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Research Article

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Spatio-Temporal Assessment of Classroom Air Quality and Thermal Comfort as Determinants of Respiratory Health Risks in Urban Pre-Tertiary Institutions

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Abstract

Poor indoor environmental quality (IEQ) remains a significant driver of pediatric morbidity, yet data on the interplay between particulate matter (PM), building design, and health in tropical schools are sparse. In this study, the spatio-temporal dynamics of classroom air quality and thermal comfort were investigated to identify the key environmental determinants of respiratory health risks among primary and secondary school students in Benin City, Nigeria. IEQ parameters ($PM_{2.5}$, PM_{10}, CO, and CO_2) and thermal indices were monitored across six schools for ten weeks. Health data were collected through modified BMR questionnaires and analysed using descriptive, inferential, and multivariate logistic regression. To estimate non-carcinogenic health risks, the hazard quotient (HQ) was calculated using the United States Environmental Protection Agency (US EPA) framework. The $PM_{2.5}$ and PM_{10} concentrations ranged from 11.2–81.4 µg/m³ and 20.1–138.6 µg/m³, respectively. The CO_2 concentration peaked at 729.3 ± 28.4 ppm, while high temperature–humidity index (THI) values (28.3–30.1) indicated severe heat discomfort. Health risk assessment revealed that all HQ values for $PM_{2.5}$ and PM_{10} remained below unity (HQ < 1), suggesting that students were not at immediate risk of chronic non-carcinogenic effects; however, respiratory symptoms were highly prevalent: coughing (58.2%), phlegm (32.5%), and chest pain (26.7%). Multivariate analysis revealed that high PM risk was a near-perfect predictor of coughing ($p < 0.001$) and significantly increased the odds of chest pain (Crude OR = 2.74; $p = 0.001$). Poor sanitation was the strongest predictor of phlegm production (AOR = 5.54; 95% CI: 1.35–22.80; $p = 0.018$) after adjustment for confounders, including age, sex, and socio-economic status. This study highlights the critical link between a school-built environment and students' respiratory health. While chronic risk thresholds (HQs) were not exceeded, particulate matter and sanitation were the primary drivers of acute respiratory symptoms. These findings suggest that targeted spatio-temporal interventions, such as improved cleaning protocols and air quality policies, are essential for mitigating health risks and optimizing the learning environment.

Keywords: Indoor air quality, Particulate matter, Respiratory symptoms, Thermal comfort, School health policy, Logistic regression.

Introduction

Air pollution in schools indicates a critical environmental challenge, manifesting as the presence of hazardous contaminants in both indoor and outdoor settings that significantly impair student health, cognitive development, and academic performance (Gartland et al., 2022). Globally, educational facilities are often burdened by particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide

(NO_2), carbon dioxide (CO_2), and volatile organic compounds (VOCs), stemming from complex interactions between internal sources such as building materials and cleaning agents, and external drivers such as industrial emissions and heavy traffic (Manisalidis et al., 2020, Anake and Nnamani, 2023). Children are uniquely susceptible to these environmental stressors due to their developing immunological systems and higher respiratory rates relative to body size, which increase their effective dose of inhaled toxins (Aithal et al., 2023; Ha, 2021). Beyond chemical pollutants, the physical microenvironment, characterized by air temperature and relative humidity, plays a pivotal role in human well-being. The "comfort index," a metric that integrates these meteorological factors, directly influences productivity and general well-being; for students, maintaining an ideal thermal comfort level is essential for concentration and academic success (Yang et al., 2022; Dominguez-Amarillo et al., 2020).

In Nigeria, air pollution levels frequently exceed international permissible limits because of unregulated vehicle emissions, biomass burning, and fossil fuel combustion (Okedere et al., 2021). Indoor air quality (IAQ) in many Nigerian schools is further compromised by outdated infrastructure, limited ventilation, and the pervasive use of diesel generators to compensate for unstable energy supplies, which introduce dangerous concentrations of carbon monoxide (CO) and nitrogen oxides (NOx) directly into the classroom microenvironment (Toyinbo et al., 2019). While developed nations in the U.S. and EU benefit from extensive regulatory frameworks such as the EPA's Indoor Air Quality Tools for Schools, which mandate routine monitoring and strict enforcement, Nigeria lacks comprehensive national standards tailored to the unique requirements of educational settings (Chatzidiakou et al., 2023; Toyinbo et al., 2019). This regulatory vacuum, compounded by fragmented oversight and insufficient funding for monitoring programs, leaves a vast majority of the 229.94 million population, particularly those in urban centers such as Benin City in Nigeria, without necessary safeguards against environmental hazards (Ilaboya and Otuaro, 2021).

