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INDOOR AIR QUALITY IN COMPUTER-BASED EXAMINATION HALLS: ASSESSING STUDENT-GENERATED $PM_{2.5}$, CO_2, AND VOCS FOR RISK EVALUATION AND MITIGATION

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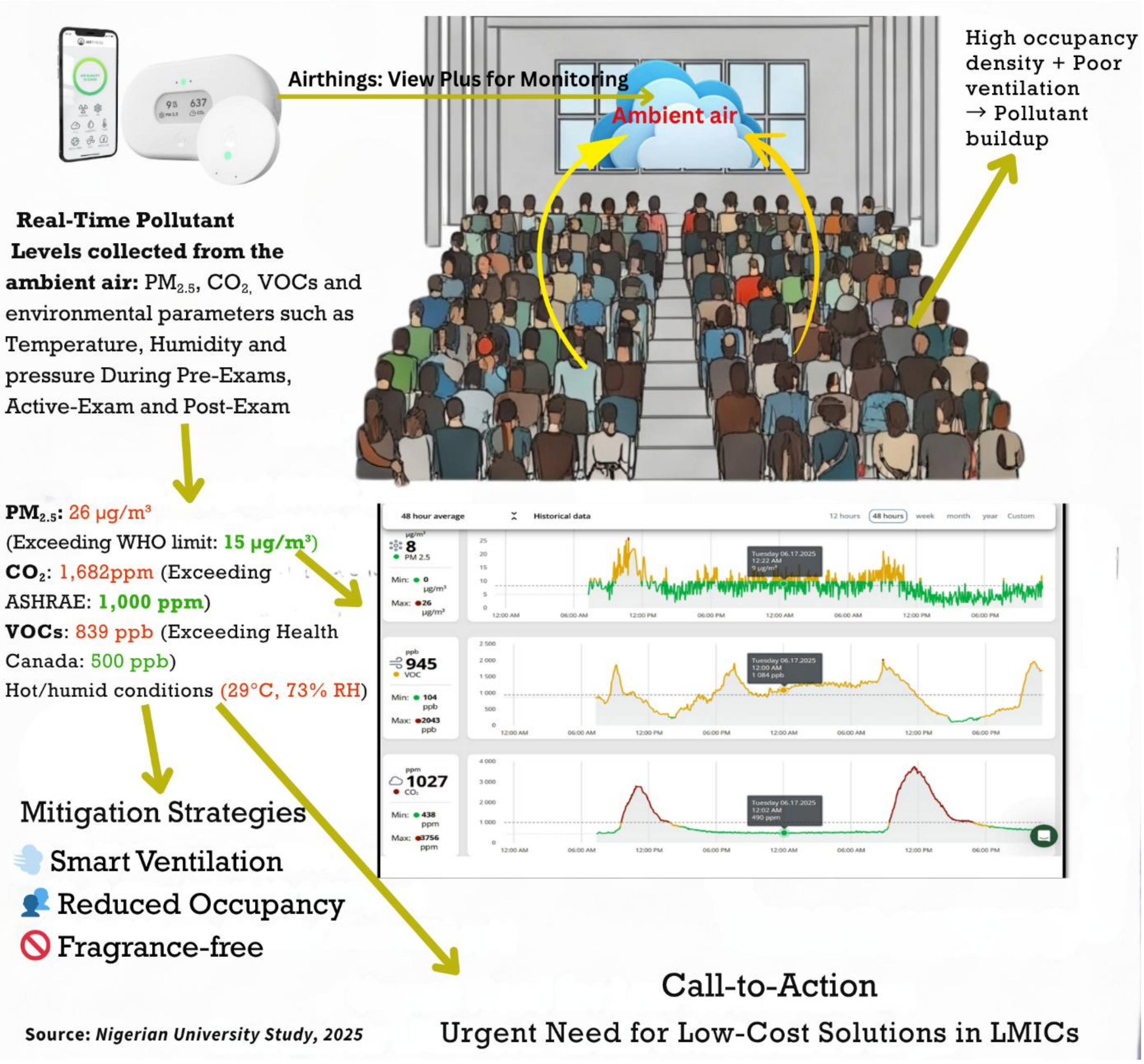
Abstract

Computer-based examinations are vital for modern education, but poor indoor air quality (IAQ) in enclosed exam halls, especially in low- and middle-income countries (LMICs), can harm students' health and cognitive functions. This study investigates real-time changes in pollutants produced by students ($PM_{2.5}$, CO_2, and total VOCs) during live exams at a Nigerian university, which exemplifies an LMIC setting with natural ventilation and high occupant density. Using cloud-connected Airthings View Plus monitors, we recorded pollutant levels during pre-exam, active exam, and post-exam phases. The results revealed notable IAQ decline: $PM_{2.5}$ peaked at 26 μg/m³ (exceeding WHO 24-hour guidelines), CO_2 reached 1,682 ppm (68% above ASHRAE standards), and VOCs increased to 839 ppb (almost three times Health Canada's limit). Elevated temperature (29°C) and humidity (73%) intensified pollutant persistence through hygroscopic particle growth and VOC volatilisation. Although pollutant levels remained below occupational hazard limits, frequent breaches of health guidelines highlight risks in poorly ventilated exam environments. This study underscores the need for affordable, immediate interventions such as improved ventilation schedules, reduced occupancy, and fragrance-free policies to minimise exposure. Our findings offer empirical evidence of IAQ concerns in LMIC academic settings and lay a foundation for future research on VOC composition and thermal comfort trade-offs. The work advocates for context-specific strategies over large infrastructure modifications, considering the resource limitations in LMICS.

