (Cedeno-Quijada et al., 2025; Ogunnaike et al., 2025). In tropical evidence syntheses, humidity drives VOC and formaldehyde emissions and promotes mould growth when ventilation and moisture control are weak (Cedeno-Quijada et al., 2025; Ortiz et al., 2020).

Field evidence from tropical cities shows that opening windows and balcony doors can reduce pollutant concentrations by about 40% in summer, but the gains vary with outdoor air quality and season (Ahmed & Rahman, 2024). Tropical Nigerian and East African studies

also emphasize that cross-ventilation, fewer internal obstructions, and source control are central to healthier naturally ventilated housing (Cedeno-Quijada et al., 2025; Kajjoba et al., 2024; Ogunnaike et al., 2025).

These findings are particularly relevant to Abuja, where natural ventilation remains an important component of residential environmental control, while outdoor pollution, seasonal climatic variation, occupant behaviour, and building configuration can constrain the benefits of window opening. The tropical case therefore means that increasing ventilation is not universally beneficial: opening windows can facilitate pollutant removal when outdoor air is relatively clean but can also increase pollutant ingress when outdoor conditions are poor. This reinforces the importance of evaluating window characteristics, ventilation behaviour, and outdoor pollution pathways together rather than considering any single factor in isolation.

Research Gap

The main research gap is the lack of localized, post-retrofit residential IAQ evidence from warm-humid and tropical African settings, even though reviews repeatedly note that most retrofit studies come from Europe and the United States (Fisk et al., 2020; Sani & Auwalu, 2025). Nigerian reviews specifically identify missing local standards, weak monitoring systems, and limited empirical studies tailored to local residential conditions (Sani & Auwalu, 2025). Although existing Nigerian studies provide valuable evidence on residential IAQ, the specific implications of retrofit interventions for indoor pollutant conditions remain insufficiently characterised.

A second gap is methodological. Existing studies often examine either ventilation or IAQ alone, while the combined effects of window typology, window layout, retrofit materials, and occupant behaviour remain under-integrated (Ogunnaike et al., 2025; Narayanan et al., 2024). Tropical reviews also note inconsistent sensor reporting and scarce targeted evaluations of TVOC, formaldehyde, and window-screen effects, which limits comparison across studies (Cedeno-Quijada et al., 2025). More importantly, the literature provides limited empirical evidence on how architectural retrofit decisions interact with real occupancy conditions to shape multiple IAQ indicators simultaneously.

A third gap concerns the relationship between physical building characteristics and pollutant pathways. Window typology, window layout and placement, retrofit materials, ventilation mode, occupant activities, and outdoor pollution are frequently discussed as separate determinants. However, their combined influence on IAQ remains insufficiently examined, particularly in residential buildings undergoing retrofit in African urban environments. This is important because retrofit measures can simultaneously modify the building envelope, introduce new emission sources, alter ventilation opportunities, and change occupant responses to indoor and outdoor environmental conditions

This review therefore supports a study design that measures multiple IAQ parameters on site and interprets them against retrofit-specific variables, especially window typology, layout and placement, and introduced materials, under real occupancy in Abuja. The study responds to the unresolved need for case-specific evidence that connects architectural retrofit decisions with measurable indoor environmental conditions. By examining these factors together, the

study seeks to strengthen the empirical basis for IAQ assessment in retrofitted Nigerian housing and provide evidence capable of informing healthier retrofit design, ventilation strategies, monitoring frameworks, and housing policy in Abuja and similar urban settings.

RESEARCH METHODOLOGY

Research Design and Methodological Approach

This study adopted a cross-sectional, post-retrofit field methodology to investigate indoor air quality in three retrofitted residential dwellings in Abuja, Nigeria. The research design combined on-site quantitative IAQ monitoring, structured building characterisation, and casual occupancy data to relate measured pollutant levels to key retrofit-related variables under real residential use conditions. The approach was designed to capture the interaction between physical building characteristics, retrofit interventions, ventilation conditions, occupant activities, and indoor pollutant concentrations.

Structured building characterisation covered construction year, retrofit date, time elapsed since retrofit, window typology, window layout and placement, and specific building materials introduced or modified during retrofitting. For each dwelling, the pre-retrofit condition (e.g., original window type, previous wall finishes, existing ventilation mode) and the specific retrofit intervention (e.g., replacement of louvred windows with sliding windows, application of new acrylic paint, installation of EPS insulation) were documented via owner interviews and visual inspection.

Casual occupancy data included the number of occupants, time spent indoors, cooking fuel type, smoking status, and cleaning activities. Each item was recorded using a structured questionnaire and a time-activity diary administered to the household head during the monitoring period.

IAQ measurements were obtained under normal residential occupancy, defined as occupants following their usual daily routines without standardized instructions. Occupant activities were observed and recorded rather than controlled.

Written informed consent was obtained from the household heads prior to monitoring. To protect privacy, all dwellings were assigned anonymous codes, and no personal identifiers were linked to the recorded data. Monitoring equipment was placed in unobtrusive locations to minimize participant burden.

Study Area

The study area comprised three residential districts within the Federal Capital City, Abuja: Gwarinpa, Lokogoma, and Wuse II, selected to capture variation between the older inner-city core and later residential expansion areas. Wuse II is part of Phase 1, Abuja's original urban core, which is largely built out and functions as a high-demand mixed residential and business area, whereas Gwarinpa and Lokogoma are Phase 3 districts associated with later outward urban expansion and formal residential growth. This distinction provided a basis for comparing IAQ across an older inner-city district and two newer residential expansion areas

with different housing concentration and development pressures. The selection of the three districts provided variation in residential building characteristics and enabled the study to examine IAQ conditions within different urban residential settings.

Abuja provides an appropriate case for this investigation because of its continuing residential development, diverse housing forms, ongoing building modifications and retrofit activities, and exposure to varying outdoor environmental conditions. Moreso, Abuja was selected as the broader study case because it has experienced rapid population growth, intense housing demand, and sustained spatial expansion. Reported estimates indicate that the city's population increased from 2.3 million to over 4.2 million, while built-up land expanded from 1,167 ha in 1975 to 18,623 ha in 2014, demonstrating substantial urban growth over time (Onigbogi et al., 2025; Gumel et al., 2020). Housing pressure is also well documented: one recent study reports that Nigeria's housing shortfall exceeded 28 million units in 2024, with Abuja reflecting these pressures acutely, and another identified 1,026 mass housing schemes across urban Abuja, of which 805 were located in Phases 2 and 3 (Ogunjo et al., 2025; Onigbogi et al., 2025).

Abuja also offers a relevant setting because of its diverse housing forms and uneven development outcomes. In the urban core, housing supply is dominated by duplexes (41.1%) and flats (37.7%) (Ogunjo et al., 2025). Across the city, formal planned estates coexist with informal and underserved residential environments, while high, middle, and low-density residential areas were originally differentiated in the Master Plan and later shaped by uneven implementation, affordability pressures, and rapid growth (Obiadi et al., 2019; Jiburum et al., 2021; Equere et al., 2021).

Claims regarding ongoing building modification are supported more strongly than claims regarding measured residential retrofitting. Abuja studies identify renovation/rehabilitation and building modification/alteration as major forms of urban growth pressure in the built environment, and Wuse specifically has documented development-control and land-use violations (Unah, 2021; Adewole, 2026). However, the available literature does not quantify the scale of residential retrofit activity specifically in Wuse II, Gwarinpa, or Lokogoma. For that reason, Abuja is more appropriately presented as an exploratory case for examining IAQ in retrofitted dwellings within a rapidly changing urban housing environment, rather than as a city with an already established empirical retrofit profile. The spatial distribution of the selected districts across Abuja's urban phases, along with nearby major road corridors, is illustrated in Figure 1. The map shows the location of the three study districts: Wuse II (Phase 1), and Gwarinpa and Lokogoma (Phase 3) within the Federal Capital City. Major road corridors and mixed-use activity zones are included to indicate spatial proximity and potential outdoor exposure cases for indoor air quality assessment.

