Analysis of thermal comfort and indoor air quality in a mechanically ventilated basement bank vault

Benjamin Anyaegbuna[1*], *Olalekan* Olayemi[2], *Ikechukwu* Anyaegbuna[3], *Isaac* Adegun[4], *Anthony* Onokwai[1], *Innocent* Osuizugbo[5], and *Onoriode* Avbenake[1]

[1]Department of Mechanical Engineering, School of Science and Technology, Pan Atlantic University, Lagos, Nigeria

[2]Department of Aeronautics and Astronautics, Faculty of Engineering and Technology, Kwara State University, Malete, Kwara State, Nigeria.

[3]Department of Civil Engineering & Environmental Engineering, University of Lagos, Lagos, Nigeria.

[4]Department of Mechanical Engineering, Faculty of Engineering and Technology of Environmental, University of Ilorin, Ilorin, Nigeria.

[5]Department of Building Technology, College of Environmental, Bells University of Technology, Ota, Nigeria.

Abstract. Indoor air quality (IAQ) and thermal comfort are critical for health and productivity in enclosed basements. This study investigates a mechanically ventilated bank vault, comparing the performance of mixing ventilation (MV) and displacement ventilation (DV). An occupant survey captured environmental complaints, while field measurements recorded carbon dioxide (CO_2), radon, fine particulates ($PM_{2.5}$), and thermal parameters. Computational Fluid Dynamics (CFD) and analytical models were used to determine Air Change Efficiency (ACE), Contaminant Removal Effectiveness (CRE), Predicted Mean Vote (PMV), and Predicted Percentage Dissatisfied (PPD). The DV system, supplied at low-level inlets with ceiling exhaust, significantly improved air distribution and pollutant removal. Results showed ACE increased from 0.41 (MV) to 0.68 (DV). CRE values for CO_2, radon, and $PM_{2.5}$ were 1.52, 0.79, and 1.12, respectively, outperforming MV. Comfort also improved, with DV achieving a near-neutral PMV (−0.03) and 5% dissatisfaction, compared to a slightly warm PMV (0.29) and 6.7% dissatisfaction under MV. Additionally, an air curtain at entrances helped reduce particulate ingress. Overall, DV demonstrated superior IAQ and comfort, offering practical guidance for retrofitting HVAC systems in basements and other confined urban workplaces.

Keywords: Indoor Air Quality (IAQ); Thermal Comfort; Basement Ventilation; Displacement Ventilation; Air Change Efficiency; Particulate Matter

*Corresponding author**:** banyaegbuna@pau.edu.ng

1 Introduction

Indoor Air Quality (IAQ) and thermal comfort are central to building performance and human health. Modern buildings are becoming increasingly airtight to conserve energy, which reduces uncontrolled air infiltration but also restricts fresh air supply and promotes accumulation of indoor contaminants [1]. IAQ is defined as the condition of indoor air as it affects health, comfort, and productivity. It is influenced by both outdoor sources (pollution ingress) and indoor sources such as occupant emissions, building materials, soil gases, and operational activities [2]. In hot-humid climates, such as Nigeria, IAQ is particularly critical since occupants spend significant time indoors, often in air-conditioned spaces. Prolonged exposure to poor IAQ has been associated with discomfort, respiratory problems, headaches, reduced cognitive performance, and Sick Building Syndrome (SBS) [3].

Basements represent a unique IAQ challenge [4]. Being fully or partially below grade, they often lack natural ventilation pathways, creating conditions that favor accumulation of pollutants. Radon gas, a soil-derived radioactive contaminant, can infiltrate through cracks and foundations, posing long-term health risks. Moisture ingress and high humidity further increase risks of mold and discomfort. In Nigeria, radon surveys in bank basements revealed concentrations that, while mostly below critical thresholds, demonstrated variability across cities, underscoring the need for continuous monitoring [5]. Other pollutants typical in basements include volatile organic compounds (VOCs), carbon monoxide from standby generators, particulates ($PM_{2.5}$), and CO_2 from occupancy.

Effective ventilation remains the primary engineering control to ensure acceptable IAQ. Bringing in outdoor air and exhausting indoor air dilutes pollutants, controls humidity, and enhances comfort. However, effectiveness depends heavily on ventilation type, diffuser design, placement, and whether the system incorporates filtration [6], [7]. Poorly designed systems can recirculate contaminants or create stagnant zones, particularly in confined spaces such as basements.

