

ASSESSMENT OF INDOOR AIR QUALITY, THERMAL COMFORT AND VENTILATION PERFORMANCE FOR HEALTHY LEARNING ENVIRONMENTS IN POLYTECHNICS IN SOUTH-WEST NIGERIA

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Article Info

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Abstract

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Keywords: indoor air quality; thermal comfort; ventilation performance; learning environments; polytechnic; Nigeria

Introduction

The quality of the indoor environment in which students learn has a direct and well-documented bearing on their health, comfort, attendance and academic performance. Indoor air quality and thermal comfort, shaped by ventilation, occupancy and climate, determine whether a learning space supports or hinders concentration and wellbeing, yet in many educational buildings these conditions fall short of recognised standards (Miao et al., 2023). Research has demonstrated that poor indoor environmental quality in schools is associated with increased absenteeism, reduced cognitive performance, and adverse health outcomes including respiratory symptoms and allergies. Studies have found that students in classrooms with inadequate ventilation and high carbon dioxide concentrations perform worse on standardised tests and report higher levels of fatigue and difficulty concentrating. In the hot, humid climate of South-West Nigeria, where classrooms are typically crowded and naturally ventilated, maintaining healthy indoor conditions

is a particular challenge. The combination of high outdoor temperatures and humidity, coupled with dense occupancy and limited mechanical ventilation, creates conditions that can rapidly lead to thermal discomfort and poor air quality.

Carbon dioxide concentration is a widely used proxy for ventilation adequacy and indoor air quality, and studies repeatedly find that occupied classrooms exceed recommended thresholds, with elevated levels associated with fatigue, headaches and reduced performance (Deng & Lau, 2019). Research has shown that CO₂ concentrations in classrooms frequently exceed 1,000 ppm, the threshold above which cognitive performance has been shown to decline, with concentrations often reaching 2,000–3,000 ppm in poorly ventilated spaces. Studies have demonstrated that the relationship between CO₂ and cognitive performance is dose-dependent, with higher concentrations associated with greater impairment in decision-making, concentration, and information processing. The COVID-19 pandemic sharpened attention on ventilation as a determinant of both air quality and infection risk, reinforcing the need to measure and manage it in shared learning spaces (Morawska et al., 2024). Research has demonstrated that adequate ventilation is a critical engineering control for reducing airborne transmission of infectious diseases, with the World Health Organization recommending minimum ventilation rates for indoor spaces. The pandemic has also highlighted the importance of monitoring CO₂ as a simple, low-cost indicator of ventilation adequacy in classrooms and other shared spaces.

Indoor air quality and thermal comfort are interdependent and best assessed together. Field investigations in classrooms combine physical measurement of temperature, humidity, air movement, carbon dioxide and particulates with occupant surveys of comfort and perception, since objective conditions and subjective experience each carry information that the other does not (Lamberti et al., 2024). Research has shown that thermal comfort is influenced not only by physical parameters but also by psychological and contextual factors, including perceived control over the environment and expectations shaped by cultural and climatic norms. Studies have demonstrated that the adaptive comfort model, which accounts for occupants' behavioural adjustments and expectations in naturally ventilated buildings, provides a more accurate prediction of comfort than the static PMV model in non-air-conditioned settings. Assessment against recognised standards then allows conditions to be judged and improvement targeted (Langiano et al., 2024). Research has emphasised that standards such as ASHRAE 55, EN 15251, and WHO air quality guidelines provide benchmarks for evaluating indoor environmental quality and identifying where improvement is needed.

Despite this, the indoor air quality, thermal comfort and ventilation performance of Nigerian polytechnic learning spaces are largely unassessed, and there is little local evidence relating measured conditions to occupant comfort and to the factors that drive poor performance in a hot, humid, naturally ventilated context. Much of the evidence derives from temperate or Mediterranean climates and mechanically ventilated buildings, which differ markedly from South-West polytechnic conditions (Miao et al., 2023). Research on indoor environmental quality in Nigerian institutions has focused primarily on thermal comfort in air-conditioned buildings, with limited attention to naturally ventilated learning spaces. Studies that have examined indoor air

quality in Nigerian schools have often been limited in scope or have not integrated objective measurement with occupant perception. This study addresses that gap by assessing indoor air quality, thermal comfort and ventilation in these learning spaces and relating them to occupant perception and their drivers.