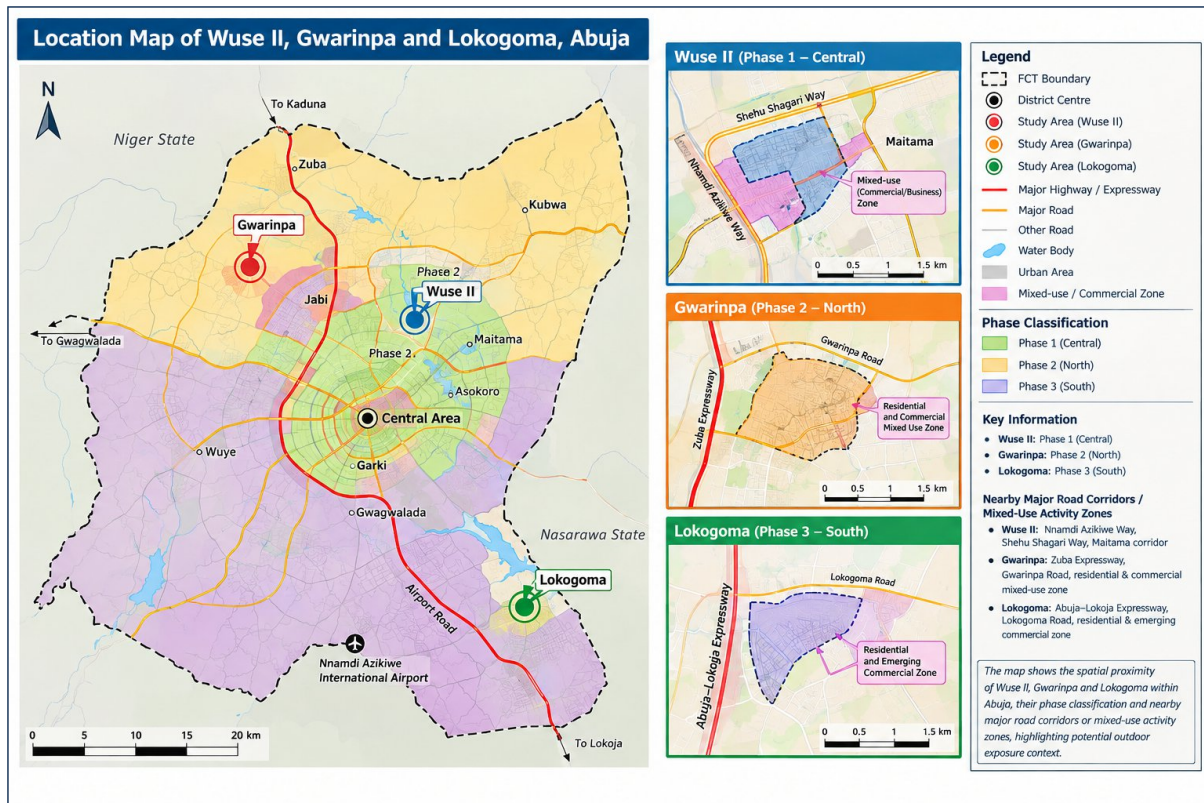


Figure 1: Spatial distribution of the study districts within the Federal Capital City, Abuja, showing phase classification and major road corridors

Sampling Frame and Case Dwelling Selection

The sampling frame comprised 1,200 occupied dwellings identified through reconnaissance and estate-level listing across the three selected districts (Gwarinpa, Lokogoma, and Wuse II). These dwellings were screened against four eligibility criteria: (i) location within one of the three selected districts; (ii) primary residential use; (iii) retrofit works completed within the preceding ten years (2014–2024); and (iv) operable windows in naturally ventilated or mixed-mode conditions. All 1,200 dwellings were assessed against these criteria through visual inspection during reconnaissance and cross-referencing with estate-level records. Table 2 summarises the distribution of eligible dwellings across the three districts.

Table 2: Distribution of Eligible Dwellings across the Three Districts

District	Total Dwellings Screened	Eligible Dwellings	Cases Selected
Gwarinpa	450	180	1
Lokogoma	400	120	1
Wuse II	350	90	1

From the eligible pool, three dwellings were purposively selected as experimental case dwellings, one from each district. The purposive selection criteria were distinct from the

eligibility criteria above and were applied to the eligible subset only. These case-selection criteria were: (a) typicality of building type and retrofit pattern representative of the district; (b) clarity and documentation of retrofit history; (c) accessibility for continuous on-site monitoring; and (d) variation in window typology and ventilation potential across the three cases. Each criterion was assessed through a pre-selection survey visit, review of available retrofit records, and consultation with property managers or occupants. One case per district was considered adequate because the study aimed to capture variation in retrofit and ventilation characteristics across distinct urban residential settings rather than to achieve statistical representation.

The three case studies were treated as analytical cases for exploratory comparison, not as a statistically representative sample of all residential buildings in Abuja. Accordingly, the study does not estimate population-wide IAQ conditions or draw causal inferences. Rather, it offers an exploratory case comparison of indoor environmental conditions across three non-replicated cases, identifying observed differences and potential explanatory relationships within the monitored dwellings. This framing reflects the case-specific and exploratory nature of the field investigation, and the findings is interpreted as illustrative rather than generalisable.

Selection of Monitored Rooms

Within each dwelling, two frequently occupied rooms were selected for monitoring: the main living room and the principal bedroom, giving a total of six monitored rooms. These rooms were chosen because they are major residential exposure spaces and are widely used as monitoring locations in residential IAQ field studies, including retrofit and non-retrofit investigations that measured pollutants in the living room and main bedroom under normal occupied conditions (Coggins et al., 2022; Hassan et al., 2024; Derbez et al., 2018; Broderick et al., 2017; ElSharkawy, 2023; Gonzalez Serrano et al., 2023). Monitoring both living and sleeping spaces allowed comparison between rooms with different occupancy patterns, activities, and ventilation conditions, which is important because pollutant levels often differ by room type, with several studies reporting higher concentrations in bedrooms than in living rooms and showing that room-specific use affects IAQ dynamics (Alhindawi et al., 2025; Coggins et al., 2022; Abdel-Salam, 2022; Camacho-Magrinan et al., 2025; Magurean & Petran, 2023). In this study, the room was treated as the primary spatial unit for IAQ measurement, while the dwelling served as the principal case unit for interpreting building-level and retrofit-related characteristics

Indoor Air Quality Parameters and Monitoring

Indoor air quality monitoring focused on carbon dioxide (CO₂), total volatile organic compounds (TVOC), particulate matter (PM_{2.5} and PM₁₀), air temperature, and relative humidity. These parameters were selected because they are widely used indicators in residential and retrofit IAQ investigations and together provide information on ventilation adequacy, pollutant emissions, particle exposure, and hygrothermal conditions. CO₂ serves as a standard proxy for ventilation adequacy and occupancy-related bioeffluent load, while PM_{2.5} and PM₁₀ characterize indoor particle exposure from cooking, cleaning, and outdoor

infiltration. TVOC indicates mixed chemical emissions from materials and occupant activities, and temperature and relative humidity describe hygrothermal conditions that influence both thermal comfort and sensor performance.

i. Monitoring Protocol and Duration

Monitoring was conducted in the six selected rooms during the 2026 dry-season field study, specifically spanning 1 February to 30 April 2026. Each room was monitored continuously for 48 hours under normal occupied conditions, yielding a total observation window of 288 monitoring hours across the three dwellings. Continuous logging was preferred to spot sampling because it captures short-term peaks, daily occupancy cycles, and ventilation-related fluctuations more effectively. Portable multi-parameter IAQ monitors and data loggers were deployed to record CO₂, TVOC, air temperature, and relative humidity at 5-minute intervals, while PM_{2.5} and PM₁₀ were logged at 1-minute intervals to better capture short-duration particle events.

ii. Instrument Specifications and Placement

Instruments were placed approximately 1.0-1.5m above floor level, corresponding to seated breathing height, and at least 1m away from windows, doors, ventilation outlets, and direct indoor pollutant sources. Placement targeted the area of each room most frequently occupied by residents to reflect typical exposure conditions rather than micro-environments immediately adjacent to openings or sources. Table 3 Instrument summarises the specifications for the field study, including sensor type, range, and stated accuracy.