Keywords*: Indoor air quality (IAQ); Computer-based exams; LMICs (Low- and Middle-Income Countries); CO_2 & $PM_{2.5}$; Ventilation & Total VOCs.*

Graphical Abstract



1.0 INTRODUCTION

Indoor air quality (IAQ) is widely recognized as a fundamental determinant of respiratory health, cognitive performance, and overall well-being, particularly in educational settings where prolonged concentration is required [1]. Over the past decade, research in this area has predominantly focused on classrooms, libraries, and lecture theatres, often in contexts where air conditioning systems, mechanical ventilation, or energy-efficient retrofits are standard features—most notably in high-income countries (HICs) [1,2]. These studies have linked elevated indoor pollutants, particularly carbon dioxide (CO_2), fine particulate matter ($PM_{2.5}$), and volatile organic compounds (VOCs), to adverse physiological and cognitive outcomes, such as diminished memory retention, impaired decision-making, and increased risk of respiratory illness [3,4,5].

However, less attention has been paid to indoor microenvironments unique to digital education infrastructure, especially computer-based examination halls. Unlike classrooms that accommodate routine interaction and variable seating arrangements, examination halls are characterised by transient high-density occupancy, minimal physical activity, heightened psychological stress, and limited air exchange due to exam integrity protocols. These conditions create a unique chemical and physical environment where indoor pollutants can accumulate rapidly and interact synergistically.

This issue is even more pronounced in low- and middle-income countries (LMICs), where digital examination infrastructure often lacks mechanical ventilation, air filtration, or climate-adaptive design features. In many LMIC institutions, natural ventilation is the only source of air exchange, and

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window access is sometimes restricted during examinations to prevent cheating or noise intrusion [6]. These constraints exacerbate IAQ degradation, especially in hot and humid tropical climates where thermal loads and moisture levels amplify pollutant behavior. Comparatively, HIC-based studies have shown more favourable IAQ baselines due to building codes, HVAC installations, and air quality regulations [6].

From a chemical standpoint, the examination hall becomes a dynamic indoor atmosphere governed by principles of thermodynamics, mass transfer, and reaction kinetics [7]. CO_2, the primary byproduct of human respiration, serves as a key indicator of ventilation adequacy and as a weak acid in indoor buffer systems, influencing pH-sensitive reaction equilibria [7,8]. VOCs, which comprise a diverse group of semi-volatile and volatile organic compounds, such as alcohols, aldehydes, and terpenes, which originate from personal care products, exhaled breath, and heated electronics [9,10]. These compounds undergo oxidation reactions indoors, sometimes forming secondary organic aerosols (SOAs) under the influence of photochemical initiators and residual indoor ozone [10]. The $PM_{2.5}$ derived from resuspension of settled dust, textile abrasion, and outdoor infiltration tends to act as both a physical carrier and as a reactive matrix for gas-to-particle phase interactions. The particle phase at elevated relative humidity (RH) is promoted by a process called hygroscopic particle growth. Thus, increasing the particle size deposition probability in the respiratory tract and surface reactivity [11].

While IAQ in classrooms has been extensively studied [12,13,14,15,16,17], no prior work has quantified real-time $PM_{2.5}$, CO_2, and VOC interactions in computer-based examination halls under tropical conditions. Existing studies from LMICs often report average pollutant concentrations over prolonged periods and seldom focus on pollutant surges during specific student activities [18,19,20,21]. Furthermore, real-time, multi-parameter environmental monitoring that integrates atmospheric chemistry interpretations remains limited in Sub-Saharan educational contexts. This leaves a critical knowledge gap in understanding how student density, thermal stress, and pollutant interaction dynamics evolve during digital exam events that are increasingly central to academic progress and national education policy.

Consequently, this study presents the first real-time, multi-pollutant investigation of student-generated indoor air quality degradation in computer-based examination halls, using high-resolution Airthings View Plus sensors. The research was conducted in an LMIC university setting within the humid tropical climate of Southern Nigeria, offering a unique chemical-environmental profile rarely captured in global IAQ literature. By integrating chemical principles, environmental dynamics, and exposure science, the study aims to (i) characterise pollutant buildup and decay patterns, (ii) identify the influence of temperature, humidity, and pressure on pollutant interactions, and (iii) propose context-sensitive mitigation strategies suitable for educational institutions with limited resources.