The health implications of these environmental stressors are profound, with high concentrations of $PM_{2.5}$ and VOCs being linked to a high incidence of bronchitis, asthma, and long-term cardiovascular disorders (Maji et al., 2023). Furthermore, poor thermal comfort, marked by high temperatures and humidity, leads to fatigue, decreased attention spans, and increased absenteeism (Makaremi et al., 2024; Ragab et al., 2025). Despite these known risks, there is a glaring research gap in Nigeria regarding localized, high-resolution data that integrates spatio-temporal air quality variations with biometeorological comfort indices. Most existing studies focus on general urban air quality rather than the specific classroom microenvironments where children spend a significant portion of their day (Brumberg and Karr, 2021). There is a critical need to establish the indoor-to-outdoor (I/O) ratio of pollutants to understand penetration efficiency and to model the correlation between these stressors and student respiratory distress.

The significance of this study lies in its potential to provide a data-driven baseline for school administrators and policymakers to implement targeted interventions. By quantifying the inhalation health risk through the average daily dose (ADD) and hazard quotient (HQ), this research moves beyond simple monitoring to provide a comprehensive toxicological risk profile. Consequently, this study aims to conduct a comparative spatio-temporal analysis of indoor-outdoor air quality (CO, CO_2, $PM_{2.5}$, and PM_{10}) and comfort indices (the heat-index and THI) across selected public and private secondary schools in Benin City. Specifically, it seeks to

characterize pollutant variations, evaluate microclimatic diurnal trends, quantify thermal stress, establish the I/O pollutant penetration efficiency, assess the prevalence of respiratory symptoms among students, and model the primary environmental drivers of health risks to inform strategies for a safer, more productive learning environment.

Methodology

Study area

This research was conducted in Benin City, the capital of Edo State, located within Nigeria's southern tropical rainforest belt. Geographically, the city is defined by latitudes of 6°11'N to 6°29'N and longitudes of 5°33'E to 5°47'E, with an average elevation of 77.8 m. (Figure 1). The region is characterized by high annual precipitation (2000–3000 mm) and elevated relative humidity levels (75–80%). Benin City experiences two distinct seasons: a wet season featuring a brief "August break" and a dry season marked by dusty, northeasterly Harmattan winds between December and January. Administratively, the metropolis comprises five local government areas (LGAs): Oredo, Ikpoba-Oka, Ovia North–East, Egor, and Uhunmwonde.