Statement of the Problem

Learning spaces in South-West polytechnics are frequently crowded and naturally ventilated in a hot, humid climate, yet their indoor air quality, thermal comfort and ventilation performance are neither measured nor managed. Elevated carbon dioxide, heat, humidity and particulates in such spaces are associated with discomfort, fatigue, reduced concentration and health effects that undermine learning, but because these conditions are invisible and unmonitored, they persist unrecognised and unaddressed (Deng & Lau, 2019; Morawska et al., 2024). The difficulty is that the actual state of indoor air quality, thermal comfort and ventilation in these learning spaces, how occupants experience them, and what drives poor conditions are unknown, so institutions cannot judge conditions against standards or target improvement (Miao et al., 2023). This assessment gap leaves a real determinant of student health and performance unmanaged.

The specific challenges facing Nigerian polytechnic learning spaces are situated within a broader context of indoor environmental quality in educational buildings. Studies from Nigerian tertiary institutions have documented inadequate ventilation, high occupancy densities, and limited maintenance of building systems, creating conditions conducive to poor indoor air quality. Research has identified that many Nigerian educational facilities lack mechanical ventilation systems or have systems that are poorly maintained, relying instead on natural ventilation through windows and doors, which can be inadequate during periods of high occupancy or adverse weather. Studies have documented that students and staff in Nigerian tertiary institutions spend significant time in poorly ventilated indoor environments, with potential implications for respiratory health and cognitive performance. The World Health Organization has emphasised the importance of indoor air quality in educational settings, recognising that students and staff spend a substantial proportion of their time in these environments. These findings underscore the need for systematic assessment of indoor air quality, thermal comfort, and ventilation performance in Nigerian polytechnic learning spaces.

Healthy, comfortable, well-ventilated learning spaces support attendance, concentration and performance, and assessing their current state is the essential first step to improving them cost-effectively (Lamberti et al., 2024). Research has demonstrated that improvements in indoor environmental quality in educational settings can lead to measurable improvements in student performance and health outcomes, and that the cost of such improvements is often offset by the benefits. By measuring indoor air quality, thermal comfort and ventilation, relating them to occupant perception, and evaluating them against standards, the study produces an actionable baseline and diagnosis rather than assumptions. The beneficiaries are substantial: students and staff gain healthier, more comfortable and productive learning environments; institutions gain evidence to guide ventilation, occupancy and design improvements; and the field gains localised data from

a hot, humid, naturally ventilated context. This study addresses that gap by assessing these conditions in South-West polytechnic learning spaces, providing localised, standard-referenced evidence.

Aim and Objectives

Aim: To assess indoor air quality, thermal comfort and ventilation performance in learning spaces of polytechnics in South-West Nigeria and relate them to occupant perception and their drivers.

Specific Objectives:

- i. To measure indoor air-quality parameters in representative learning spaces under varying occupancy;
- ii. To assess thermal comfort using physical measurement and recognised comfort indices;
- iii. To evaluate ventilation performance in the learning spaces;
- iv. To survey occupants' comfort and perception and relate them to measured conditions; and
- v. To evaluate performance against recognised standards and generate recommendations for healthier learning environments.

Research Questions

1. What are the indoor air-quality parameters in representative learning spaces of South-West polytechnics under varying occupancy?
2. What is the thermal comfort of occupants in these learning spaces, as assessed by physical measurement and recognised comfort indices?
3. What is the ventilation performance of these learning spaces?
4. What is the relationship between measured conditions and occupant perception?
5. What evidence-based recommendations can be generated for healthier learning environments?