The remainder of this paper is structured as follows: Section 2 outlines the materials, instruments, and monitoring strategy adopted in the study. Section 3 presents the results, including pollutant trends, compliance benchmarking, and statistical correlations. Section 4 discusses the atmospheric chemistry mechanisms, thermal-humidity feedbacks, and pollutant interactions. Section 5 concludes with implications for academic health, policy formation, and environmental management in examination settings.

2.0 MATERIALS AND METHODS

2.1 Materials

All instruments and monitoring materials were selected based on their suitability for high-resolution, multi-pollutant indoor air quality (IAQ) assessment under varying environmental conditions. The primary monitoring device used was the Airthings View Plus, a factory-calibrated smart environmental sensor capable of measuring fine particulate matter ($PM_{2.5}$), carbon dioxide (CO_2), total volatile organic compounds (VOCs), relative humidity (RH), temperature, and barometric pressure with specifications described in Table 1. For VOC cross-validation, an auxiliary Airthings Wave Mini was deployed in a separate indoor location to strengthen measurement reliability. Both sensor types were procured directly from Airthings (Oslo, Norway) and operated in their default calibrated states.

These devices supported cloud-based data synchronization at five-minute intervals, enabling real-time logging with tamper-resistant cloud storage as shown in Figure 1. Data processing, statistical analysis, and regulatory benchmarking were conducted using Microsoft Excel 365.

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Table 1: Airthings View Plus Sensor Technical Specifications and Performance Characteristics

Category	Specification	References
Sensors Included	Radon, PM_1, $PM_{2.5}$, CO_2, VOCs, Humidity, Temperature, Air Pressure	[22, 23, 25]
Sampling Intervals		
Radon	60 minutes (fixed)	[23,25]
CO_2/VOCs/Temp/Humidity/Pressure	5 minutes (2.5 min with USB)	[23,25]
PM_1/$PM_{2.5}$	Configurable: 10/60 min (2.5 min with USB)	[23,25]
CO_2 (NDIR)		
Range	400-5,000 ppm	[23,25]
Accuracy	±50 ppm or ±3% (10-35°C, 0-80% RH)	[23,25]
$PM_{2.5}$ (Laser OPC)		
Range	0-1,000 µg/m³	[24,25]
Accuracy	<150 µg/m³: ±(5+15%) >150 µg/m³: ±(5+20%)	[24,25]
VOCs	0-10,000 ppb (7-day settling)	[24,25]
Temperature	±0.5°C accuracy, 0.1°C resolution	[24,25]
Humidity	±3% RH accuracy (20-80% RH at 25°C)	[24,25]

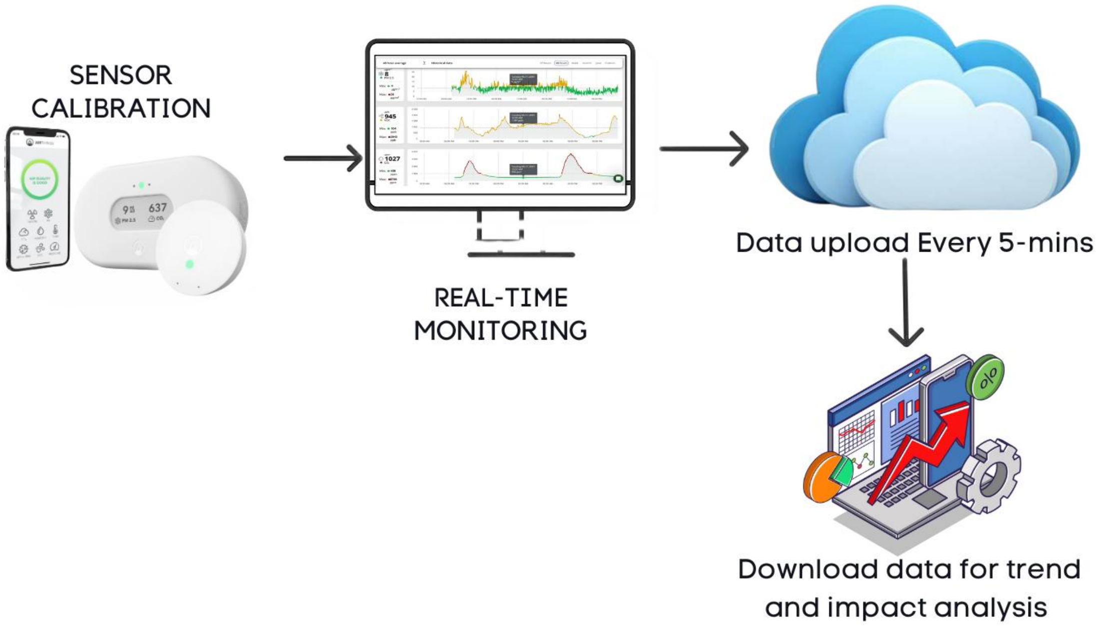

Figure 1. illustrates the workflow and data transmission structure of the Airthings View Plus system, encompassing sensor calibration, real-time monitoring, and secure cloud upload at fixed intervals.