Mechanical ventilation strategies are typically divided into Mixing Ventilation (MV) and Displacement Ventilation (DV). MV supplies conditioned air at ceiling level at relatively high velocity to induce mixing, creating uniform pollutant distribution [6]. This approach can dilute but may also spread contaminants within the occupied zone. In contrast, DV supplies air at low velocity near the floor, allowing cool clean air to remain in the occupied zone while buoyancy carries warm, polluted air upward to be exhausted [8]. Global studies confirm that DV enhances ventilation effectiveness, contaminant removal, and occupant comfort in settings ranging from hospital rooms [7] to sports facilities [9]. Nigerian CFD-based investigations further show that DV strategies can improve IAQ in basement environments [10].

Locally, capacity for IAQ research is strengthening, with studies on radon in bank vaults [5], IAQ simulations [10], and development of laboratory equipment. These highlight the relevance of IAQ research to Nigerian conditions, where urban air pollution, generator use, and tropical humidity intensify risks. Against this backdrop, the present study investigates IAQ and thermal comfort in bank basement vaults in Nigeria under existing MV conditions and explores DV retrofits through simulations and performance analysis. The aim is to provide data-driven recommendations for IAQ improvement, occupant comfort, and energy efficiency in underground commercial environments.

2 Materials and methods

2.1 Study Location and Baseline Ventilation

The study was conducted in the basement vaults of three commercial bank branches located in Lagos, Ilorin, and Akure, Nigeria. These basements represent typical high-occupancy underground workplaces in Nigerian urban centers. Each vault is partially below grade, with reinforced concrete walls, limited natural infiltration, and no operable windows.

The existing ventilation systems in all three vaults followed a Mixing Ventilation (MV) configuration. Conditioned air was supplied through nine ceiling-mounted diffusers, each approximately 0.25 × 0.25 m in size, distributed uniformly at a height of about 3.0 m. Two ceiling-level return grilles connected the vaults to the air-handling unit (AHU) via plenum ducts. The systems operated as constant air volume (CAV) systems, in which the AHU provided cooling and recirculated most of the indoor air. A small proportion of outdoor air was introduced at the AHU, but there was no dedicated exhaust path to the outdoors. This meant that air was largely recirculated, a deficiency previously highlighted in Nigerian basement IAQ studies [5], which increases the risk of contaminant accumulation since pollutants generated indoors are not actively removed.

2.2 Environmental Measurements

Simultaneously with the survey, on-site environmental monitoring was performed using calibrated instruments. Carbon dioxide concentrations were measured with a nondispersive infrared (NDIR) analyzer that had an accuracy of ±50 ppm. Radon concentrations were determined using passive radon detectors deployed for periods of 24 hours, consistent with procedures reported in prior Nigerian studies [5]. Fine particulate matter ($PM_{2.5}$) concentrations were measured with a portable laser particle counter capable of detecting particles in the range of 0.3–10 µm, with an accuracy of ±10%.

Indoor temperature and relative humidity were recorded using digital thermohygrometers, with accuracies of ±0.5 °C and ±2%, respectively. Air velocity near the breathing zone was spot-checked using hot-wire anemometers to evaluate local airflow conditions. Data were collected across an entire workday (08:00–18:00) to capture variations due to occupancy. Radon detectors were also left in place overnight to assess accumulation during HVAC off periods. Measured values were compared against international guidelines, including the World Health Organization (WHO) thresholds for $PM_{2.5}$ [11], the U.S. Environmental Protection Agency (EPA) radon action level [12], and ASHRAE standards for thermal comfort and ventilation [13], [14].

2.3 CFD Simulation and Modeling

In addition to field measurements, airflow and contaminant transport in the basement vault were modeled using ANSYS Fluent 2022R1, following procedures validated in CFD studies [10]. The vault geometry was recreated in detail, and an unstructured tetrahedral mesh of about 750,000 cells was generated. Grid independence was confirmed to ensure reliable results. The turbulence model employed was the RNG k–ε model, and a steady-state SIMPLE pressure-velocity coupling scheme was used for numerical stability.