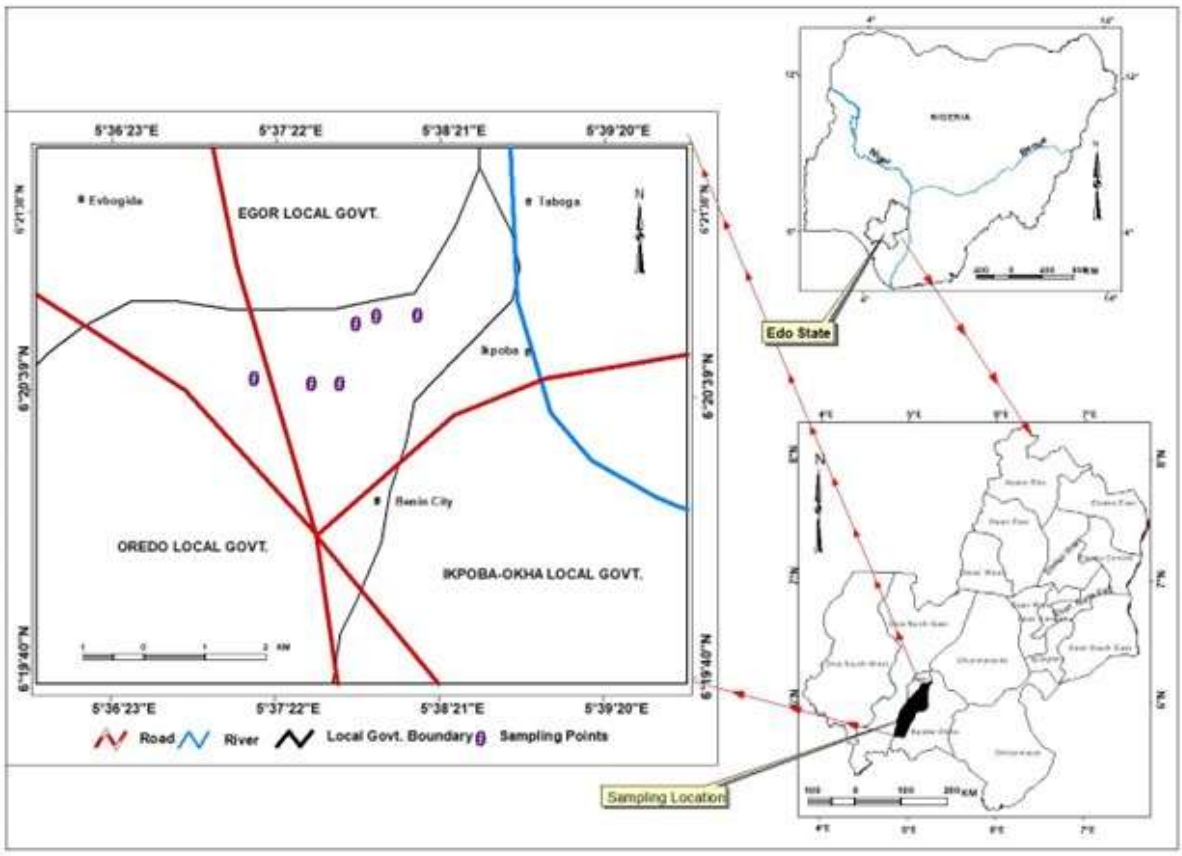


Figure 1: Map of Benin City showing the sampling sites

Description of Sampling Sites

For this study, a total of six schools were selected within the Oredo LGA to provide a comparative analysis of the indoor and outdoor air quality. These include three secondary schools and three primary schools, categorized by their distinct architectural designs, occupant densities, and proximity to external pollution sources. The geographical coordinates and physical characteristics of these sites are summarized in Table 1.

Table 1: Detailed Comparative Characteristics of the Sampling Sites

Sampling sites	Coordinates	Building Type	Ventilation	Avg. Occupancy	External Environment
SS1	6.3469°N, 5.6195°E	Bungalow blocks	Natural (Windows/Doors)	30	Near Main Road
SS2	6.3464°N, 5.6290°E	One-story concrete	Windows, Door, Fan	15	Near Mission Road
SS3	6.3540°N, 5.6349°E	3-Story concrete	Windows, Door, Fan	~50+	Near New Benin Market
PS1	6°21'14"N, 5°38'0"E	Clustered Bungalow	Natural (Windows/Doors)	30–35	Road and Marketplace
PS2	6°21'11"N, 5°38'1"E	3-Story concrete	Natural (Windows/Doors)	10–15	Road and Marketplace
PS3	6°20'47"N, 5°37'46"E	Concrete complex	Natural (Windows/Doors)	10–15	Road and Marketplace

For this study, a total of six schools were selected within the Oredo LGA to provide a comparative analysis of the indoor and outdoor air quality. These include three secondary schools and three primary schools, categorized by their distinct architectural designs, occupant densities, and proximity to external pollution sources.

SS1: This is a vast, open-air public institution located a short distance from the main road. The senior secondary section includes five bungalow buildings. Each block is divided into three fairly spacious classrooms with cemented floors and whiteboards. Ventilation is heavily reliant on windows and two metal doors per room. Each sampled classroom housed approximately thirty students.

SS2: Located close to Mission Road, this private facility utilizes a one-story building for its secondary section. The classrooms are medium-sized with a single entry/exit door and whiteboards. Ventilation is facilitated by windows, a door, and a ceiling fan. Occupancy is relatively low, with approximately fifteen students per sampled classroom.

SS3: Situated near the New Benin Market, this institution uses a three-story concrete building for its secondary section. The classrooms are small, cramped, and filled to near maximum capacity with at least fifty students. Ventilation relies on windows, doors, and a ceiling fan.

PS1: This school consists of clustered bungalows near a road and marketplace. Classrooms are staffed by one teacher for every 30–35 pupils. The school has approximately 18 teachers and a total of 540–630 pupils. Ventilation is natural (open windows and doors), and marker boards are used in every classroom.

PS2: The primary section is housed in a three-story building. Classrooms have a low occupant density of 10–15 pupils per teacher. The school is situated near a road and a marketplace. Ventilation is strictly natural through open windows and doors; no ceiling fans or marker boards are utilized.

PS3: This institution features creche, primary, and secondary sections. The primary section classrooms house 10–15 pupils per teacher. Like the other primary sites, it is near a road and marketplace and depends entirely on open ventilation through windows and doors.