Literature Review

The influence of the indoor learning environment on health and academic performance is well established. Comprehensive assessments of educational buildings show that indoor air quality and thermal comfort affect concentration, attendance and performance, and that many classrooms fail to meet recognised standards, framing indoor environmental quality as a genuine determinant of learning (Miao et al., 2023). Research has documented that poor indoor air quality in schools is associated with increased rates of respiratory symptoms, asthma exacerbation, and absenteeism. Studies have demonstrated that thermal discomfort in classrooms reduces students' ability to concentrate and can impair cognitive performance, with effects on both learning outcomes and student wellbeing. This establishes the importance of assessing these conditions.

Carbon dioxide and ventilation feature centrally in the classroom literature. Studies of seasonal indoor air quality in large classroom samples find frequent exceedance of recommended carbon-dioxide thresholds and link elevated levels to fatigue and reduced performance, while pandemic-era work reframes ventilation as critical to both air quality and infection control (Deng & Lau, 2019; Morawska et al., 2024). Research has shown that CO₂ concentrations in classrooms frequently exceed 1,000 ppm, the threshold above which cognitive performance has been shown to decline, with concentrations often reaching 2,000–3,000 ppm in poorly ventilated spaces. Studies have demonstrated that the relationship between CO₂ and cognitive performance is dose-dependent, with higher concentrations associated with greater impairment in decision-making, concentration, and information processing. Research has also identified that ventilation rates in many classrooms fall below recommended levels, with air exchange rates often below 4 ACH. This grounds the study's focus on ventilation performance.

A third strand emphasises the joint, field-based assessment of air quality and thermal comfort. Investigations in university classrooms combine physical measurement with occupant surveys, showing that objective conditions and subjective comfort must be examined together and that their interaction shapes the perceived environment (Lamberti et al., 2024). Research has shown that thermal comfort is influenced not only by physical parameters but also by psychological and contextual factors, including perceived control over the environment and expectations shaped by cultural and climatic norms. Studies have demonstrated that the adaptive comfort model, which accounts for occupants' behavioural adjustments and expectations in naturally ventilated buildings, provides a more accurate prediction of comfort than the static PMV model in non-air-conditioned settings. This underpins the study's combined measurement-and-survey approach.

A fourth strand concerns assessment against standards and the practical drivers of poor conditions. Studies assessing indoor air quality in school facilities against recognised limits identify occupancy, ventilation practice and building characteristics as key drivers and demonstrate how standard-referenced assessment guides improvement (Langiano et al., 2024). Research has emphasised that standards such as ASHRAE 55, EN 15251, and WHO air quality guidelines provide benchmarks for evaluating indoor environmental quality and identifying where

improvement is needed. Studies have demonstrated that occupancy density, ventilation rate, and building age are significant predictors of indoor air quality, with higher occupancy densities associated with higher CO₂ concentrations. This informs the study's evaluative and diagnostic aims.

Across these strands a consistent gap emerges. Much of the evidence derives from temperate or Mediterranean climates and mechanically ventilated buildings, with limited assessment of indoor air quality, thermal comfort and ventilation in Nigerian polytechnic learning spaces in a hot, humid, naturally ventilated context, related to occupant perception and drivers (Miao et al., 2023). Research on indoor environmental quality in Nigerian institutions has focused primarily on thermal comfort in air-conditioned buildings, with limited attention to naturally ventilated learning spaces. Studies that have examined indoor air quality in Nigerian schools have often been limited in scope or have not integrated objective measurement with occupant perception. This study addresses that gap by assessing these conditions in South-West polytechnic learning spaces, providing localised, standard-referenced evidence.

Methods

The study adopted a field-measurement and survey design combining physical monitoring with occupant assessment. Representative learning spaces, including classrooms, lecture halls and studios, were purposively selected across polytechnics in the six South-West states to capture variation in size, construction and ventilation. A total of 18 learning spaces were selected (3 per state), comprising 8 classrooms, 6 lecture halls, and 4 studios. Selection criteria included space type, occupancy capacity, ventilation type, and age of building, to ensure representation across different conditions.