Boundary conditions were defined to represent the two ventilation schemes under evaluation. For the MV case, ceiling supply air was introduced at 20 °C and 2.5 m/s through the nine diffusers, with returns located at ceiling level. For the DV case, supply air was introduced at floor level through low-velocity diffusers at 21.5 °C and 0.2 m/s, while pollutants and warm air were extracted via ceiling exhausts. Contaminant sources were specified in the model to simulate CO_2 generation by occupants, radon infiltration from the floor slab, and dust ingress from entrances.

Governing Equations: The CFD model solves the fundamental governing equations for steady, incompressible airflow. Mass conservation is enforced via the continuity equation:

$$\nabla \cdot \mathbf{v} = 0 \tag{1}$$

and momentum conservation is given by the Navier–Stokes equations (in Reynolds-averaged form for turbulence):

$$\rho\,(\mathbf{v} \cdot \nabla\mathbf{v}) = -\nabla p + \mu\,\nabla^2\mathbf{v} + \mathbf{S}, \tag{2}$$

where ρ is air density, $\boldsymbol{v}$ is the velocity vector, p is the pressure, μ is the dynamic viscosity, and $\boldsymbol{S}$ represents additional source terms (such as gravitational buoyancy). The RNG k–epsilon turbulence model provides closure by introducing transport equations for turbulent kinetic energy and its dissipation, accounting for the effects of fluctuating eddies [10]. All simulations assumed steady-state conditions and were run to convergence on residuals of continuity, momentum, and energy equations.

The DV retrofit design followed ASHRAE 62.1 [13] requirements for minimum outdoor airflow per occupant. Air change rates were maintained comparable to those of the MV system to ensure fair comparison. In addition, an air curtain was modeled at the main entrance to minimize infiltration of dust and outdoor pollutants, as recommended in recent engineering applications [15]. Figure 1 outlined the modelled 3-D view of the internal spaces of the basement section of the building generated with the DesignBuilder modelling software.

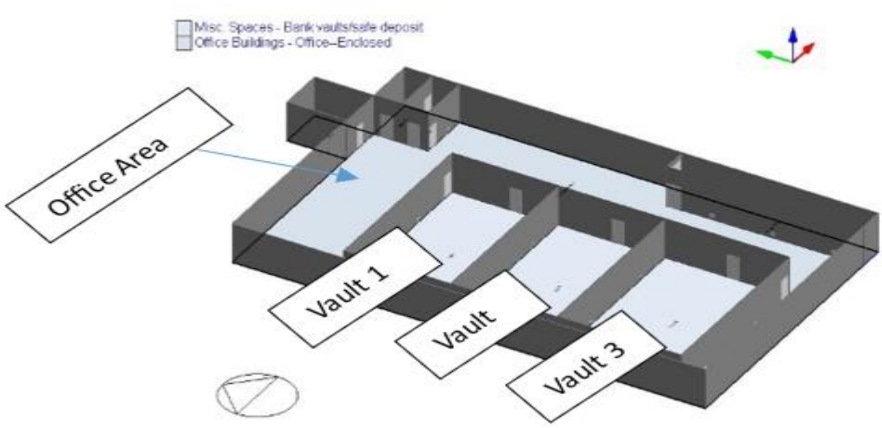

Fig. 1: Modelled internal spaces of the basement

2.4 Performance Indices and Equations

Three sets of performance metrics were employed to evaluate the ventilation schemes. The first was Air Change Efficiency (ACE), which measures how effectively a system delivers fresh air. It is defined as the ratio of the nominal time constant,

$$\tau_n = \frac{V}{Q} \quad (3)$$

Where; V is the volume of the space, Q is balanced flow of air in the space.
The lower the value of τ_n, the better the air quality. An ACE of 0.5 represents perfectly mixed air, while higher values indicate more efficient airflow [6]. The second metric was Contaminant Removal Effectiveness (CRE), which assesses how efficiently a system removes pollutants. It is calculated as:

$$\varepsilon = \frac{C_e - C_s}{C - C_s} \quad (4)$$

Where C_e, is the contaminant concentration at the exhaust, C_s is the contaminant concentration measured at the inlet diffusers, C, is the mean concentration within the occupied zone.
In this study, the contaminant removal effectiveness, $\mathcal{E}$, was used to determine three pollutants as $\mathcal{E}_{CO_2}$, $\mathcal{E}_{Rn}$ and $\mathcal{E}_{PM_{2.5}}$
Where, $\mathcal{E}_{CO_2}$ is contaminant removal effectiveness for carbon dioxide; $\mathcal{E}_{Rn}$ is contaminant removal effectiveness for radon; and $\mathcal{E}_{PM_{2.5}}$ is contaminant removal effectiveness for particulate matter, $PM_{2.5}$. Values greater than 1 indicate more effective contaminant removal than mixing ventilation [8].