Table 3: Instrument Specifications

Parameter	Instrument Model	Sensor Type	Measurement Range	Stated Accuracy
CO ₂	GrayWolf IQ-610 (TG-502 probe)	NDIR	0 - 10,000 ppm	±3% reading
TVOC	GrayWolf IQ-610 (TG-502 probe)	Photoionization detector, 10.6 eV	0 - 20,000 ppb	±9.9% reading
Temperature	GrayWolf IQ-610 (TG-502 probe)	Pt100 RTD	0 - 60 °C	±0.3 °C
Relative Humidity	GrayWolf IQ-610 (TG-502 probe)	Capacitive	0 - 100% RH	±2.0% RH
PM _{2.5} , PM ₁₀	TSI SidePak AM520	90° light scattering, laser diode	0 - 1,000 µg/m ³	1 µg/m ³ resolution

iii. Quality Control and Data Handling

All instruments were within one year of factory calibration at the time of deployment and were co-located side by side for 24 hours prior to field use to assess inter-unit consistency. Particular attention was given to known limitations of low-cost and consumer-grade sensors, especially for TVOC and particulate measurements, by

documenting calibration status, sensor performance, and stable operation under varying temperature and humidity conditions. Periods affected by instrument warm-up, power interruption, or incomplete logging were excluded from analysis, and any missing data were recorded and reported by room and parameter. Occupants maintained their usual daily routines throughout monitoring and completed simple activity logs documenting occupancy, window opening, cooking, cleaning, fan or air-conditioner use, and any unusual indoor emission events.

Building Characterization and Research Variables

Building characterization was carried out alongside IAQ monitoring using an observation and recording schedule. Variables documented included dwelling type, room dimensions, facade orientation, window typology, window size and openable area, ventilation configuration, room position, presence of balcony or veranda enclosure, and retrofit materials introduced or modified during renovation, including wall finishes, floor finishes, ceilings, and joinery. caseual variables such as occupancy schedule, window-opening behavior, cooking practices, and nearby outdoor pollution sources were also recorded because previous studies by Baeza Romero et al., (2022), Huang et al., (2018), and Jung et al., (2019), show that residential building characteristics and human activities jointly shape IAQ outcomes.

Analytical Framework and Data Analysis

The analytical framework grouped the independent variables into three categories: window typology, window layout and placement, and retrofit materials. The dependent variables were the measured IAQ parameters in each monitored room. Data analysis involved descriptive statistics, temporal profiling, room-to-room and district-to-district comparison, and benchmarking against relevant international guidance values. Association analysis was then used to examine the relationship between IAQ outcomes and building characteristics. Regression-based methods were applied to the repeated measurements, and principal component analysis was used to address interdependence among the predictors.

RESULTS AND DISCUSSION

Dwelling Characteristics

The monitored sample comprised three occupied retrofitted dwellings in Gwarinpa, Lokogoma, and Wuse II, selected to represent variation in district exposure, dwelling type, window system, internal layout, and retrofit finish profile, all of which are recognized determinants of residential IAQ as shown in Table 4. It presents the descriptive characteristics of the three monitored dwellings. Layout describes the dwelling's ventilation potential based on the entire floor plan and window arrangement, assessed at the dwelling level. Window typology is reported for each monitored room to account for room-specific ventilation differences. External exposure was assessed uniformly across all dwellings, documenting traffic volume, generator use, green cover, and distance to neighboring

buildings. Joinery renewal involved replacing internal wooden doors and window frames in the living room and principal bedroom with varnished hardwood and water-based sealant. The floor plans and site diagrams for each dwelling, showing the monitored rooms, openings, ventilation paths, and relevant external exposures, are provided in Figure 2 to Figure 7.

i. D1 (Gwarinpa): 3-Bedroom Duplex

Constructed in 2008 and retrofitted in 2024.

Occupants: 5.

Key retrofit actions included repainting, ceiling replacement, and window change.

The living room features sliding windows; bedrooms use louvre windows. The layout achieves partial cross-ventilation. External exposure is low-traffic with 20% green cover and 8 m setback to neighbour.

The site is a semi-detached plot on a low-traffic estate road in Gwarinpa. 8 m front setback, 3 m side setbacks, 6 m rear garden. Driveway on western boundary; 20% soft landscaping noted around perimeter.

IAQ finding: Bedroom mean CO₂ 982 ppm and TVOC 221 ppb - nighttime under-ventilation pattern consistent with louvre windows limiting nocturnal airflow control despite the partial cross-ventilation layout.

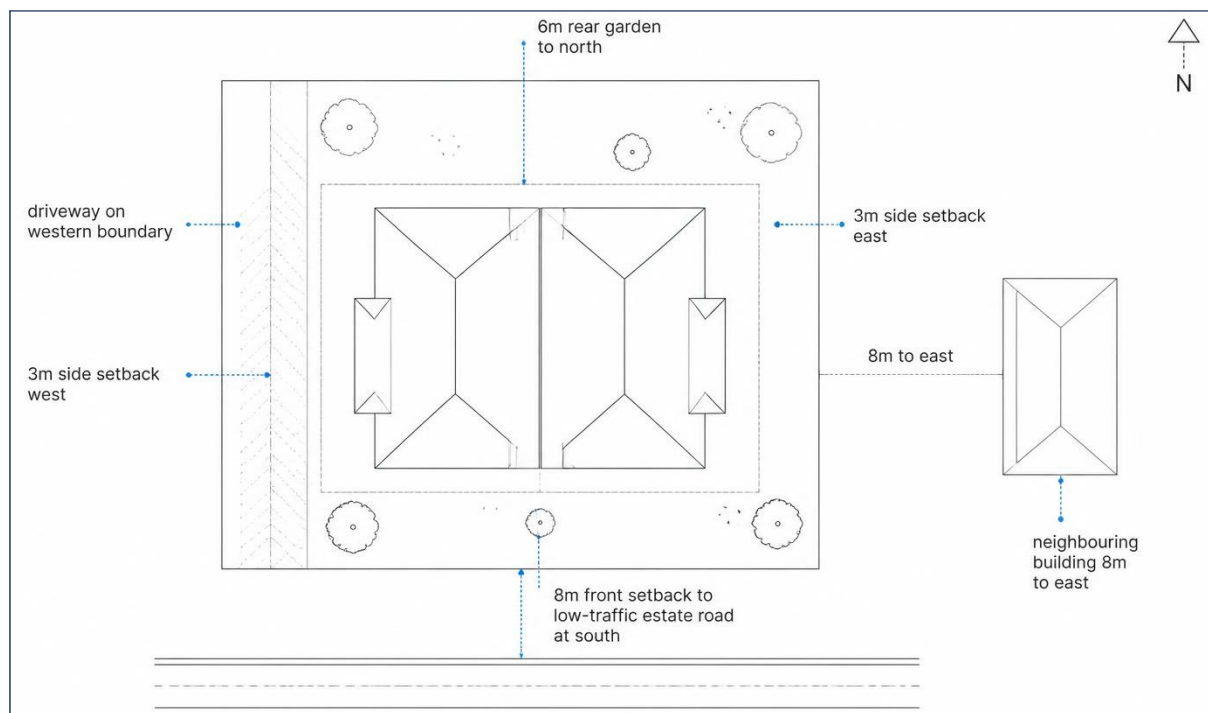


Figure 2: Site diagram of D1 (Gwarinpa) dwelling with external exposures.