2.2 Indoor Monitoring Protocol

The study was conducted in two computer-based examination halls located at the main campus of Benson Idahosa University, Benin City, Nigeria. Each hall had a seating capacity of at least 50 students, minimal natural ventilation, and a ceiling height below 3 meters. These characteristics are typical of digital examination settings in low- and middle-income countries (LMIC) educational institutions. Real-time monitoring was carried out over a continuous 48-hour period, covering multiple examination cycles. Sensors were mounted on adjustable tripods at approximately 1.2 meters above ground level, aligning with the seated breathing zone of adult occupants (Figure 2). This elevation conforms to occupational health and exposure standards, ensuring that recorded pollutant levels reflect real inhalation conditions during exams [26]. Sensor placement was carefully chosen to maintain thermal and spatial neutrality. Devices were positioned at the geometric center of the seating area, away from direct heat sources such as computer vents, and distant from windows or mechanical air outlets. Monitoring was structured into three temporal phases: a Pre-Exam Phase, starting 30 minutes before student entry to capture unoccupied baseline conditions; an Active Exam Phase, from 9:00 AM to 3:00 PM, representing peak occupancy and activity; and a Post-Exam Phase, beginning at 3:00 PM, to monitor decay curves and return to baseline levels.

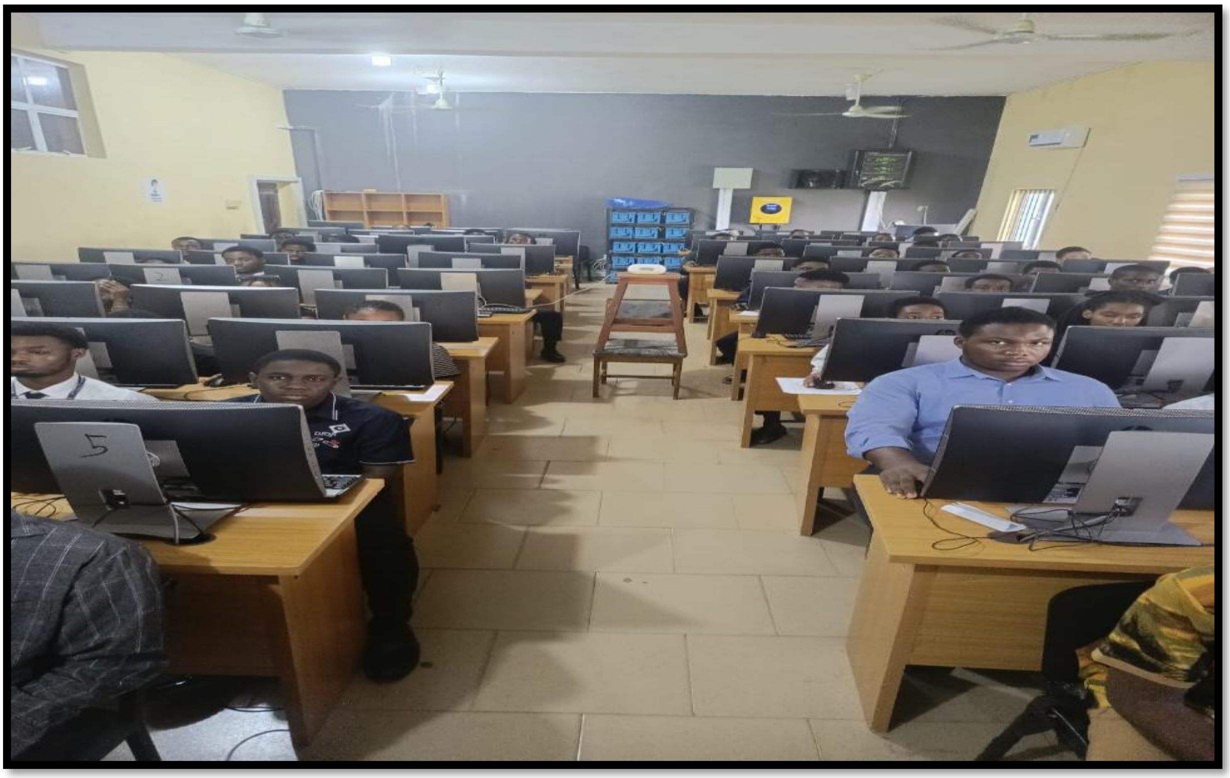

Figure 2. presents a schematic diagram of the IAQ monitoring setup within a computer-based examination hall, showing seating layout, computer stations, and sensor positioning at a central elevation of 1.2 meter

2.3 Hall Characterisation and Occupancy Logging

To contextualise IAQ measurements, each examination hall was geometrically mapped using a digital laser rangefinder. Dimensions such as room volume, floor area, window-to-wall ratio, and air outlet locations were documented. Observational data on infrastructure, including the number of computers, insulation materials, and seating density, were also recorded. Occupancy was logged manually through regular headcounts.