Air Quality and Microclimate Monitoring

The concentrations of criteria air pollutants (CO, CO_2, $PM_{2.5}$, and PM_{10}) and microclimatic parameters (air temperature and relative humidity) were monitored concurrently using a BOSEAN Multi-Gas Detector. This real-time, portable instrument employs high-precision electrochemical sensors for gaseous detection and the light-scattering (laser diffraction) method for particulate matter quantification. Monitoring was conducted weekly for a duration of 10 weeks, spanning the peak academic period (September to November 2024). Sampling was strategically timed between 08:00 and 13:00 to coincide with the peak hours of classroom occupancy and metabolic activity. To determine the penetration efficiency of pollutants, measurements were taken simultaneously in both the indoor and outdoor classroom environments across the six selected secondary and primary schools (SS1, SS2, and SS3, PS1, PS2, and PS3, respectively). At each sampling location, the device was positioned at a height of 1.5 to 2.0 meters above ground level, approximating the human breathing zone and avoiding the influence of floor-level fugitive dust. To ensure statistical representativeness, data were collected in triplicate at 5-minute intervals. By taking three readings at 5-minute intervals for every parameter, the impact of random errors and spikes caused by transient events such as a single vehicle passing the school or a momentary burst of classroom activity was minimized. During outdoor sampling, the sensors were shielded from direct sunlight and wind gusts to prevent thermal interference with the electrochemical sensors and to ensure stable laminar flow through the particulate intake. The instrument was allowed to stabilize at each point, and the stabilized mean values were recorded for subsequent analysis. The raw data were screened for outliers. Any readings deviating by more than two standard deviations from the triplicate mean were re-evaluated for instrumental error.

Quality Assurance and Quality Control (QA/QC)

To ensure the precision, accuracy, and reproducibility of the data, the BOSEAN Multi-Gas Detector underwent a two-stage calibration process following the manufacturer's specifications and the WHO (2021) guideline. Zero calibration was performed before each sampling trip in a clean-air environment to ensure that the sensors were free from residual contaminants and "drift." A span calibration was also performed periodically to verify the sensor's response to known concentrations of target gases, ensuring that the light-scattering mechanism for particulates

remained consistent across varying humidity levels. Regular calibration is essential to minimize sensor drift, a common phenomenon in electrochemical and optical sensors where environmental factors such as high tropical humidity (75–80% in Benin City) can interfere with signal accuracy.

Determination of Comfort Indices

The comfort index is a physiological metric used to quantify human thermal perception within a specific microenvironment. It integrates ambient air temperature and relative humidity to determine the suitability of a space for improving cognitive productivity and health (Noviani et al., 2023). In this study, thermal stress is characterized using two distinct indices:

Temperature–Humidity Index (THI)

The THI provides a linear assessment of comfort based on the synergistic effect of heat and moisture. It is calculated using the following formula (Noviani et al., 2023):

$$THI = 0.8T_a + \frac{RH \times T_a}{500} \qquad \text{Eqn 1.}$$

where:
Ta = Air temperature (°C)
RH = relative humidity (%)
Classification Scale for THI
<15: Cold discomfort
15–19: Cool, but comfortable
19–26: Comfortable (Optimal learning zone)
26–29: Uncomfortable
>29: Severe heat discomfort

Heat Index (HI)

The heat index, often referred to as the "apparent temperature," estimates how hot the classroom environment actually feels to the human body by adjusting for the cooling effect (or lack thereof) of evaporation. It is particularly relevant for the tropical climate of Benin City and is determined as follows (Hoang et al., 2022):

$$HI = T + H \qquad \text{Eqn 2.}$$

Classification Scale for the HI
<27: Comfortable
27–32: Caution (Fatigue possible with prolonged exposure)
32–41: Extreme Caution (Heat cramps and exhaustion possible)
41–54: Danger (Heat stroke likely)
>54: Extreme Danger

Penetration Efficiency and I/O Ratio

To establish the relationship between the classroom microenvironment and the external atmosphere, the indoor-to-outdoor (I/O) ratio is calculated for each measured pollutant (CO, CO_2, $PM_{2.5}$, and PM_{10}). This ratio serves as a proxy for the penetration efficiency of ambient pollutants and the strength of internal emission sources.

$$\text{I/O Ratio} = \text{Cindoor/Coutdoor} \qquad \text{Eqn 3.}$$

where:
Cindoor represents the concentration of pollutants inside the classroom.
Coutdoor = concentration of pollutants measured simultaneously outside the school building.
Interpretation of Results
I/O>1: indicates the presence of significant internal sources
I/O<1: Indicates that the school's building envelope

Inhalation Health Risk Assessment

To estimate the noncarcinogenic health risks associated with the inhalation of particulate matter (PM2.5 and PM10) and gaseous pollutants (CO) during school hours, the average daily dose (ADD) and hazard quotient (HQ) will be calculated on the basis of the US EPA risk assessment framework (US EPA, 2011). The specific input parameters, standard values, and primary references used for these calculations are summarized in Table 2.