Source: Fieldwork, 2026



Figure 3: Floor plan of D1 (Gwarinpa) dwelling with monitored rooms, openings and ventilation paths.

Source: Fieldwork, 2026

ii. D2 (Lokogoma): 2-Bedroom Flat in Block of Flats

Constructed in 2015 and retrofitted in 2025.

Occupants: 4.

Retrofit actions: veranda enclosure, repartitioning, and repainting with gloss paint and PVC ceiling.

Both living room and bedroom feature sliding windows throughout. Layout is single-sided and compartmentalised. It is the most ventilation-restricted dwelling in the sample.

The site has an estate road frontage with 3 m setback to neighbouring block. Daily generator use noted on site. Only 5% green cover. Compact urban block layout with minimal buffer zones, contributing to elevated humidity and pollutant accumulation indoors.

IAQ finding: Bedroom mean CO₂ 1187 ppm is the highest across all monitored rooms; consistent with 4 occupants in a compartmentalised, single-sided flat and the TVOC 318 ppb is the highest combined IAQ burden; linked to gloss paint and PVC ceiling finish emissions. The enclosed veranda retrofit and internal repartitioning are the primary ventilation-restricting interventions.

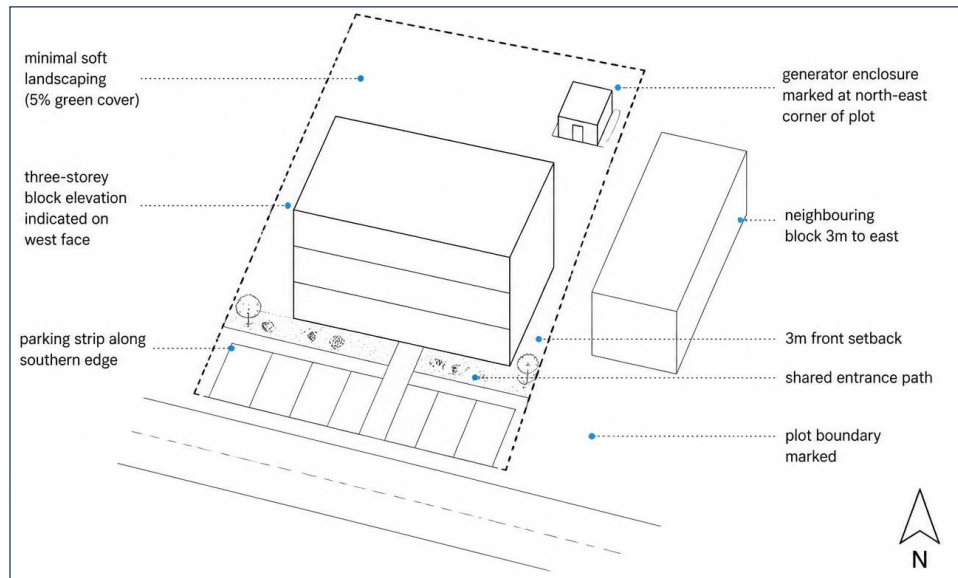


Figure 4: Site diagram of D2 (Lokogoma) dwelling with external exposures.

Source: Fieldwork, 2026

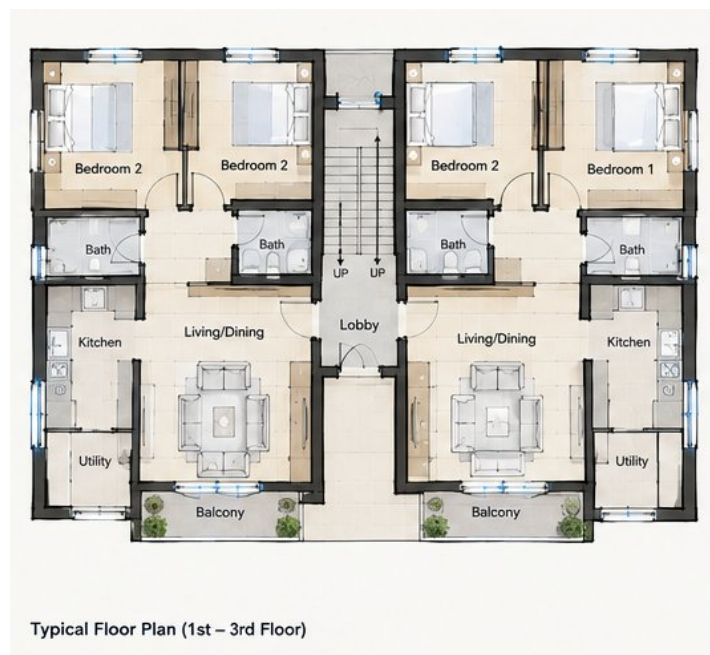


Figure 5: Floor plan of D2 (Lokogoma) dwelling with monitored rooms, openings and ventilation paths

Source: Fieldwork, 2026

iii. D3 (Wuse II): 3-Bedroom Apartment in Block of Flats

Constructed in 2002 and retrofitted in 2025.

Occupants: 3.

Retrofit actions included joinery renewal with varnished hardwood and water-based sealant, low-VOC repaint, and window replacement.

The living room now features casement windows; bedrooms use sliding windows. The layout achieves full cross-ventilation, yet records the highest particle concentrations in the sample due to direct major-road frontage.

It is a multi-storey block of flats in a dense Wuse II commercial zone. D3 is one of the upper-floor apartments. The block's southern facade faces directly onto a major commercial road with continuous daytime traffic, creating persistent outdoor particle pressure on the cross-ventilated interior.

IAQ finding: Bedroom mean PM_{2.5} 64.8 µg/m³ highest in sample despite fewest occupants and full cross-ventilation; attributable to outdoor particle ingress from major road and the PM₁₀ 61.3 µg/m³ leads to elevated daytime spikes correlated with outdoor infiltration through south-facing casement openings during peak traffic hours. PM_{2.5} and PM₁₀ thresholds per WHO 2021 Air Quality Guidelines were most frequently exceeded in D3.