2.4 Pollutant Measurement and Analysis

The Airthings View Plus sensor measured $PM_{2.5}$ in micrograms per cubic meter (µg/m³; range: 0–500), CO_2 in parts per million (ppm; range: 400–5,000), and total VOCs in parts per billion (ppb; range: 0–10,000) as articulated in Table 1. The device also logged temperature, humidity, and barometric pressure continuously. Measurements were categorised according to the three temporal monitoring phases, and descriptive statistics: mean, maximum, and standard deviation, were computed for each pollutant. These results were benchmarked against international air quality guidelines, including the World Health Organization [27, 28] for $PM_{2.5}$ (≤15 µg/m³, 24-hour average), ASHRAE Standard [29] for CO_2 (≤1,000 ppm), and Health Canada and LEED [30] thresholds for VOCs (≤250–500 ppb). Pearson correlation analysis (significance threshold at $p < 0.05$) was used to explore relationships between pollutants and environmental variables such as temperature, humidity, and pressure. These statistical interactions are further discussed in Section 3.

2.5 Environmental Condition Assessment

Environmental variables recorded in parallel with pollutant measurements included temperature, relative humidity, and barometric pressure. The temperature range spanned from 4°C to 50 °C, with an accuracy of ±1 °C. Relative humidity ranged from 0% to 80%, with ±3% accuracy. Barometric pressure was recorded within a 22–32 inHg range, accurate to ±0.1 inHg. These variables were analysed to assess their influence on the dynamics of indoor pollutant behaviour over time.

2.6 Instrument Reusability and Data Reliability

Sensor reliability and data consistency were assessed through pre- and post-study calibration checks performed in standardised indoor settings. Duplicate tests showed a measurement variation of less than 3%, verifying device stability. Internal diagnostics, accessed via the Airthings dashboard, confirmed battery health, signal quality, and cloud synchronization accuracy throughout the monitoring period, supporting the credibility of the recorded data.

3. Results and Discussion

3.1 Pollutant Concentration Trends and Regulatory Comparison

The indoor air quality data demonstrated clear temporal trends in $PM_{2.5}$ concentrations, strongly modulated by occupancy patterns and indoor activities. During the Pre-Exam Phase, baseline $PM_{2.5}$ levels averaged 8 ± 2 µg/m³, indicating a relatively clean indoor environment. However, during the Active Exam Phase, concentrations rose significantly to a peak of 26 µg/m³, driven largely by student movement, keyboard usage, and the operation of electronic devices. These physical interactions resuspended dust and contributed to airborne particle generation.

When benchmarked against various international air quality standards, the $PM_{2.5}$ levels remained compliant with most guidelines, though some exceedances were noted (Table 1). The WHO 2021 24-hour average guideline of 15 µg/m³ was exceeded during peak exam conditions by 73%, transitioning the status from compliant to marginally acceptable. In contrast, the United States Environmental Protection Agency (US EPA) and China's GB 3095-2012 standard of 35 and 75 µg/m³, respectively classified the levels as fully compliant [31,32] . The European Union (EU) directive (25 µg/m³) was slightly exceeded during peak concentrations, indicating the need for caution in poorly ventilated, high-occupancy settings [33].

Table 2 summarises the concentration dynamics, compliance status, and the statistically significant correlates influencing $PM_{2.5}$ levels. The strongest associations were observed between $PM_{2.5}$ and student movement ($r = 0.72$, $p < 0.01$) as well as computer fan activity ($r = 0.65$, $p < 0.05$). These findings underscore the importance of occupant behaviour and device emissions in indoor pollutant loading.

Following the exam period, $PM_{2.5}$ levels declined to 15.8 µg/m³ within four hours during the Post-Exam Phase, reflecting natural decay in the absence of continued human activity and pollutant generation.

Table 2: $PM_{2.5}$ Concentration Phases and Exceedance Analysis

Monitoring Phase	Mean ± SD (µg/m³)	Peak (µg/m³)	WHO Guideline (µg/m³)	Exceedance (%)	Key Correlates (R-value)
Pre-Exam (Baseline)	8 ± 2	12.0	15	-20.0	N/A
Active Exam	26.0 ± 4.5 *	26.0 *	15	73.3	Movement (0.72**), Computers (0.65*)
Post-Exam (4-hr decay)	15.8 ± 3.2	21.3	15	5.3	Time since occupancy (-0.81**)
Regulatory Compliance Comparison for $PM_{2.5}$					
Regulatory Body	**Benchmark (24-hour avg.)**	**Baseline (8 µg/m³)**	**Exam Peak (26 µg/m³)**	**Compliance Status**	**Reference**
WHO	15 µg/m³	Compliant	Approaching Limit	Baseline: Safe; Exam: Marginally Acceptable	[30]
US EPA	35 µg/m³	Compliant	Compliant	Fully compliant	[32]
EU Air Quality Directive	25 µg/m³	Compliant	Slightly Exceeded	Baseline: Safe; Exam: Marginal Exceedance	[33]
China GB 3095	75 µg/m³	Compliant	Compliant	Fully compliant	[28]

*Significantly higher than baseline (*p* < 0.01, paired t-test). **Significant correlation (*p* < 0.01).