Table 2: Input Parameters for ADD and HQ Calculation

Parameter	Description	Standard Value / Source Unit	Primary Reference
C	Concentration of Pollutant	Variable (μg/m^3)	
IR	Inhalation Rate	10 m^3/day (School-age children)	U.S. EPA (2011)
ED	Exposure Duration	Variable (Years)	U.S. EPA (2011)
EF	Exposure Frequency	200 days/year (Nigerian school calendar)	Owoade et al. (2013)
ET	Exposure Time	5 hours/day (08:00 to 13:00)	Sadrizadeh et al. (2022)
BW	Average Body Weight	Variable (kg)	U.S. EPA (2011)
AT	Averaging Time	ED×365 days	U.S. EPA (2011)
RfC	Reference Concentration	Pollutant-specific benchmark	U.S. EPA IRIS Database

Calculation of the average daily dose (ADD)

The ADD represents the amount of a pollutant inhaled per kilogram of body weight per day. It is calculated using the following formula:

$$\mathrm{ADD} = \mathrm{C} \times \mathrm{IR} \times \mathrm{ED} \times \mathrm{EF} \times \mathrm{ET}/\mathrm{BW} \times \mathrm{AT} \quad \text{Eqn 4.}$$

where:
C: Concentration of the pollutant ($\mu g/m^3$).
IR: Inhalation rate (m^3/day). For school-age children, a standard rate of 10 m^3/day is typically applied.
ED: Exposure duration (Years).
EF: Exposure frequency (days/year). Usually, 200 days for a standard Nigerian school calendar.
ET: Exposure Time (Hours/Day). It is calculated as 5 hours (08:00 to 13:00).
BW: average body weight (kg).
AT: Averaging Time (ED×365 days).

Determination of the Hazard Quotient (HQ)

The hazard quotient is used to determine if the exposure levels exceed the reference concentration (RfC), which is the level at which no adverse health effects are expected.

$$\mathrm{HQ} = \mathrm{ADD}/\mathrm{RfC} \quad \text{Eqn 5.}$$

where:
RfC: Reference concentration for the specific pollutant (obtained from the US EPA IRIS database).
Risk characterization
HQ≤1: Indicates that adverse non-carcinogenic health effects are unlikely.
HQ>1: This indicates the potential for adverse health effects, suggesting that the school microenvironment poses a significant respiratory risk to students.

Respiratory Health Assessment

A comparative epidemiological assessment was conducted to evaluate the prevalence of respiratory symptoms among students across the six selected schools. This cross-sectional survey utilized a structured approach to link environmental exposure with health outcomes.

Selection of Respondents and Sampling Technique

A total of 200 respondents were selected for the study. To ensure a balanced comparative analysis between the two educational tiers, the sample was split equally. One hundred pupils were selected from secondary and primary schools, and a stratified random sampling technique was employed within each school to ensure representation across different grade levels and classroom blocks, accounting for varying occupant densities and ventilation configurations.

Tool Validation and Reliability

The research instrument was a well-structured questionnaire adapted from validated respiratory health tools (Toyinbo et al., 2019). Before full-scale administration, a pre-test was conducted with 10 respondents (not included in the final study) to assess clarity, wording, and timing. The reliability of the questionnaire was statistically verified using Cronbach's alpha. A coefficient of 0.8 was obtained, indicating high internal consistency and reliability of the scale items.

Questionnaire Components

The tool was designed in three sections to capture primary outcomes and potential modifiers: Section A (Household Information): Captured demographics (age, sex), socio-economic status (parental income/occupation), and home-based stressors (cooking fuel, smoking status, and proximity to highways). Section B (School Environment): Details the microenvironment, including school type, cooling systems, writing materials (chalk vs. marker), cleaning frequency, and the presence of visible moulds or generators. Section C (Respiratory Health Outcomes): Focused on five key validated symptoms experienced within the past 12 months: cough, phlegm, wheezing/whistling, shortness of breath, and chest tightness.

Inclusion criteria: Pupils/students must have been enrolled in the school for at least one academic year to ensure sufficient exposure to the microenvironment.

Exclusion criteria: Individuals with physician-diagnosed chronic conditions such as tuberculosis or pre-existing clinical asthma (prior to enrolment) were excluded to prevent the skewing of results toward non-environmental baseline illnesses.

Identification of Confounding Variables

To isolate the impact of school-based air quality, the study identified and controlled for several confounders integrated within the questionnaire. These variables are external factors that could independently cause respiratory symptoms: socio-demographic factors, the use of biomass/firewood for cooking, and household floor materials (such as rugs/carpets that harbour allergens). Exposure to second-hand smoke at the child's residence. Parental income often dictates nutritional and general health access.