Finally, thermal comfort was evaluated using the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indices defined in ASHRAE 55 [14]. PMV predicts the average thermal sensation of occupants based on heat balance models, while PPD predicts the percentage of dissatisfied occupants. The equations are given by:

$$PMV = (0.303e^{-0.036M} + 0.028)(M - W - H) \quad (5)$$

$$PPD = 100 - 95\, e^{-0.3353PMV^4 - 0.2179PMV^2} \quad (6)$$

where M is the metabolic rate, W is external work, and H represents heat losses. A PMV near zero with PPD less than 10% is considered acceptable.

3 Results and Discussion

3.1 Baseline Indoor Air Quality and Thermal Conditions under Existing Mixing Ventilation (MV)

Field measurements in the Lagos, Ilorin, and Akure basements revealed several IAQ concerns. Table I compares measured values with international guideline limits.

Table 1: Baseline IAQ Parameters vs Guidelines

Parameter	Measured Range	Guideline Limit	Observation
CO_2 (ppm)	512–681 (avg), peaks 1195	1000–1100 (comfort limit) [13], [14]	Mostly acceptable, but peaks exceed threshold during crowding.
Radon (Bq/m³)	23.7 (avg), 109 (max overnight)	150 (EPA action level) [12]	Well below action level, but accumulation occurs without ventilation.
$PM_{2.5}$ (µg/m³)	69 (avg), peaks 365	25 (24-hr mean, WHO) [11]	Exceeds safe levels by factor of 3–14. Severe issue.
Temp. (°C)	26.8 (avg)	20–26 [14]	Slightly above upper comfort range.
RH (%)	68 (Ilorin), 86 (Lagos)	20–60 [14]	Lagos exceeded comfort limit; risk of mold growth.

Measurements across the three basements highlighted substantial environmental challenges, underscoring the need for enhanced ventilation strategies. Table 1 summarizes the key parameters. Carbon dioxide (CO_2) levels averaged 512–681 ppm, remaining within acceptable limits, yet peaked at 1195 ppm during high occupancy. These surges reveal that the existing MV system lacks sufficient outdoor air reserves, permitting CO_2 accumulation when demand exceeds supply.
Radon concentrations stayed well below the EPA action level of 150 Bq/m³, though overnight readings climbed to 109 Bq/m³ with HVAC systems off, confirming basements' inherent susceptibility to accumulation. The data show that radon concentrations remained below hazardous levels during HVAC operation, but peaks occurred when systems were off, supporting earlier Nigerian radon studies [5].

Particulate matter ($PM_{2.5}$) posed the most critical issue, with averages reaching 69 µg/m³ and peaks as high as 365 µg/m³—3 to 14 times the WHO 24-hour guideline of 25 µg/m³ [4]. This severe pollution stems from external dust ingress and inadequate HVAC filtration, causing the basement vaults to function like sealed enclosures [11]. Poor vertical air movement keeps particulates suspended, exposing occupants in the breathing zone to chronic airborne particle risks. Thermally, temperatures averaged 26.8°C—marginally above ASHRAE comfort limits—while relative humidity hit 86%, particularly in Lagos. These conditions foster occupant discomfort, condensation, and mold growth potential.

3.2 CFD Performance Comparison: Mixing Ventilation (MV) vs. Displacement Ventilation (DV)

CFD simulations offered vivid visual and quantitative contrasts in air distribution and contaminant removal between MV and DV systems. In MV, high supply velocities generated turbulent mixing, uniformly dispersing contaminants into the occupied breathing zone—a counterproductive outcome. Recirculation eddies further trapped pollutants in corners and around workstations. Figure 2 shows the velocity distribution of the mixing airflow schemes.