3.2 Carbon Dioxide (CO_2) Accumulation and Ventilation Adequacy

Carbon dioxide (CO_2) concentrations demonstrated a pronounced escalation during the examination period, closely mirroring occupant density and reflecting the hall's limited ventilation capacity. Baseline CO_2 levels recorded during the Pre-Exam Phase averaged 602 ± 48 ppm, which is well within the ASHRAE 62.1 indoor guideline of 1,000 ppm. During active exam sessions, however, mean CO_2 concentrations surged to 1,892 ± 312 ppm, with recorded peaks reaching 2,450 ppm with an exceedance factor of 2.5 relative to ASHRAE standards. The Post-Exam Phase showed partial recovery, with average concentrations falling to

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857 ± 92 ppm, though transient peaks still exceeded the 1,000ppm threshold.
Statistical analysis revealed a strong positive correlation between CO_2 levels and real-time student counts during exams ($r = 0.89$, $p < 0.001$), confirming the primary role of human respiration in CO_2 accumulation. A significant negative correlation was also observed between CO_2 concentrations and time elapsed post-occupancy ($r = -0.76$, $p < 0.001$), reflecting slow decay in the absence of adequate mechanical ventilation.

Compliance analysis with global indoor air quality guidelines (Table 3) indicates that while OSHA's permissible exposure limit of 5,000 ppm was not approached, thus affirming the absence of acute occupational hazard, other benchmarks were exceeded. For instance, the European EN 13779 standard (optimal range: 800–1,000 ppm) and Health Canada's indoor air quality threshold (1,000 ppm) were both violated during exam hours. These exceedances indicate suboptimal ventilation and highlight the need for active airflow management during high-occupancy periods.

Table 3: Compliance Assessment of CO_2 Concentrations with Indoor Air Quality Guidelines

Standard/Guideline	Recommended Limit	Baseline (435–602 ppm)	Exam Peak (1,682–2,450 ppm)	Compliance Status	Reference
ASHRAE 62.1	1,000 ppm	Compliant	Exceeded	Acceptable during baseline; exceeded during exam use	[29]
OSHA (8-hr TWA)	5,000 ppm	Safe	Safe	Well below occupational exposure threshold	[29]
EN 13779 (CEN, 2007)	800–1,000 ppm	Compliant	Exceeded	Indicative of inadequate ventilation during occupancy	[34]
Health Canada (2021)	1,000 ppm	Compliant	Exceeded	Exceeded during full occupancy; intervention recommended	[35]

These findings reinforce the importance of implementing dynamic ventilation protocols in examination environments, particularly within resource-constrained educational facilities in LMICs. Without mechanical ventilation or strategic ventilation breaks, CO_2 accumulation not only poses long-term health risks but also impairs short-term cognitive performance. Notably, the studies conducted by Cao and his team reported that CO_2 concentrations above 1,200 ppm can reduce decision-making efficiency and working memory by 10–20%, which may compromise student outcomes in high-stakes testing scenarios [36]

3.3 Volatile Organic Compounds (VOCs): Emission Patterns, Compound Classification, and Exposure Assessment

Total volatile organic compounds (VOCs) demonstrated episodic yet pronounced fluctuations during the 48-hour monitoring period, with concentrations directly linked to both preparatory and operational activities within the computer-based examination hall. Baseline concentrations during the Pre-Exam Phase averaged 132 ppb, a value compliant with most global indoor air quality (IAQ) guidelines (Table 4). However, peak concentrations during the Active Exam Period reached 553 ppb, thereby exceeding several critical health and comfort thresholds.
According to LEED v4.1 guidelines [37], widely adopted in green building certifications, the recommended limit for total VOC concentration is below 250 ppb (converted from 500 µg/m³ based on standard assumptions). The observed peak values during both the cleaning and exam periods exceeded this limit by more than 100%, indicating that the indoor environment failed to meet healthy air standards under full operational load. Similarly, Health Canada's short-term exposure threshold of 500 ppb was surpassed, while the ISO 16000-29 comfort guideline (< 300 ppb) was exceeded during high-activity periods. The German AgBB threshold of 500 ppb was approached but not exceeded, suggesting potential long-term advisory concern during prolonged exposure.
Period-specific compound classification based on likely sources and literature profiles provides additional insight into these patterns:

Pre-Exam Cleaning (210 ± 45 ppb → 680 ppb)
The sharp VOC increase during cleaning is consistent with the release of alcohols (ethanol, isopropanol) and terpenes (limonene, α-pinene) from aerosolized disinfectants, detergents, and fragranced cleaning products. Alcohols tend to evaporate quickly, producing short-lived but high-intensity peaks, while terpenes may linger slightly longer due to lower volatility.