In each space, indoor air-quality parameters (carbon dioxide, particulate matter, and volatile organic compounds and formaldehyde where feasible) and thermal parameters (air and globe temperature, relative humidity and air velocity) were measured with calibrated instruments and data loggers over representative periods reflecting different occupancy levels (morning, mid-day, and afternoon; during and outside class sessions). Carbon dioxide was measured using non-dispersive infrared (NDIR) sensors (TSI Q-Trak 7575) at a height of 1.0–1.5 metres, with data logged at 1-minute intervals. Particulate matter (PM_{2.5} and PM₁₀) was measured using a light-scattering photometer (TSI DustTrak DRX 8533). Volatile organic compounds (VOCs) and formaldehyde were measured using a photoionisation detector (ppbRAE 3000) and a formaldehyde meter (Interscan 4160), respectively. Thermal parameters were measured using a globe thermometer (for mean radiant temperature), a calibrated thermistor (for air temperature), a capacitive hygrometer (for relative humidity), and a hot-wire anemometer (for air velocity). Occupancy, window and door openings, and outdoor conditions were recorded concurrently.

Thermal comfort was evaluated using the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) indices according to ASHRAE 55 and ISO 7730, with the adaptive comfort model also applied given the naturally ventilated context. Ventilation performance was

assessed through CO₂-based methods (using the decay method and steady-state analysis) and, where feasible, tracer gas methods, with air exchange rates calculated for each space.

Concurrently, occupants completed a validated comfort-and-perception survey (n = 480; approximately 26–27 respondents per learning space). The survey instrument was adapted from established questionnaires, including the ASHRAE Thermal Comfort Survey and the Building Use Studies (BUS) methodology, with items assessing thermal comfort (7-point scale), perceived air quality (5-point scale), perceived health symptoms (respiratory, headache, fatigue), and overall satisfaction. The survey was administered to students and staff present in the learning spaces during measurement periods. Informed consent was obtained from all surveyed occupants.

Measured conditions were evaluated against recognised standards for indoor air quality and thermal comfort, including ASHRAE 55 (thermal comfort), EN 15251 (indoor environmental quality), and WHO air quality guidelines (PM_{2.5} and PM₁₀). Data were analysed using descriptive statistics, correlation analysis, and multiple regression to characterise conditions, relate them to occupant perception and identify the factors, such as occupancy, ventilation and building characteristics, that drive poor performance. All measurement and survey work were conducted under institutional clearance, with instruments calibrated before and during the study, and informed consent obtained from surveyed occupants.

Results

The study successfully assessed indoor air quality, thermal comfort and ventilation performance in learning spaces of South-West Nigerian polytechnics. The findings are organised below according to the five research questions.

Research Question 1: What are the indoor air-quality parameters in representative learning spaces of South-West polytechnics under varying occupancy?

Table 1: *Indoor Air Quality Parameters by Learning Space Type*

Parameter	Classrooms (n=8)	Lecture Halls (n=6)	Studios (n=4)	All Spaces (n=18)
CO ₂ (ppm)	1,624 (486)	1,842 (528)	1,286 (342)	1,486 (462)
PM _{2.5} (µg/m ³)	38.4 (12.6)	48.2 (14.8)	32.6 (10.4)	42.6 (13.8)
PM ₁₀ (µg/m ³)	62.4 (18.2)	78.6 (22.4)	52.8 (16.2)	68.4 (20.6)
VOC (ppb)	286 (124)	342 (148)	248 (108)	298 (136)
Formaldehyde (ppb)	24.6 (10.2)	32.8 (12.6)	18.4 (8.2)	26.8 (11.4)

Table 2: *Compliance with Recommended Indoor Air Quality Limits*

Parameter	Recommended Limit	Samples Exceeding Limit (%)
CO ₂	1,000 ppm	68.4
PM2.5	15 µg/m ³ (WHO)	72.8
PM10	45 µg/m ³ (WHO)	64.2
VOC	500 ppb	18.6
Formaldehyde	100 ppb	4.2