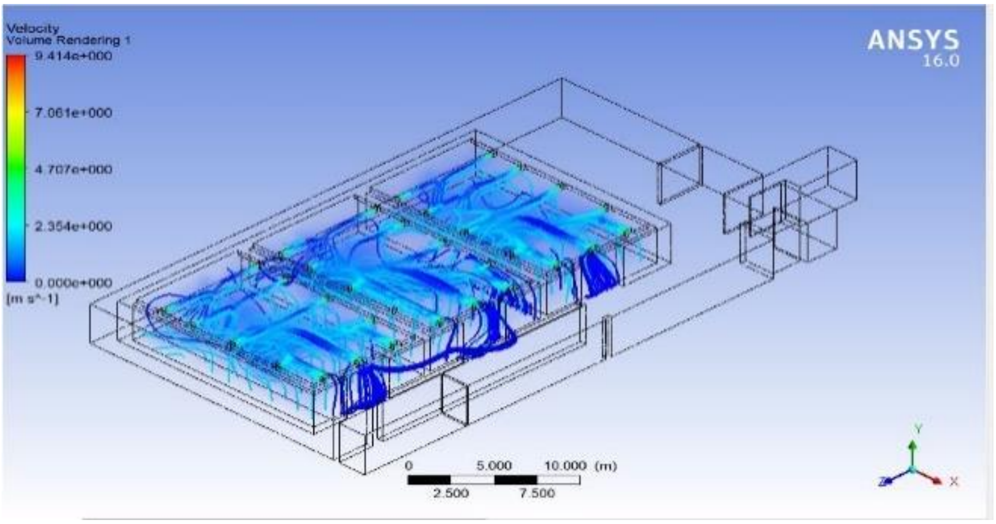

Fig. 2: Velocity streamline pattern of the mixing airflow schemes

Conversely, DV supplied cool air at floor level, allowing it to rise naturally as it warmed and creating vertical stratification: a cleaner lower zone for occupants and a polluted upper layer. Pollutants migrated upward efficiently for ceiling extraction. Intuitively, DV acts like a gentle river of clean air through the occupied space, with contaminants rising toward the ceiling exhaust, markedly improving breathing zone conditions. The velocity distributions of the DV simulations is shown in figure 3.

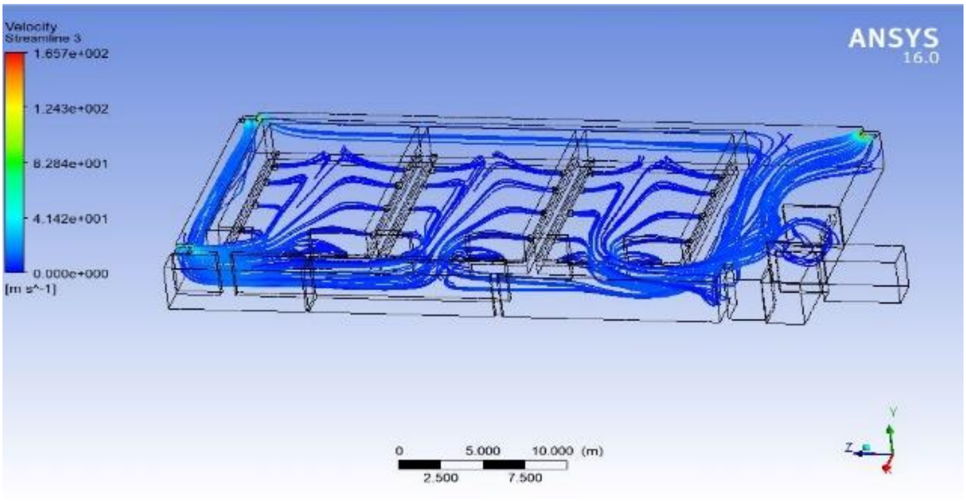

Fig. 3: Velocity distribution pattern of Displacement airflow schemes

3.3 Ventilation Effectiveness Metrics

Air change efficiency (ACE) underscored DV's superiority, scoring 0.68 versus MV's 0.41 (where a perfectly mixed ideal is 0.5). This indicates DV delivers fresh air directly to occupants rather than wasting it in futile circulation.

Contaminant removal effectiveness (CRE) further favored DV, as detailed in Table 2. For CO_2, DV achieved 1.52 compared to MV's value below 1, enabling 52% more effective removal. $PM_{2.5}$ saw DV at 1.12 versus MV below 1, despite floor-level infiltration, while radon reached 0.79 under DV—still outperforming MV despite its floor origin. A CRE exceeding 1 signifies pollutants exiting the occupied zone faster than they accumulate; MV permits stagnation, whereas DV channels them upward like an efficient elevator shaft.