Data Analysis

Statistical analyses were performed using IBM SPSS (Version 26.0) and Microsoft Excel 2021, with the threshold for statistical significance set at $p<0.05$ for all tests. Environmental and microclimatic assessments involved the calculation of descriptive statistics, including arithmetic means and standard deviations (SDs), for all criteria air pollutants and meteorological parameters, such as temperature and relative humidity. Integrated multi-panel boxplots were constructed to visualize the distributions of pollutants across the six sampling sites (SS1–SS3 and PS1–PS3). The variation in air quality over the 10-week monitoring period was characterized using time series line graphs with weekly mean values, while significant differences across locations were determined using one-way ANOVA. The prevalence of respiratory symptoms (cough, phlegm,

wheezing, shortness of breath, and chest tightness) was expressed as a percentage, and the chi-square ($\chi 2$) test of independence was employed to determine associations between reported risk variables and symptom prevalence. Multiple logistic regression models were employed to estimate crude and adjusted odds ratios (AORs) with 95% confidence intervals (CIs) for reported respiratory symptoms. Environmental predictors were dichotomized into 'High Risk' (exceeding regulatory limits) and 'Low Risk' based on total pollutant concentrations ($PM_{2.5}$ and PM_{10}). The analysis further incorporated thermal comfort indices (THI and HI) as key independent variables, while adjusting for potential socio-demographic and household confounders, including primary cooking fuel, flooring materials, parental socioeconomic status, and exposure to environmental tobacco smoke (ETS).

Results

Spatial variations in air pollutants and meteorological parameters

The descriptive statistics for the indoor and outdoor air pollutants and meteorological parameters across the six sampling sites (secondary schools: SS1–SS3 and primary schools: PS1–PS3) are summarized in Table S1. The boxplots in Figure 2 illustrate the distribution and central tendencies of each variable, with the "X" notation representing the mean value. Indoor particulate matter concentrations showed notable spatial variation; the concentrations of $PM_{2.5}$ ranged from 42.4 ± 15.4 μg/m³ (PS1) to 67.6 ± 34.7 μg/m³ (SS3). Compared with the indoor concentrations, the outdoor $PM_{2.5}$ concentrations at secondary school sites often exhibited higher variability and slightly higher median values, whereas compared with the primary school sites, the primary school sites presented more balanced distributions of indoor and outdoor concentrations. The observed indoor PM_{10} concentration reached 101.4 ± 52.1 μg/m³ at SS3, as shown in Figure 1, revealing a significant spread of data and higher indoor medians than outdoor values across most of the sites. The indoor carbon dioxide (CO_2) levels were notably higher than the outdoor levels across all the sites, peaking at 607.3 ± 234.2 ppm (PS1). The boxplot for CO_2 reveals several indoor outliers at SS1, SS2, and PS2, suggesting periodic spikes in occupancy or reduced ventilation during specific sampling intervals. Indoor carbon monoxide (CO) concentrations remained low overall, ranging from 0.57 ± 0.81 ppm to 1.13 ± 0.77 ppm, with PS1 having the highest mean and median concentrations. The meteorological conditions were largely consistent, as evidenced by the tight distributions shown in Figure 1. Indoor temperatures ranged from 29.2 ± 1.2°C to 30.1 ± 1.7°C, while relative humidity (RHi) fluctuated between 55.6 ± 12.5% and 62.1 ± 4.4%. The overlap between the indoor and outdoor boxes for both temperature and humidity suggest that the building envelopes provide limited thermal buffering from the outdoor environment. One-way ANOVA revealed highly significant variations across the six locations for all measured indoor and outdoor parameters ($p<0.001$) (S2). Specifically, the spatial dependence of the indoor particulate matter was strong, with the differences in the concentrations of $PM_{2.5}$ ($F=14.24$; $p<0.001$) and PM_{10} ($F=30.50$; $p<0.001$) being the most pronounced. Significant variations were also confirmed for the concentrations of indoor gases, including CO ($F=6.85$; $p<0.001$) and CO_2 ($F=6.33$; $p<0.001$), as well as thermal comfort parameters such as TEMP ($F=7.38$; $p<0.001$) and RH ($F=6.32$; $p<0.001$). Similar statistically significant trends were observed for all the outdoor areas ($p<0.001$), with CO and CO_2 having particularly high F values (25.60 and 21.63, respectively), indicating that the ambient air quality and meteorological baseline significantly differed between the primary and secondary school neighbourhoods.