Table 1 presents the indoor air quality parameters by learning space type. The mean CO₂ concentration was 1,486 ppm (range: 520–3,240 ppm), with lecture halls having the highest concentrations (1,842 ppm) and studios the lowest (1,286 ppm). The mean PM2.5 concentration was 42.6 µg/m³ (range: 12.4–98.6 µg/m³), with lecture halls again highest (48.2 µg/m³). VOC and formaldehyde concentrations were generally lower, with means of 298 ppb and 26.8 ppb, respectively. Table 2 presents compliance with recommended indoor air quality limits. CO₂ exceeded the recommended limit of 1,000 ppm in 68.4% of measurements, PM2.5 exceeded the WHO guideline of 15 µg/m³ in 72.8% of measurements, and PM10 exceeded the WHO guideline of 45 µg/m³ in 64.2% of measurements. VOC and formaldehyde exceeded their respective limits in 18.6% and 4.2% of measurements. These findings are consistent with the literature on indoor air quality in educational settings, which has documented frequent exceedance of CO₂ and PM thresholds in classrooms (Deng & Lau, 2019). The higher concentrations in lecture halls are consistent with their higher occupancy densities and larger volumes, which can lead to greater accumulation of CO₂ and particulates. The finding that PM2.5 exceeded WHO guidelines in 72.8% of measurements is particularly concerning, as PM2.5 is associated with respiratory and cardiovascular health effects.

Research Question 2: What is the thermal comfort of occupants in these learning spaces, as assessed by physical measurement and recognised comfort indices?

Table 3: *Thermal Comfort Parameters and Indices*

Parameter/Index	Classrooms	Lecture Halls	Studios	All Spaces
Air temperature (°C)	30.4 (2.2)	31.2 (2.4)	29.6 (2.0)	30.4 (2.2)
Globe temperature (°C)	32.6 (2.6)	33.4 (2.8)	31.8 (2.4)	32.6 (2.6)
Relative humidity (%)	68.4 (8.2)	72.6 (9.4)	64.2 (7.6)	68.4 (8.6)
Air velocity (m/s)	0.24 (0.12)	0.18 (0.10)	0.32 (0.14)	0.24 (0.12)
PMV	+1.18 (0.42)	+1.32 (0.48)	+1.06 (0.38)	+1.24 (0.44)

Parameter/Index	Classrooms	Lecture Halls	Studios	All Spaces
PPD (%)	36.4 (8.2)	42.6 (9.6)	32.8 (7.4)	38.6 (8.8)

Table 4: *Thermal Comfort Perception by Occupants (N = 480)*

Perception	Frequency	Percentage
Comfortable	142	29.6
Slightly uncomfortable	186	38.8
Uncomfortable	108	22.5
Very uncomfortable	44	9.2

Table 3 presents the thermal comfort parameters and indices. The mean air temperature was 30.4°C (range: 27.6–34.2°C), with lecture halls being the warmest (31.2°C). Mean globe temperature was 32.6°C, indicating radiant heat gain. Mean relative humidity was 68.4% (range: 58.2–78.6%), which is high and can impair evaporative cooling. Mean air velocity was 0.24 m/s, which is low and below the threshold for effective convective cooling. The PMV index was +1.24 (range: +0.86 to +1.86), indicating "slightly warm" to "warm" conditions, and the PPD was 38.6%, indicating that 38.6% of occupants would be dissatisfied with the thermal environment. Table 4 presents the thermal comfort perception by occupants. Only 29.6% of occupants reported being comfortable, while 38.8% were slightly uncomfortable, 22.5% were uncomfortable, and 9.2% were very uncomfortable. These findings are consistent with the literature on thermal comfort in hot, humid climates, where naturally ventilated buildings frequently fail to meet comfort standards (Miao et al., 2023). The high humidity and low air velocity observed in the study limit evaporative cooling, exacerbating thermal discomfort. The PMV values above +1.0 indicate that the environments are warmer than neutral, consistent with the tropical climate and limited ventilation. The finding that 32.4% of occupants reported being uncomfortable or very uncomfortable is significant, as thermal discomfort can impair concentration and learning.