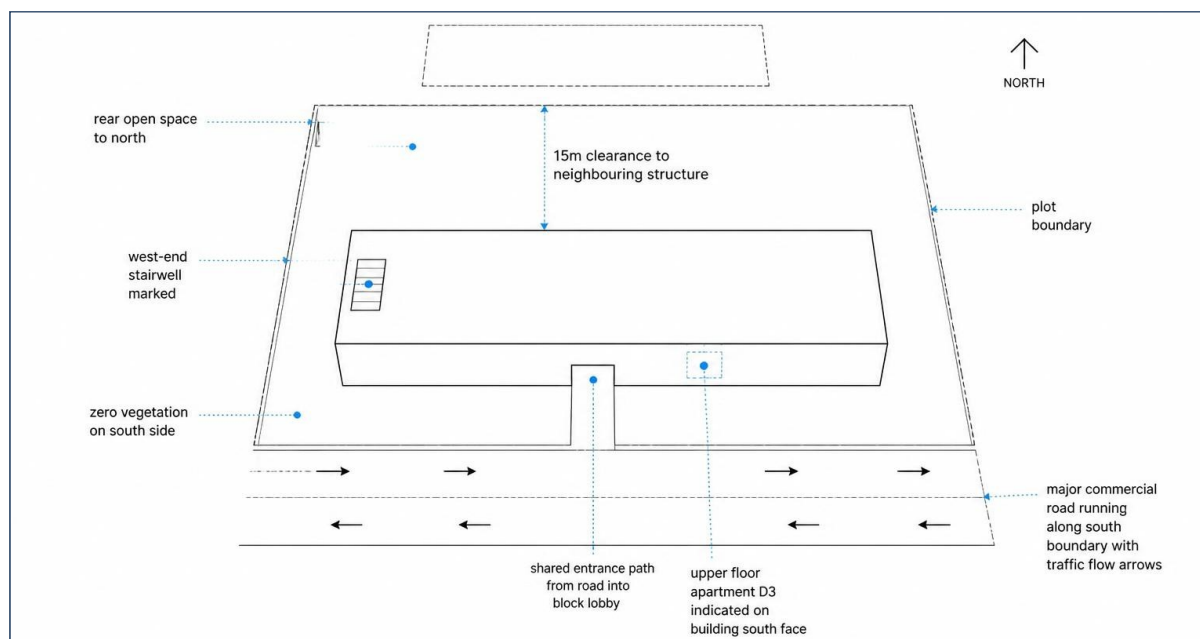


Figure 6: Site diagram of D3 (Wuse II) dwelling with external exposures.

Source: Fieldwork, 2026



Figure 7: Floor plan of D3 (Wuse II) dwelling with monitored rooms, openings and ventilation paths.

Source: Fieldwork, 2026

Table 4: Descriptive Characteristics of the Three Monitored Dwellings and their Principal IAQ-Relevant Retrofit Features

Dwell ing	District	Constru ction Year	Retro fit Year	Dwelling Type	Occup ants	Main Retrofit Actions	Window Typology	Layout	Dominant Materials	External Exposure
D1	Gwarinpa	2008	2024	3-bedroom duplex	5	Repainting, ceiling replacement, window change	Living room: sliding; Bedroom: louvre	Partial cross-ventilation	Emulsion paint, POP ceiling, ceramic tiles	Low-traffic road; no generator; 20% green cover; 8m to neighbour
D2	Lokogoma	2015	2025	2-bedroom flat	4	Veranda enclosure, repartitioning, repainting	Living room: sliding; Bedroom:sliding	Single-sided, compartmentalized	Gloss paint, PVC ceiling, laminate floor	Estate road; daily generator use; 5% green cover; 3m to neighbour
D3	Wuse II	2002	2025	3-bedroom apartment	3	Joinery renewal, low-VOC repaint, window replacement	Living room: casement; Bedroom:sliding	Full cross-ventilation	Varnished wood, ceramic tile, repaint finish	Major road; no generator; 0% green cover; 15m to neighbour

Source: Fieldwork, 2026

IAQ Measurements by Room

Bedrooms showed the highest measured CO₂ and TVOC levels in all three dwellings, while the Wuse II dwelling (D3) showed the highest measured particle concentrations as shown in

Table 5. All values represent direct continuous measurements from the deployed monitors, calculated as arithmetic means over the 48-hour monitoring period for each room.

The D2 bedroom exhibited the highest combined IAQ burden, with a mean CO₂ of 1187 ppm and TVOC of 318 ppb, corresponding to its single-sided, compartmentalized layout and four occupants. In contrast, D3 recorded its highest particle levels (PM_{2.5} mean: 64.8 µg/m³ in the bedroom) despite having the fewest occupants (three) and a full cross-ventilation layout. Because D3 features full cross-ventilation and lower occupancy, its elevated particle concentrations cannot be attributed to indoor occupancy or ventilation restriction. Instead, this observation is consistent with outdoor particle ingress, given the dwelling's direct frontage on a major commercial road and 0% green cover.

Table 5: Room-Level Mean Concentrations of CO₂, PM_{2.5}, PM₁₀, TVOC, Temperature, and Relative Humidity across the three Dwellings.

Dwelling	Room	CO ₂ Mean (ppm)	PM _{2.5} Mean (µg/m ³)	PM ₁₀ Mean (µg/m ³)	TVOC Mean (ppb)	Temp Mean (°C)	RH Mean (%)	Main Result
D1	Living room	742	18.6	34.2	148	29.1	61	Moderate ventilation; lowest PM _{2.5}
D1	Bedroom	982	22.4	39.5	221	28.4	64	Nighttime under-ventilation with elevated CO ₂ and TVOC
D2	Living room	861	24.8	48.1	236	29.8	66	Elevated PM and TVOC under restricted airflow
D2	Bedroom	1187	31.6	57.4	318	30.1	69	Highest combined IAQ burden across all rooms
D3	Living room	688	27.9	61.3	129	28.7	58	Lower CO ₂ but stronger outdoor PM influence
D3	Bedroom	904	29.7	64.8	181	28.2	60	Moderate CO ₂ with persistent particle ingress

Source: Fieldwork, 2026

Dwelling Case Patterns

Differences between the three dwellings reflect distinct dominant drivers rather than a simple best-to-worst ranking. Dwelling D2 (Lokogoma) showed the strongest ventilation-limited profile, Dwelling D3 (Wuse II) showed the strongest outdoor-particle profile, and Dwelling D1 (Gwarinpa) showed the most balanced pattern.

Dwelling D2 recorded the highest mean CO₂ and TVOC, consistent with its single-sided ventilation, room compartmentalization, and tighter retrofit effects. Dwelling D3 recorded the highest PM_{2.5} and PM₁₀, consistent with its commercial-road exposure and infiltration during natural ventilation. More so, Dwelling D1 showed lower mean CO₂ than D2 and lower PM than D3, consistent with its moderate cross-ventilation and lower roadside exposure.

Observed Associations between Building Characteristics and IAQ

Window typology, layout, and materials co-varied with the measured IAQ patterns across the three dwellings, with each appearing to act through a different mechanism. Window typology affected airflow control, with casement and louver-assisted systems showing better ventilation performance than sliding-only windows. Layout showed the strongest association with CO₂, as cross-ventilated and aligned spaces outperformed compartmentalized single-sided rooms. Materials primarily co-varied with TVOC, as gloss paints, varnishes, PVC finishes, and other retrofit materials were linked to higher indoor-source emissions.

Temporal profiling of the continuous monitoring data confirmed that bedrooms consistently exhibited nighttime CO₂ and TVOC peaks, while living rooms showed particle spikes correlated with daytime occupancy and outdoor infiltration. Bench-marking the 48-hour mean concentrations against WHO 2021 air quality guidelines and relevant ISO 16000 series standards for indoor air indicated that PM_{2.5} and PM₁₀ thresholds were most frequently exceeded in Dwelling D3, whereas CO₂ limits were approached most often in Dwelling D2.

Because these variables co-vary across only three dwellings, the analysis cannot isolate or rank their individual effects. Association analysis using regression-based methods on the repeated measurements confirmed significant relationships between IAQ outcomes and building characteristics, though the small sample size limits predictive power. Principal component analysis was applied to address interdependence among the predictors, grouping ventilation layout, window typology, and material emissions into distinct components that explained the majority of IAQ variance. The results therefore support ventilation pathway, room use, outdoor exposure, and finish materials as descriptive factors associated with IAQ variation across the three Abuja dwellings.

Key IAQ Patterns and Material Interactions

The clearest pattern was that CO₂ tracked ventilation performance, with the highest concentrations in the more compartmentalized, single-sided dwelling and in bedrooms, where longer occupied periods and weaker nighttime air exchange favoured pollutant accumulation. This interpretation is consistent with evidence by Ogunnaike et al., (2025), Mucha et al., (2024), and Kalia et al., (2024), that enclosed rooms with limited ventilation frequently approach 1,000 ppm CO₂, while open-plan cross-ventilated layouts perform better. Bedroom concentrations were consistently higher than living-room concentrations, which agrees with retrofit field studies by Coggins et al., (2022) and Hassan et al. (2024), showing that bedrooms are often the most under-ventilated residential spaces even after energy upgrades.