Active Exam Period (195 ± 41 ppb → 553 ppb)
VOC elevation during examination activities likely reflects a mixture of aldehydes (formaldehyde, acetaldehyde) emitted from furniture surfaces, building materials, and thermal degradation of polymers in electronics, as well as aromatic hydrocarbons (toluene, xylenes) from printers,

markers, and electronic device casings. These compounds have longer indoor lifetimes than alcohols and can contribute both to odor and to chronic health concerns.

Post-Exam Idle (185 ± 39 ppb → 290 ppb)
The slow decline in VOC levels post-occupancy suggests residual emissions of semi-volatile aldehydes and ketones (acetone) from surface off-gassing. These are often released from composite wood products, adhesives, and flooring materials, persisting for hours after the source activity has ceased.
The dominance of rapidly evaporating alcohols and terpenes explains the steep pre-exam peaks, while aldehydes and aromatic hydrocarbons contribute to the sustained concentrations observed during and after the exam period. This pattern aligns with findings from similar IAQ studies in high-occupancy, equipment-intensive indoor environments, where mixed-source VOC profiles are common.

Table 4: VOC Emission Sources, Compound Classes, and Magnitude

Activity Period	VOC Baseline (ppb)	Peak VOC (ppb)	ΔVOC (ppb)	LEED Guideline (ppb)	Likely Source(s) & Dominant Compound Classes
Pre-Exam Cleaning	210 ± 45	680*	+470	250–500	Alcohols (ethanol, isopropanol), terpenes (limonene, α-pinene) from disinfectant aerosols
Active Exam Period	195 ± 41	553*	+358	250–500	Aldehydes (formaldehyde, acetaldehyde), aromatics (toluene, xylenes) from human activity, equipment usage
Post-Exam Idle	185 ± 39	290	+105	250–500	Aldehydes and ketones (acetone) from residual off-gassing of surfaces

*Exceeds LEED upper threshold by 40–180%. ΔVOC = peak minus baseline.

3.4 Environmental Conditions: Influence of Temperature, Humidity, and Pressure on Indoor Air Pollutants
Environmental parameters such as temperature, relative humidity, and barometric pressure, though not pollutants themselves, are critical determinants of indoor air chemistry. These microclimatic factors modulate the generation, transformation, and persistence of airborne contaminants, including particulate matter ($PM_{2.5}$), carbon dioxide (CO_2), and volatile organic compounds (VOCs). Table 5 presents a compliance evaluation of these parameters against internationally recognized indoor environmental standards, while Table 6 summarises their mechanistic influence on key pollutants.

3.4.1 Thermal Conditions and Air Quality Dynamics
According to ASHRAE (2020) and the World Health Organisation (WHO, 2018), the recommended indoor temperature range for thermal comfort and health is 22–26°C. However, measurements from this study revealed sustained thermal non-compliance, with average baseline and examination temperatures of 28 ± 0.5°C and 29 ± 0.5°C, respectively (Table 5).

Table 5: Compliance Assessment of Measured Environmental Parameters with International Indoor Standards.

Parameter	Standard/Guideline Range	Baseline (Mean ± SD)	Examination (Mean ± SD)	Compliance Status	Reference
Humidity (%)	30–70% (ASHRAE); ≤65% (Health Canada)	61 ± 5%	73 ± 4%	Baseline: Compliant; Exam: Marginal Excess	[29,35]
Temperature (°C)	22–26°C (ASHRAE/WHO)	28 ± 0.5°C	29 ± 0.5°C	Non-compliant for both conditions	[29,35]
Pressure (inHg)	~29.8–30 typical indoor (not regulated)	29.9 ± 0.03	29.9 ± 0.03	Not applicable	–

Elevated temperatures significantly affect indoor pollutant dynamics. For $PM_{2.5}$, increased thermal energy can promote resuspension behaviour settled particulates due to convection currents and occupant movement, especially in environments with limited filtration or poorly designed airflow paths. In addition, warmer indoor environments may lead to higher metabolic activity among occupants, indirectly increasing CO_2 concentrations via enhanced respiratory output. Although temperature is not a direct source of CO_2, its influence on human physiology and behavior can exacerbate the buildup in densely occupied zones [39].

More critically, temperature exerts a direct influence on VOCs. Higher ambient temperatures accelerate the volatilization of semi-volatile organic compounds, increasing emissions from building materials, disinfectants, electronics, and furniture finishes [40]. This phenomenon may explain the elevated VOC levels observed even during post-exam periods, as residual off-gassing continues under thermally stressed conditions. Thus, the temperature profile not only breaches comfort standards but also exacerbates chemical exposure risks (Table 6).