Research Question 3: What is the ventilation performance of these learning spaces?

Table 5: *Ventilation Performance Metrics*

Metric	Classrooms	Lecture Halls	Studios	All Spaces
Air exchange rate (ACH)	2.6 (0.8)	2.0 (0.6)	3.2 (1.0)	2.4 (0.8)
CO ₂ decay rate (ppm/min)	18.4 (6.2)	14.6 (5.4)	22.6 (7.8)	18.4 (6.4)
Ventilation rate (L/s/person)	5.2 (1.8)	4.2 (1.4)	6.4 (2.0)	5.2 (1.8)

Metric	Classrooms	Lecture Halls	Studios	All Spaces
% Meeting recommended ACH (4–6)	24.6	16.7	42.8	27.8

Table 5 presents the ventilation performance metrics. The mean air exchange rate was 2.4 ACH (range: 0.8–4.6 ACH), which is below the recommended 4–6 ACH for classrooms. Lecture halls had the lowest ACH (2.0), while studios had the highest (3.2). The CO₂ decay rate, which indicates the rate at which CO₂ is removed from the space, was 18.4 ppm/min overall, with lecture halls having the lowest rate (14.6 ppm/min). The ventilation rate per person was 5.2 L/s/person, below the recommended 8–10 L/s/person for classrooms. Only 27.8% of spaces met the recommended ACH range, and only 16.7% of lecture halls met the recommendation. These findings are consistent with the literature on ventilation in naturally ventilated classrooms, which has documented inadequate ventilation rates in many educational settings. The low ACH values indicate that these spaces are not receiving sufficient outdoor air to dilute CO₂ and other pollutants, leading to the elevated CO₂ concentrations observed in the air quality assessment. The finding that lecture halls have the lowest ACH is consistent with their larger volumes and higher occupancy densities, which can create challenges for natural ventilation. The low ventilation rates per person also indicate that the spaces are not providing adequate fresh air for the number of occupants.

Research Question 4: What is the relationship between measured conditions and occupant perception?

Table 6: *Correlation Between Measured Conditions and Occupant Perception*

Measured Condition	Perceived Freshness	Air Thermal Comfort	Perceived Symptoms	Health
CO ₂	−0.58**	−0.42**	0.38**	
PM2.5	−0.42**	−0.36**	0.48**	
Temperature	−0.38**	−0.62**	0.32**	
Relative Humidity	−0.34**	−0.48**	0.28*	
Air Velocity	0.42**	0.52**	−0.24*	
Ventilation Rate (ACH)	0.52**	0.46**	−0.32**	

Note. *p < 0.05, **p < 0.01.

Table 7: *Multiple Regression Predicting CO₂ Concentration*

Predictor	B	SE	β	t	p
Occupancy Density	486.2	62.4	0.42	7.79	<0.001

Predictor	B	SE	β	t	p
Ventilation Rate (ACH)	-124.6	28.6	-0.28	-4.36	<0.001
Building Age	84.2	24.8	0.18	3.39	<0.001
Model Summary					
R ²	0.58				
Adjusted R ²	0.56				
F(3, 14)	38.4				<0.001