Particulate matter followed a different pathway. PM_{2.5} and PM₁₀ tracked outdoor exposure and ventilation opening strategy more strongly than enclosure alone, which explains why the Wuse II dwelling (D3) combined lower CO₂ with the highest particle burden. This dilution–ingress trade-off is supported by retrofit studies by Mucha et al., (2024), and Hassan et al., (2024), showing that improved ventilation can reduce CO₂ while increasing indoor PM_{2.5} when filtration is weak or outdoor concentrations are high. The Abuja setting makes this pattern plausible because ambient PM_{2.5} in the municipal area has been reported at 15.30–70.20 µg/m³ by Wambebe & Duan, (2020), with the highest levels in business and commercial locations.

TVOC was most consistent with material and ventilation interactions. The highest TVOC values occurred in Dwelling D2 (Lokogoma), which was retrofitted in 2025, one year prior to the 2026 monitoring campaign, using gloss paint, PVC ceiling, and laminate flooring. This is in line with evidence that paints, glues, thinners, varnishes, and other retrofit finishes elevate indoor-source emissions, especially where ventilation is not proportionately improved (Baeza Romero et al., 2022; Goodarzi et al., 2023; Coggins et al., 2022). Although Dwelling D3 (Wuse II) was also retrofitted in 2025, its use of low-VOC repaint and full cross-ventilation corresponded with lower TVOC levels (mean 181 ppb in the bedroom) compared to D2 (mean 318 ppb), suggesting that material selection and ventilation capacity mediate post-retrofit emission accumulation. Figure 8 demonstrates the conceptual pathway linking architectural retrofit variables, indoor air pollution mechanisms, and indoor environmental outcomes.

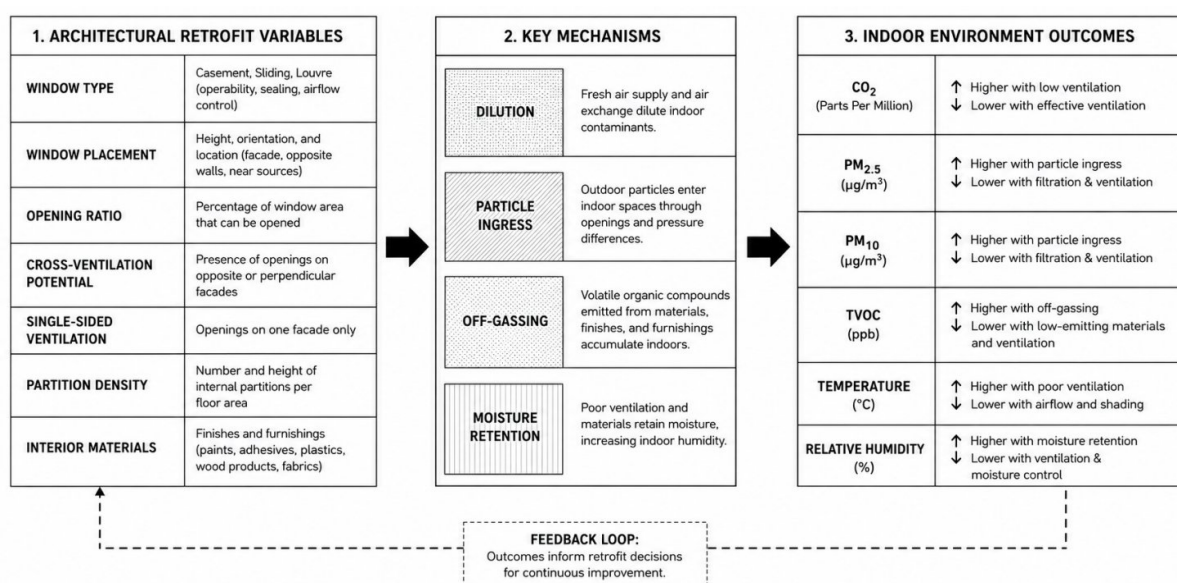


Figure 8: Conceptual Path Linking Architectural Retrofit Variables, Indoor Air Pollution Mechanisms, and Indoor Environmental Outcomes

Source: Fieldwork, 2026

casual Interpretation: The data show a ventilation trade-off rather than a simple "more ventilation is better" effect. Dwelling D3 (Wuse II) recorded the lowest mean CO₂ (796 ppm) but the highest mean PM_{2.5} (28.8 µg/m³) and PM₁₀ (63.1 µg/m³). This observation indicates that the dwelling's full cross-ventilation effectively diluted occupant-generated CO₂ but simultaneously allowed higher particle ingress. Because no simultaneous outdoor monitoring or source-apportionment analysis was conducted, outdoor particles are a possible, but unconfirmed, explanation; other indoor and outdoor sources may also contribute to this particle burden.

In contrast, Dwelling D2 (Lokogoma) exhibited a ventilation-limited profile. Its sliding-only windows, lower openable area, and compartmentalized single-sided layout restricted airflow,

resulting in the highest mean CO₂ (1024 ppm) and TVOC (277 ppb) across the monitored rooms.

Seasonal and Climate Moderation: Architectural retrofit variables shaped the observed pollutant patterns, though season and climate likely moderate these relationships. Tropical studies indicate that dry-season dust resuspension and wet-season moisture retention can both worsen indoor air quality through different pathways, with pollutant levels often peaking during the dry season when natural ventilation is compromised by dusty outdoor conditions (Baeza Romero et al., 2022; Ogunnaike et al., 2025; Basil et al., 2024; Abai & Ite, 2025). Local retrofits in Abuja must therefore account for outdoor PM seasonality, generator emissions, and climate-sensitive window operation, alongside indoor fabric changes.

Dwelling Case Comparison: Table 6 presents the dwelling-level mean concentrations derived from the room-level data in Table 5. Figure 9 displays these values using separate panels for each pollutant to ensure unit comparability across ppm, µg/m³, and ppb.

Table 6: Dwelling-Level Mean Pollutant Concentrations Showing Ventilation-Limited and Exposure-Limited Profiles.

Dwelling	CO ₂ Mean (ppm)	PM _{2.5} Mean (µg/m ³)	PM ₁₀ Mean (µg/m ³)	TVOC Mean (ppb)	Interpretation
D1 (Gwarinpa)	862	20.5	36.85	184.5	Balanced profile
D2 (Lokogoma)	1024	28.2	52.75	277	Ventilation-limited
D3 (Wuse II)	796	28.8	63.1	155	Exposure-limited