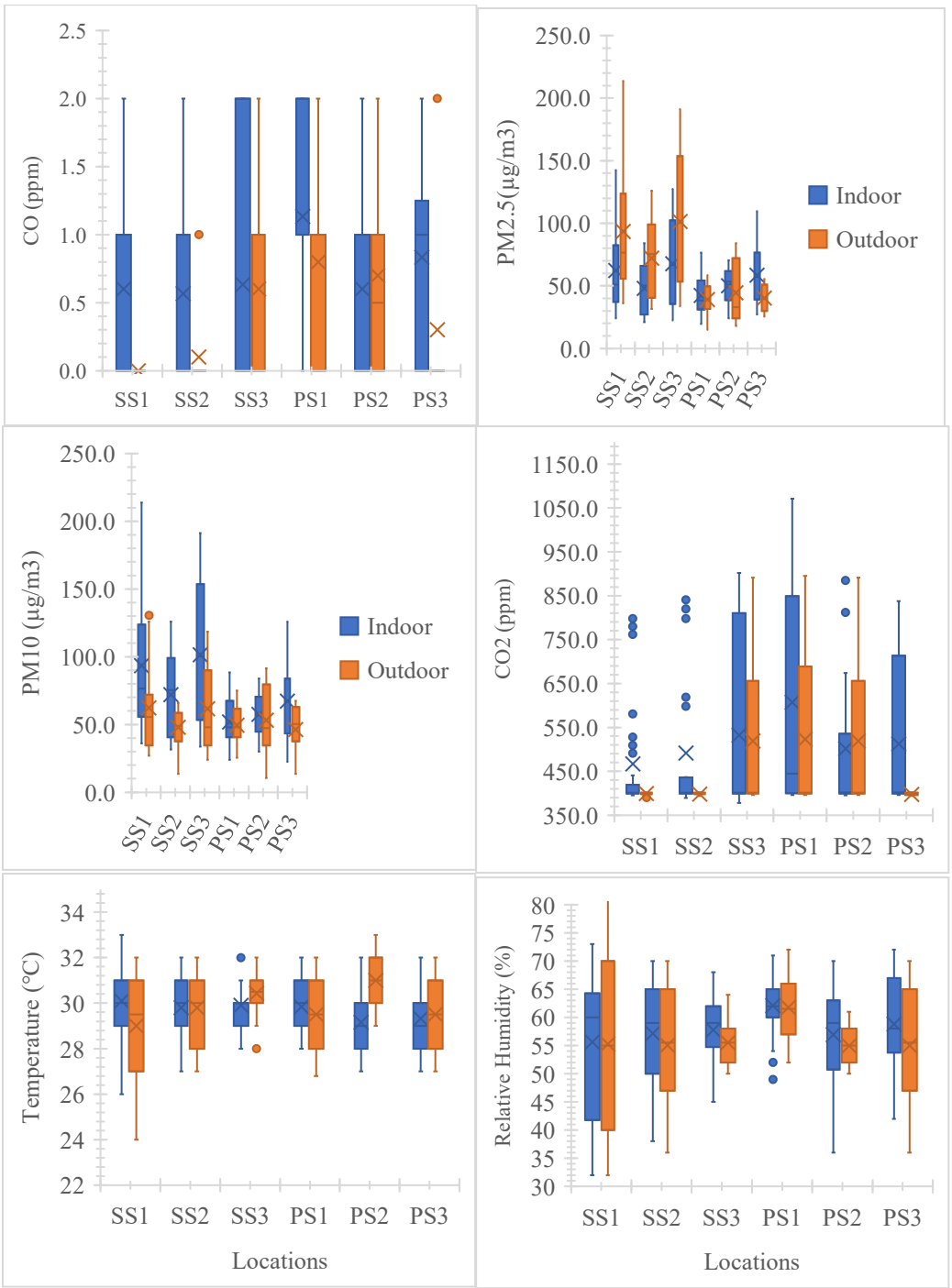


Figure 2. Spatio-temporal distribution of indoor and outdoor air pollutants and meteorological parameters across school sites. "**X**" represents the mean, and dots represent outliers.

Weekly Temporal Variation in Air Quality Parameters

The temporal variations in the air quality parameters across the ten-week study period are presented in Figure 3. The analysis of weekly mean concentrations revealed significant temporal shifts for both particulate and gaseous pollutants. Weekly concentrations of $PM_{2.5}$ and PM_{10} remained relatively stable and lower during weeks 1 to 5. A substantial increase was observed starting at week 6, with the concentration of $PM_{2.5}$ increasing from approximately 42.1 ± 1.0 µg/m³ during week 4 to a peak of 77.9 ± 2.6 µg/m³ during week 8. The concentration of PM_{10} followed an identical trend, peaking at 102.2 ± 5.0 µg/m³ during week 8. Throughout the study, indoor particulate matter levels consistently remained higher than outdoor levels did, particularly during the peak period in the following weeks. Conversely, CO_2 levels were highest during the initial three weeks, with a maximum mean of 729.3 ± 28.4 ppm in Week 2. After Week 3, the concentrations decreased sharply and stabilized near 400 ppm from Week 6 through Week 10. This stabilization at ambient levels suggests a significant change in classroom ventilation or occupancy patterns during the second half of the study. Indoor CO concentrations peaked early in Week 2 at 1.6 ± 0.1 ppm before a general downwards trend was observed. By the final weeks of the study, concentrations remained minimal, fluctuating between 0.2 and 0.5 ppm.