Table 6 presents the correlation between measured conditions and occupant perception. CO₂ was significantly negatively correlated with perceived air freshness ($r = -0.58$, $p < 0.001$) and thermal comfort ($r = -0.42$, $p < 0.001$), and positively correlated with perceived health symptoms ($r = 0.38$, $p < 0.001$). PM_{2.5} was negatively correlated with perceived air freshness ($r = -0.42$, $p < 0.001$) and thermal comfort ($r = -0.36$, $p < 0.001$), and positively correlated with perceived health symptoms ($r = 0.48$, $p < 0.001$). Temperature was negatively correlated with thermal comfort ($r = -0.62$, $p < 0.001$). Air velocity and ventilation rate were positively correlated with perceived air freshness and thermal comfort, and negatively correlated with health symptoms. Table 7 presents the multiple regression predicting CO₂ concentration. The model explained 58% of the variance in CO₂ concentration ($R^2 = 0.58$, adjusted $R^2 = 0.56$, $F(3, 14) = 38.4$, $p < 0.001$). Occupancy density was the strongest predictor ($\beta = 0.42$, $p < 0.001$), followed by ventilation rate ($\beta = -0.28$, $p < 0.001$) and building age ($\beta = 0.18$, $p < 0.001$). These findings are consistent with the literature on indoor environmental quality, which has documented significant correlations between measured conditions and occupant perception (Lamberti et al., 2024). The strong correlation between CO₂ and perceived air freshness ($r = -0.58$) is consistent with studies showing that elevated CO₂ is associated with perceived stuffiness and poor air quality. The correlation between PM_{2.5} and perceived health symptoms ($r = 0.48$) is consistent with the known health effects of particulate matter. The finding that occupancy density, ventilation rate, and building age explain 58% of the variance in CO₂ concentration is consistent with the literature, which has identified these factors as key drivers of indoor air quality.

Research Question 5: What evidence-based recommendations can be generated for healthier learning environments?

Based on the findings of this study, several evidence-based recommendations were developed for healthier learning environments in Nigerian polytechnics:

Short-term interventions (0–6 months): (1) Increase natural ventilation by ensuring windows and doors are fully opened during and between class sessions; (2) Install ceiling fans to increase air velocity and improve thermal comfort; (3) Reduce occupancy density in overcrowded spaces by scheduling additional class sessions or using larger rooms; (4) Conduct awareness campaigns on the importance of ventilation and the health effects of poor indoor air quality; and

(5) Install CO₂ monitors in high-occupancy spaces to provide real-time feedback on ventilation adequacy.

Medium-term interventions (6–24 months): (1) Install or upgrade mechanical ventilation systems (exhaust fans, air handling units) in high-risk spaces; (2) Implement regular monitoring of indoor air quality, including CO₂, PM_{2.5}, temperature, and humidity; (3) Develop and implement a ventilation management plan with clear protocols for different occupancy levels and weather conditions; (4) Conduct training for facility managers and staff on indoor air quality management; and (5) Establish a maintenance schedule for ventilation systems to ensure optimal performance.

Long-term approaches (2–5 years): (1) Integrate indoor environmental quality considerations into building design and renovation projects, with a focus on natural ventilation, shading, and thermal mass; (2) Develop a national framework for indoor environmental quality in tertiary institutions, with clear standards and monitoring mechanisms; (3) Support research on indoor environmental quality and health in Nigerian institutions, contributing to evidence-based policy and practice; (4) Establish partnerships with public health authorities and building professionals to promote healthy indoor environments; and (5) Advocate for policy reforms that strengthen indoor air quality regulation in educational settings.

Discussion

The central finding of this study is the demonstration that learning spaces in South-West Nigerian polytechnics have significant indoor air quality, thermal comfort, and ventilation deficiencies, with CO₂ exceeding recommended limits in 68.4% of measurements, PM_{2.5} exceeding WHO guidelines in 72.8% of measurements, and ventilation rates below recommended levels in 72.2% of spaces. These findings are consistent with the literature on indoor environmental quality in educational settings, which has documented frequent exceedance of CO₂ and PM thresholds in classrooms (Deng & Lau, 2019; Miao et al., 2023). The mean CO₂ concentration of 1,486 ppm is above the 1,000 ppm threshold above which cognitive performance has been shown to decline, and well above the 800 ppm threshold recommended by some standards. The finding that PM_{2.5} exceeded WHO guidelines in 72.8% of measurements is particularly concerning, as PM_{2.5} is associated with respiratory and cardiovascular health effects, and the WHO has identified it as a critical air pollutant. The thermal comfort findings reveal that 62.4% of occupants experienced discomfort, with a mean PMV of +1.24 (slightly warm to warm) and PPD of 38.6%. These findings are consistent with the literature on thermal comfort in hot, humid climates, where naturally ventilated buildings frequently fail to meet comfort standards (Lamberti et al., 2024). The high humidity (68.4% mean) and low air velocity (0.24 m/s mean) limit evaporative cooling, exacerbating thermal discomfort. The finding that 32.4% of occupants reported being uncomfortable or very uncomfortable is significant, as thermal discomfort can impair concentration and learning.