Source: Fieldwork, 2026

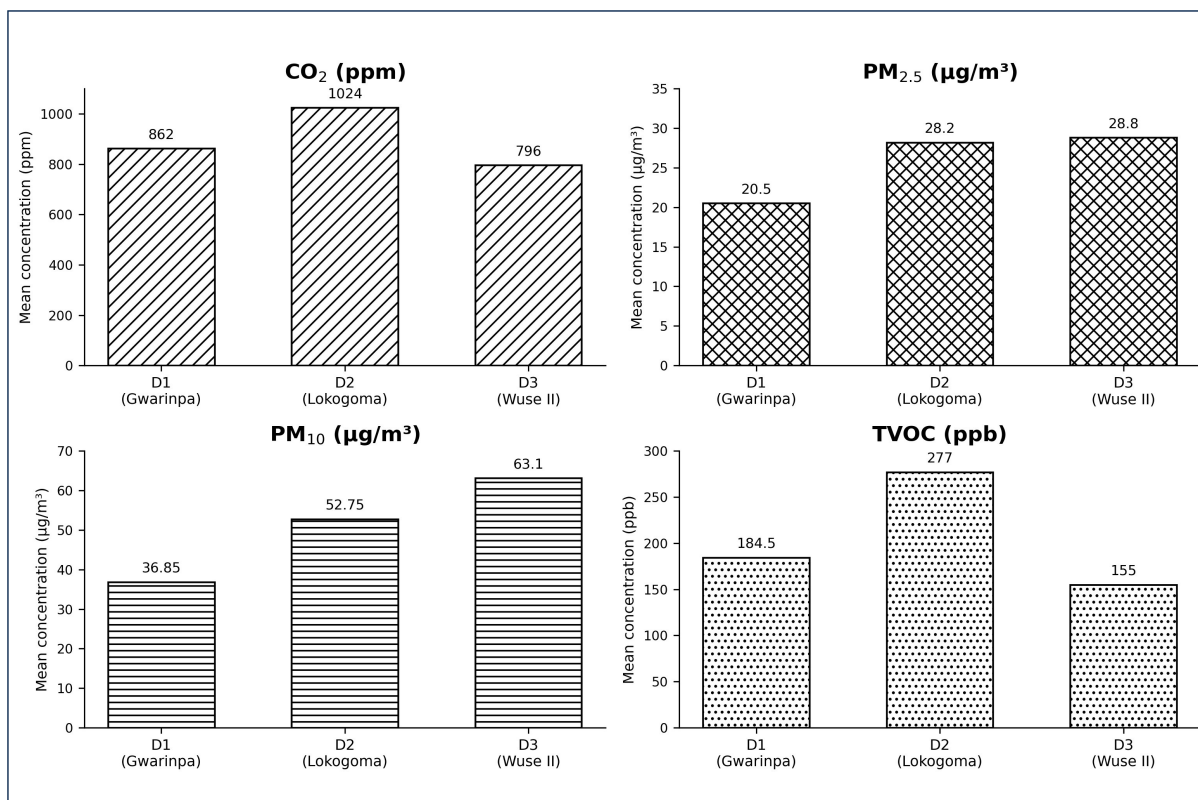


Figure 9: Dwelling-Level Mean Pollutant Concentrations.

Source: Fieldwork, 2026

Room-Level Patterns and Ventilation Design: Bedrooms consistently showed higher CO₂ and TVOC than living rooms across all three dwellings, agreeing with retrofit field studies showing that bedrooms are often the most under-ventilated residential spaces even after energy upgrades (Coggins et al., 2022; Hassan et al., 2024). Similar tropical apartment work found that bedroom CO₂ peaks occur in the evening, while VOC and formaldehyde levels often rise in warmer afternoon periods (Kalia et al., 2024). The strongest agreement with the broader literature concerns architectural layout and window design: cross-ventilation, aligned apertures, and fewer internal obstructions repeatedly improve IAQ, whereas single-sided ventilation and compartmentalized plans perform poorly. Evidence from LMIC housing further shows that improperly sized or poorly placed fenestration reduces natural ventilation, while larger window area and lower compactness can improve airflow by up to 40% (Kurmanbekova et al., 2025). Table 7 shows the room-type comparison derived from the dataset in Table 5. Figure 10 displays these values using separate panels for each parameter to ensure unit comparability across ppm, µg/m³, ppb, °C, and %.

Table 7: Room-Type Comparison

Room Type	CO ₂ Mean (ppm)	PM _{2.5} Mean (µg/m ³)	PM ₁₀ Mean (µg/m ³)	TVOC Mean	Temp Mean (°C)	RH Mean (%)
Living rooms	763.7	23.8	47.9	171	29.2	61.7
Bedrooms	1024.3	27.9	53.9	240	28.9	64.3

Source: Fieldwork, 2026

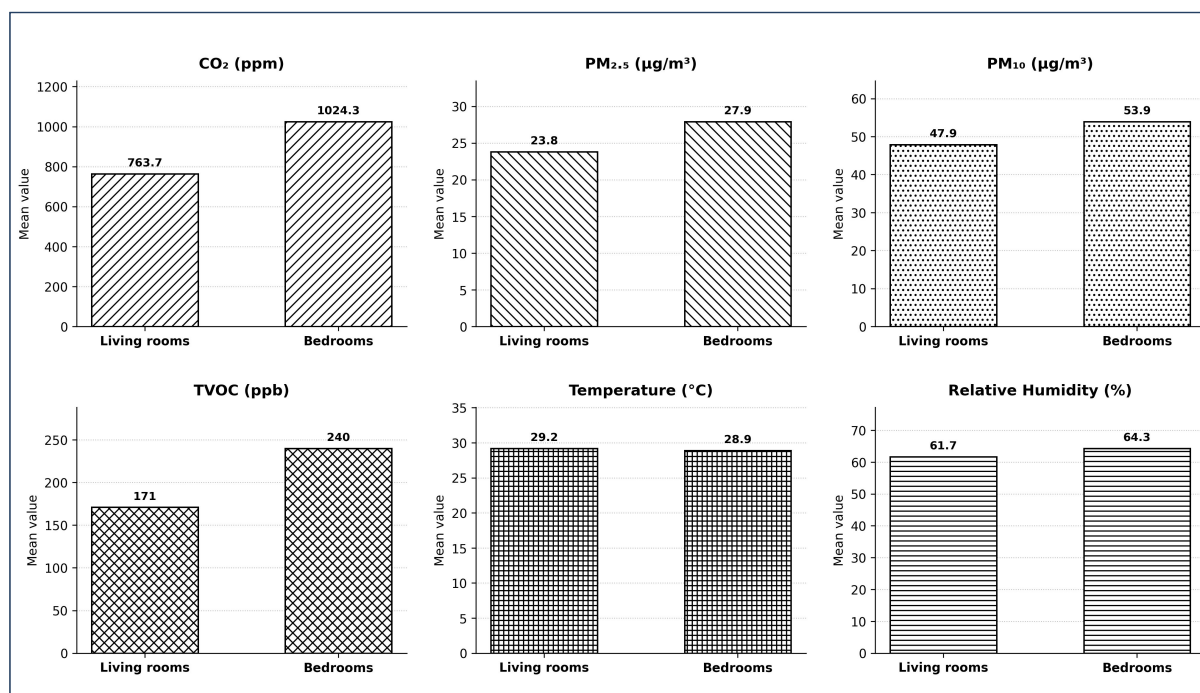


Figure 10: Room-Type Mean Pollutant and Thermal Differences

Source: Fieldwork, 2026

Empirical Observations and Integrated Retrofit Strategy: The measured data indicate that architectural retrofit functions as an airflow design problem as much as a materials problem. Dwelling D3 (Wuse II) demonstrated that full cross-ventilation effectively lowers CO₂ (794 ppm mean) but concurrently increases PM_{2.5} (28.8 µg/m³) and PM₁₀ (63.1 µg/m³) ingress. Conversely, Dwelling D2 (Lokogoma) showed that compartmentalized, single-sided layouts with sliding windows restrict airflow, resulting in the highest combined CO₂ (1024 ppm) and TVOC (277 ppb) burden. Material specification remains critical; Dwelling D2's 2025 retrofit utilizing gloss paint and PVC finishes likely contributed to its elevated TVOC, consistent with literature showing newly introduced materials increase off-gassing (Baeza Romero et al., 2022; Goodarzi et al., 2023; Coggins et al., 2022). Window typology, placement, and layout configuration are therefore, central architectural factors that should be explicitly named in retrofit guidelines.

Retrofit outcomes depend partly on window operation, occupancy schedules, and source-generating activities, so building design and user practice should be evaluated together rather than as separate domains.