3.4.2 Humidity Levels and Pollutant Behaviour

Relative humidity remained within acceptable limits (61 ± 5%) during the baseline phase, conforming to both ASHRAE's recommended range of 30–70% and Health Canada's upper limit of 65% [29,35]. However, during active examination periods, it rose to 73 ± 4%, slightly exceeding the Health Canada threshold and indicating marginal moisture excess (Table 5).

High humidity environments are known to significantly influence $PM_{2.5}$ dynamics. Hygroscopic particles such as sulfates and nitrates can absorb water vapor, leading to growth in particle diameter and mass. This not only increases their deposition potential in the respiratory tract but can also interfere with the accuracy of sensor-based particle detection systems [35]. In some scenarios, elevated humidity promotes aggregation and surface adhesion, potentially reducing airborne concentrations but increasing deposition on surfaces, with implications for re-aerosolization and surface hygiene.

For CO_2, humidity plays an indirect but important role. High moisture levels can impair the perception of indoor air freshness and comfort, which is frequently misattributed to CO_2 accumulation. Moreover, humidity can affect the efficiency of HVAC systems, potentially impacting overall air turnover and pollutant dispersion.

In the case of VOCs, elevated humidity can act as a catalyst for chemical transformations, especially for carbonyl compounds like formaldehyde. Moisture facilitates secondary reactions between primary VOCs and oxidants, resulting in the formation of more toxic intermediates [42]. Additionally, high humidity reduces adsorption of VOCs onto porous surfaces, thereby prolonging their airborne residence time and increasing cumulative exposure (Table 6).

Table 6: Influence of Environmental Parameters on Indoor Air Pollutants ($PM_{2.5}$, CO_2, and VOCs)

Parameter	$PM_{2.5}$	CO_2	VOCs	Reference
Temperature	Resuspension of particles	Increased occupant generation	Enhanced volatilization and off-gassing	[29,35]
Humidity	Hygroscopic growth, aggregation	Indirect (perceived air freshness)	Longer airborne persistence; secondary reactions	[41]
Pressure	Controls movement (not source)	Affects containment/ventilation	Influences distribution, not generation	[41]

3.4.3 Barometric Pressure and Indoor Air Exchange

Barometric pressure values during both monitoring phases remained stable at 29.9 ± 0.03 inHg, falling within the expected range for typical indoor environments (Table 5). Although indoor pressure is not formally regulated, its influence on pollutant transport and exchange dynamics is well-documented [41].

A neutral or slightly positive pressure gradient indoors is generally desirable, as it limits infiltration of outdoor contaminants. However, in the absence of adequate ventilation or pressure differentials, pollutants such as CO_2 and VOCs can accumulate, particularly in enclosed or poorly ventilated zones. Pressure stability without directional flow may also limit pollutant removal, while pressure imbalances between rooms or zones can cause unintentional redistribution of airborne pollutants, particularly low-molecular-weight gases such as VOCs [42].

3.5 Integrated Risk Assessment and Mitigation Strategies

The integrated assessment of indoor air quality (IAQ) in computer-based examination halls presents a compelling and coherent profile of environmental health risks, particularly within low- and middle-income countries (LMICs). As revealed in the preceding analyses, the several key risk vectors are the Acute $PM_{2.5}$ exposure spikes during high-activity periods, often exceeding international safety thresholds; Sustained CO_2 concentrations well above cognitive performance impairment levels; Complex mixtures of volatile organic compounds (VOCs) arising from diverse sources including cleaning agents, human presence, and electronic equipment and Amplified pollutant persistence due to tropical climate conditions (e.g., high temperature and humidity), exacerbating chemical and physical processes such as hygroscopic growth and off-gassing. These risks are emblematic of the infrastructural and operational constraints typical of LMIC educational settings. Accordingly, mitigation strategies must be low-cost, scalable, and contextually appropriate.

4.0 CONCLUSION

This study makes a significant contribution to the growing field of indoor atmospheric science in developing regions by establishing examination halls as chemically and physically distinct microenvironments that demand tailored indoor air quality (IAQ) strategies. It underscores the climate-mediated amplification of pollutant effects in tropical settings and offers a scalable, evidence-based framework for IAQ assessment and intervention in resource-constrained contexts. Engineering solutions such as CO_2-triggered ventilation, air filtration, and redesign of exam hall layouts should be coupled with administrative strategies like exam scheduling and fragrance-free policies. Beyond their practical implications, the results also provide valuable insight into the indoor environmental chemistry of high-stress academic environments, thereby contributing to the emerging field of indoor atmospheric science.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability Statement

All data supporting this study are available upon request from the corresponding author.

Authors' Contribution

All authors contributed substantially to the conception, design, data analysis, interpretation, and manuscript preparation. Each author has reviewed and approved the final version of this manuscript.

Authors' Declaration

The manuscript is original, has not been published elsewhere, and is not under consideration by any other journal. The authors accept full responsibility for the content and any claims arising from this work.

Ethical Declarations Human/Animal Studies

The authors declare that no human/animal was used for the studies

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