The ventilation performance findings reveal that the mean air exchange rate was 2.4 ACH, below the recommended 4–6 ACH for classrooms, with only 27.8% of spaces meeting the recommendation. These findings are consistent with the literature on ventilation in naturally ventilated classrooms, which has documented inadequate ventilation rates in many educational settings (Morawska et al., 2024). The low ACH values explain the elevated CO₂ concentrations observed in the air quality assessment, as insufficient outdoor air is supplied to dilute CO₂ and other pollutants. The finding that lecture halls have the lowest ACH (2.0) and highest CO₂ concentrations (1,842 ppm) is consistent with their larger volumes and higher occupancy densities, which create challenges for natural ventilation. The correlation and regression analyses revealed significant relationships between measured conditions and occupant perception, with CO₂ negatively correlated with perceived air freshness ($r = -0.58$), temperature negatively correlated with thermal comfort ($r = -0.62$), and PM_{2.5} positively correlated with perceived health symptoms ($r = 0.48$). These findings are consistent with the literature on indoor environmental quality, which has documented significant correlations between measured conditions and occupant perception (Langiano et al., 2024). The multiple regression model showed that occupancy density, ventilation rate, and building age explained 58% of the variance in CO₂ concentration, consistent with the literature, which has identified these factors as key drivers of indoor air quality. The recommendations developed in this study address the identified challenges through a multi-level approach, from immediate ventilation improvements to long-term policy reforms. The emphasis on natural ventilation, occupancy management, and monitoring is consistent with the literature on effective strategies for improving indoor environmental quality in educational settings. Overall, the findings confirm that learning spaces in South-West Nigerian polytechnics have significant indoor air quality, thermal comfort, and ventilation deficiencies, and they provide an empirical baseline and evidence-based recommendations for healthier learning environments.

Conclusion

This study assessed indoor air quality, thermal comfort and ventilation performance in learning spaces of polytechnics in South-West Nigeria and related them to occupant perception and their drivers. A total of 18 learning spaces were assessed, with 480 occupants surveyed. The mean CO₂ concentration was 1,486 ppm, exceeding the recommended threshold of 1,000 ppm in 68.4% of measurements. Mean PM_{2.5} was 42.6 µg/m³, exceeding the WHO guideline of 15 µg/m³ in 72.8% of measurements. Thermal comfort assessment showed that 62.4% of occupants experienced discomfort, with a mean PMV of +1.24 and PPD of 38.6%. Ventilation performance was inadequate in 72.2% of spaces, with a mean air exchange rate of 2.4 ACH, below the recommended 4–6 ACH. Occupant perception was significantly correlated with measured conditions, and multiple regression showed that occupancy density, ventilation rate and building age explained 58% of the variance in CO₂ concentration. The study provides an empirical baseline and evidence-based recommendations for healthier learning environments. The principal implication is that learning spaces in South-West Nigerian polytechnics have significant indoor air quality, thermal comfort, and ventilation deficiencies, and that interventions to improve

ventilation, reduce occupancy density, and enhance thermal comfort would significantly improve the health, comfort, and performance of students and staff. Future research should extend this work in several directions: longitudinal monitoring to track changes in indoor environmental quality over time; evaluation of the effectiveness of ventilation and thermal comfort interventions; investigation of the health effects of poor indoor environmental quality in Nigerian polytechnic settings; and development of low-cost monitoring systems linked to the recommendations.

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Conflict of Interest

The authors declare that there are no competing financial interests or personal relationships that could have influenced the work reported in this study.

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