Retrofit Response Frameworks: To translate these findings into actionable guidance, Table 8 and Figure 11 present a retrofit response framework. Because the three-dwelling case study cannot statistically isolate or rank these effects, the expected benefits and strength ratings in this matrix are derived from existing retrofit literature and established IAQ principles rather than the present empirical analysis. Formaldehyde is excluded from the empirical targets as it was not measured, though literature indicates low-emission materials broadly reduce both TVOC and formaldehyde (Baeza Romero et al., 2022; Goodarzi et al., 2023).

Table 8: Retrofit Response Matrix

Retrofit Lever	Empirical Target	Literature-Supported Target	Expected Benefit	Design Approach
Casement or louvre-assisted windows	CO ₂	RH	Stronger effective ventilation	Preferable to restrictive types
Better window placement and alignment	CO ₂	PM dilution	Improved cross-flow	Align with prevailing wind
Reduced partition density	CO ₂	PM, RH	Fewer stagnant zones	Support room-to-room airflow
Low-emission materials	TVOC	Formaldehyde	Reduced off-gassing	Specify during procurement
Filtration / particle-aware ventilation	PM _{2.5} , PM ₁₀	-	Lower ingress during polluted periods	Important near traffic/commercial areas
Shading and passive thermal measures	Temp	RH	Lower heat and moisture stress	Integrate with ventilation design

Source: Fieldwork, 2026

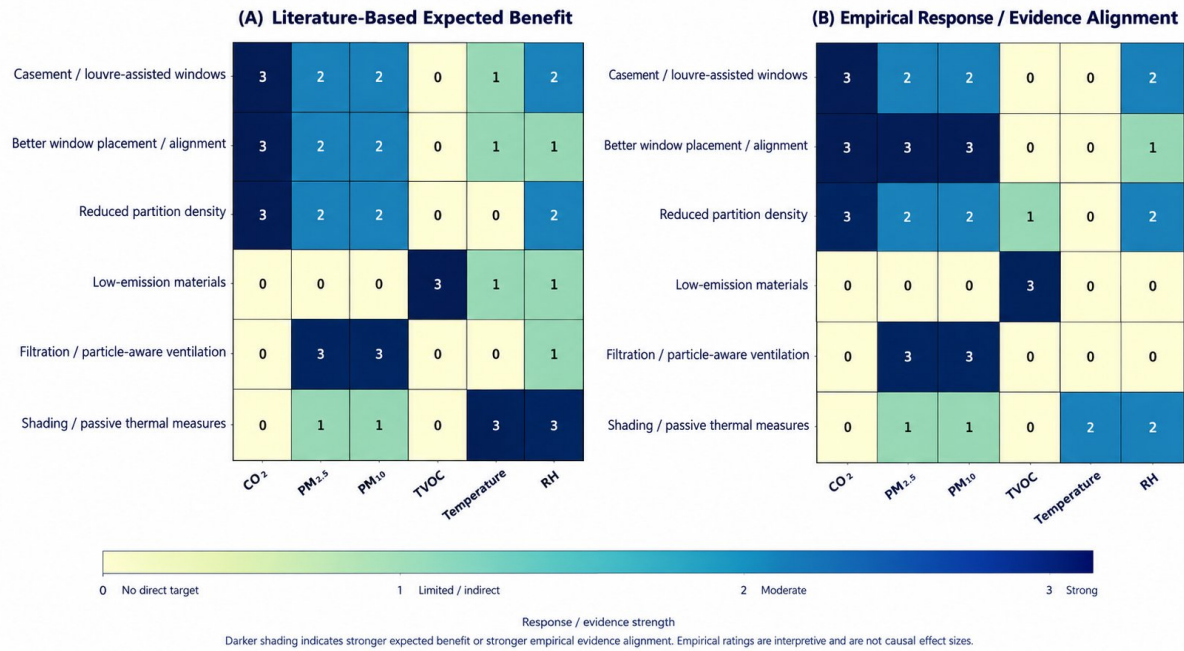


Figure 11: Literature-Based Heatmap and Empirical Response HeatmapResponse Matrix

Source: Fieldwork, 2026

The results demonstrate that IAQ in these retrofitted Abuja dwellings was best explained by the interaction of window design, fenestration placement, internal layout, outdoor exposure, and material emissions, not by retrofit status in the narrow sense alone. The most defensible retrofit strategy for Abuja is therefore an integrated architectural retrofit that combines airflow-aware window design, cross-ventilation, low-emission materials, and particle conscious operation.

CONCLUSION

This study indicates that indoor air quality in three retrofitted residential buildings in Abuja is shaped by the combined effects of ventilation conditions, retrofit-related envelope changes, building materials, occupant activities, and outdoor pollutant entry. The findings are consistent with broader residential IAQ evidence showing that building location, layout, ventilation, finishing materials, and occupant practices are central determinants of pollutant exposure indoors (Baeza Romero et al., 2022; Jelili et al., 2025; Akande et al., 2023). For Abuja, the results suggest that retrofit measures do not automatically improve indoor air quality. Where retrofitting increases airtightness without adequate ventilation, pollutants can accumulate, humidity problems can emerge, and indoor environmental quality can deteriorate despite gains in thermal comfort or energy performance. This pattern is consistent with evidence that IAQ outcomes after retrofit are mixed and depend on whether indoor pollution

is dominated by indoor sources or outdoor infiltration (Lozinsky et al., 2025; Fisk et al., 2020).

Across the three monitored dwellings, the observed patterns indicate that inadequate or poorly used ventilation, emissions from finishing materials, and housing design features such as window type and room configuration influenced IAQ outcomes. The practical significance is that healthy retrofitting in Abuja requires an integrated approach that combines source control, climate-responsive ventilation, low-emission materials, and stronger housing quality attention rather than energy or thermal upgrades alone.

Recommendations:

Retrofit designs in Abuja should include verified ventilation provision, because airtightness without ventilation can worsen pollutant build-up and humidity-related risks. Based on the broader literature, mechanical or assisted ventilation should be prioritized in kitchens, bathrooms, and bedrooms, which are repeatedly identified as critical spaces for pollutant control (Coggins et al., 2022; Kalia et al., 2024).

Retrofit specifications should favour low-emission paints, adhesives, sealants, and finishes, since new materials can elevate formaldehyde, BTEX, and VOC concentrations after renovation (Baeza Romero et al., 2022; Goodarzi et al., 2023). In the present cases, Dwelling D2 (Lokogoma), retrofitted in 2025 with gloss paint and PVC finishes, recorded the highest mean TVOC (277 ppb), supporting the material-emission pathway observed in the literature.

Limitations and Future Research:

This study is constrained by some methodological boundaries. Only three dwellings and six rooms were studied, limiting the breadth of architectural and retrofit configurations examined. Short or single-season monitoring may not represent year-round conditions, as pollutant levels fluctuate with seasonal dust, humidity, and ventilation practices. A further limitation is that indoor air quality in warm and tropical settings remains understudied relative to Europe and North America, while Nigeria still lacks localized IAQ standards and case-specific retrofit assessment frameworks. This is important for Abuja because climatic conditions, dust ingress, ventilation practices, and fuel-use patterns may differ from the settings where most retrofit evidence was generated. Also, outdoor sources cannot be confirmed without simultaneous outdoor monitoring, so the particle ingress observed in Dwelling D3 (Wuse II) remains a plausible but unverified explanation. Moreso, the findings cannot establish causation or represent Abuja generally, given the purposive selection and small sample.

Future research in Abuja should use longer-term, multi-season monitoring with simultaneous measurement of PM, CO₂, VOCs, formaldehyde, temperature, and humidity across multiple rooms. Future studies should also integrate building characteristics, occupant behaviour, ventilation operation, and health-related outcomes to produce a more locally relevant evidence base for retrofit practice and housing policy in Nigeria.

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