Table 2. Contaminant Removal Effectiveness (CRE) Comparison

Pollutant	MV	DV	Interpretation
CO_2	<1	1.52	DV removes CO_2 52% more effectively
$PM_{2.5}$	<1	1.12	DV improves particulate removal despite floor-level infiltration
Radon	Baseline	0.79	DV outperforms MV though radon originates at floor

These results align with international findings that DV outperforms MV in pollutant removal and comfort [7, [8], and confirm Nigerian CFD simulations of basement spaces [10].

3.4 Thermal Comfort (PMV and PPD)

DV also excelled in thermal comfort metrics (Table 3). Predicted mean vote (PMV) was +0.29 (slightly warm) for MV but nearly neutral at –0.03 for DV, with predicted percentage dissatisfied (PPD) dropping from 6.7% to 5%. DV's warmer supply air (21.5°C versus 20°C) and lower velocities eliminated drafts, minimizing thermal stress. Conceptually, it forms a comforting blanket of cool air at occupant level, achieving natural comfort without overcooling the full volume.

Table 3. Thermal Comfort Metrics (PMV and PPD)

Metric	MV	DV
PMV	+0.29 (slightly warm)	–0.03 (neutral)
PPD	6.7%	5%

3.5 Energy Performance and Practical Measures

CFD energy assessments revealed DV's practical advantages: approximately 65% fan energy savings, 10–15% cooling reductions, and lower overcooling risk due to elevated supply temperatures. Air curtains further curbed $PM_{2.5}$ ingress at entrances. Overall, DV accomplishes more with less by intelligently directing airflow rather than relying on brute force. Practical interventions were recommended, including installation of electrostatic air cleaners for particulates, improved dehumidification in humid sites like Lagos, and staff education on IAQ risks such as radon. These align with local engineering capacity-building efforts.

3.6 Comparative Insights

The merged results demonstrate that while MV was able to keep radon within safe levels, it failed to prevent CO_2 peaks, humidity excess, and severe particulate pollution. Occupant dissatisfaction and health complaints underscored these deficiencies. The DV retrofit, coupled with filtration and air curtains, addressed these shortcomings by delivering cleaner air to the occupied zone, removing contaminants more effectively, and improving comfort. These findings are consistent with international displacement ventilation studies [7]–[8] and extend them with context-specific validation in Nigeria [5], [10].

3.6 Key Findings

The MV system disperses pollutants uniformly into the breathing zone, exacerbating $PM_{2.5}$ exposure. In contrast, DV establishes a pristine lower zone, channeling contaminants upward to enhance IAQ and comfort. It boosts ACE by 70% and CO_2 removal by 52%, while significantly lowering the critical $PM_{2.5}$ levels through improved migration. Energy use declines alongside superior comfort, positioning DV as a compelling upgrade.

4 Conclusion

This study evaluated thermal comfort and indoor air quality (IAQ) in mechanically ventilated basement vaults of Nigerian banks through field measurements, occupant surveys, and CFD simulations. Baseline assessment of existing mixing ventilation (MV) systems revealed radon within safe limits but other IAQ parameters unacceptable: CO_2 exceeded comfort thresholds at peak occupancy, Lagos humidity reached 86%, and $PM_{2.5}$ surpassed WHO guidelines by 3–14 times. Occupant surveys confirmed dissatisfaction, with <60% satisfaction versus ASHRAE 55's 80% benchmark.

The proposed displacement ventilation (DV) retrofit yielded marked improvements. CFD simulations showed ACE rising from 0.41 (MV) to 0.68 (DV), ensuring effective fresh air delivery. CRE for CO_2 reached 1.52, with moderate $PM_{2.5}$ gains; thermal comfort improved to near-neutral PMV (−0.03) and PPD ~5%. These results align with international DV evidence for confined, high-occupancy spaces and recent Nigerian CFD studies.

Energy analysis indicated DV reduces fan consumption by ~65% and cooling loads by 10–15%, leveraging thermal stratification and higher supply temperatures (21.5°C vs. 20°C). Air curtains and electrostatic filters further mitigated dust infiltration.

For building design and facility management, DV suits basements and windowless spaces in new or retrofitted structures, enhancing IAQ and comfort without energy penalties. Standards must mandate minimum outdoor air rates and particulate filtration, as inadequate ventilation drove pollutant buildup here. Routine monitoring of radon and $PM_{2.5}$ remains critical for corrective action.

Future research should pilot DV in bank vaults under tropical conditions, with long-term validation and cost-benefit analyses to enable scale-up. Overall, DV provides a viable route to healthier, energy-efficient underground workspaces, advancing occupant well-being and sustainable practices in Nigeria.

Ethics approval and consent to participate
Not Applicable

Availability of data and materials
Extra data that supports the findings of this study are available from the Corresponding author [Anyaegbuna, B. E.] upon reasonable request.

Competing interests
Authors declare that there is no competing interest whatsoever.

Funding
This research was not funded by any third party.

References

1. L. Morawska, A. Wierzbicka, G. Buonanno, *et al.*, "Indoor air quality: the missing link in building sustainability," *Indoor Air*, **27**, pp. 227–229, (2017). doi: 10.1111/ina.12345.
2. H. Yin, C. Liu, L. Zhang, A. Li, and Z. Ma, "Measurement and evaluation of indoor air quality in naturally ventilated residential buildings," *Indoor Built Environ.*, **28**, pp. 1307–1323, (2019). doi: 10.1177/1420326X18812580.
3. K. Engvall, P. Wickman, and D. Norbäck, "Sick building syndrome and perceived indoor environment in relation to reduced ventilation flow during the heating season," *Indoor Air*, **15**, pp. 120–126, (2005). doi: 10.1111/j.1600-0668.2004.00332.x.
4. Y. Jia, K. Yanming, and Z. Zhiqiang, "Advances in research for underground buildings: Energy, thermal comfort and indoor air quality," *Energy Build.*, **215**, 109916, (2020). doi: 10.1016/j.enbuild.2020.109916.
5. I. K. Adegun, B. E. Anyaegbuna, O. A. Olayemi, T. S. Jolayemi, and M. O. Ibiwoye, "Radon concentration assessment in bank cellars in three Nigerian cities," *Nig. J. Technol.*, **38**, pp. 957–964, (2019). doi: 10.4314/njt.v38i4.22.
6. P. V. Nielsen, "Analysis and design of room air distribution systems," *HVAC&R Res.*, **13**, pp. 987–997, (2007). doi: 10.1080/10789669.2007.10390986.
7. J. M. Villafruela, I. Olmedo, and M. Ruiz de Adana, "Assessment of displacement ventilation systems in airborne infection risk in hospital rooms," *PLoS One*, **14**, e0211390, (2019). doi: 10.1371/journal.pone.0211390.
8. T. Gil-López, B. Rodríguez-Soria, E. Velasco-Gómez, and F. Guevara-García, "Energy efficiency and indoor air quality assessment of displacement ventilation systems," *Energy Build.*, **195**, pp. 221–232, (2019). doi: 10.1016/j.enbuild.2019.04.046.
9. D. Zhang, M. A. Ortiz, and P. M. Bluyssen, "A review on indoor environmental quality in sports facilities: Indoor air quality and ventilation during a pandemic," *Indoor Built Environ.*, (2022). doi: 10.1177/1420326X221145862.
10. B. E. Anyaegbuna, A. O. Onokwai, S. Iweriolor, D. E. Igharvwe, and S. O. Fayomi, "Numerical analysis on mechanical ventilation impact on indoor air quality in a basement," *Sci. Afr.*, **2024**, e02310, (2024). doi: 10.1016/j.sciaf.2024.e02310.
11. World Health Organization, *WHO Air Quality Guidelines: Global Update 2021*, Geneva: WHO, (2021).
12. U.S. Environmental Protection Agency, "What is EPA's Action Level for Radon and What Does it Mean?," U.S. EPA, (2021). [Online]. Available: https://19january2021snapshot.epa.gov/radon/. [Accessed: 25-Aug-2025].
13. ASHRAE, *ANSI/ASHRAE Standard 62.1-2001: Ventilation for Acceptable Indoor Air Quality*, Atlanta: ASHRAE, (2001).
14. ASHRAE, *ANSI/ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy*, Atlanta: ASHRAE, (2017).
15. X. Xiaoliang, W. Xueying, P. Ryoyong, L. Yemin, J. Yiwen, and L. Weiwei, "Use of recirculated air curtains inside ventilated rooms for isolation of transient contaminants," *Energy Build.*, **273**, 112407, (2022). doi: 10.1016/j.enbuild.2022.112407.