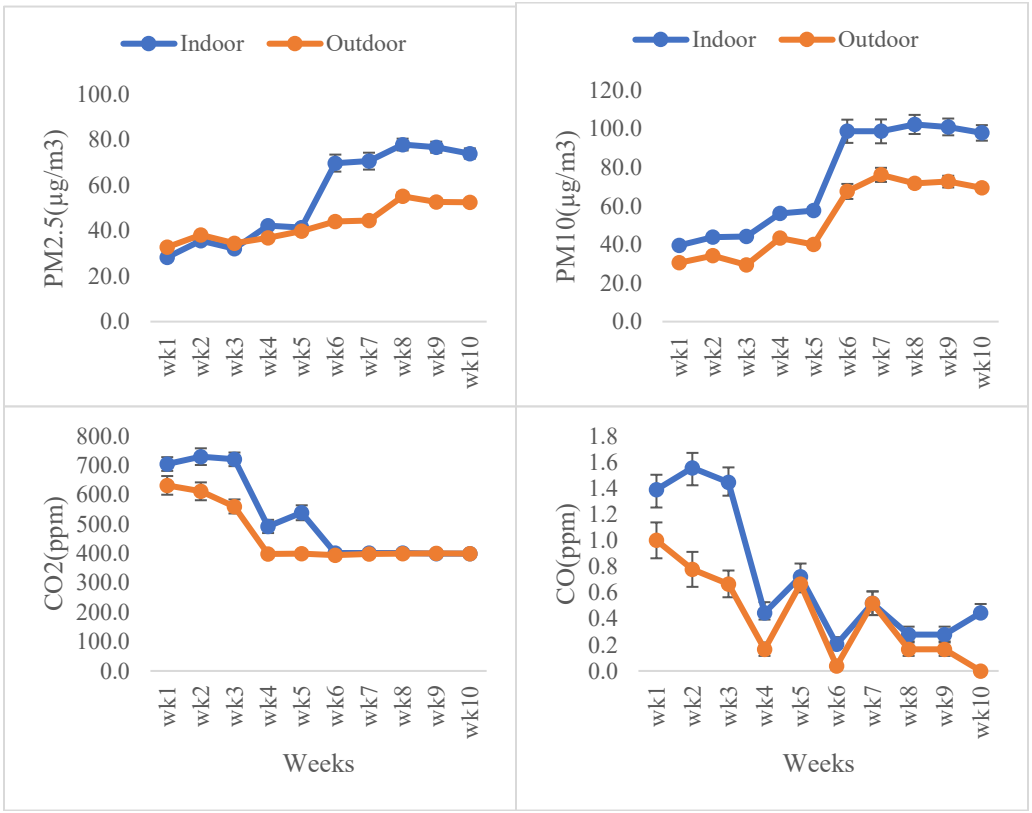


Figure 3. Weekly temporal variations in the indoor and outdoor air quality parameters

Indoor-to-Outdoor (I/O) Concentration Ratios

The relationships between the indoor air quality and the surrounding outdoor environment and the indoor-to-outdoor (I/O) ratios are presented in Figure 4. An I/O ratio greater than 1.0 typically suggests the presence of significant indoor sources or the accumulation of pollutants due to inadequate ventilation. The I/O ratios for $PM_{2.5}$ across all the sites remained consistently above the unity line, ranging from 1.08 (SS2/PS1) to a peak of 1.51 (SS3). Similarly, the I/O ratios of PM_{10} ranged from 1.05 (PS1) to 1.65 (SS3). These values indicate that indoor particulate matter concentrations were significantly higher than those measured outdoors, particularly in secondary school locations. The I/O ratio for CO showed the highest degree of variability, ranging from a low of 0.20 (SS1) to an exceptionally high peak of 5.71 (SS2). While most sites hovered near or slightly above 1.0, the extreme ratio at SS2 suggests localized indoor combustion or specific events during the sampling period. The CO_2 I/O ratios ranged from 0.97 (PS2) to 1.29 (PS3). With the exception of PS2, all the site-maintained ratios were above 1.0. The highest ratios were observed at PS3 and SS2, suggesting that these locations may experience lower air exchange rates than the other locations do.

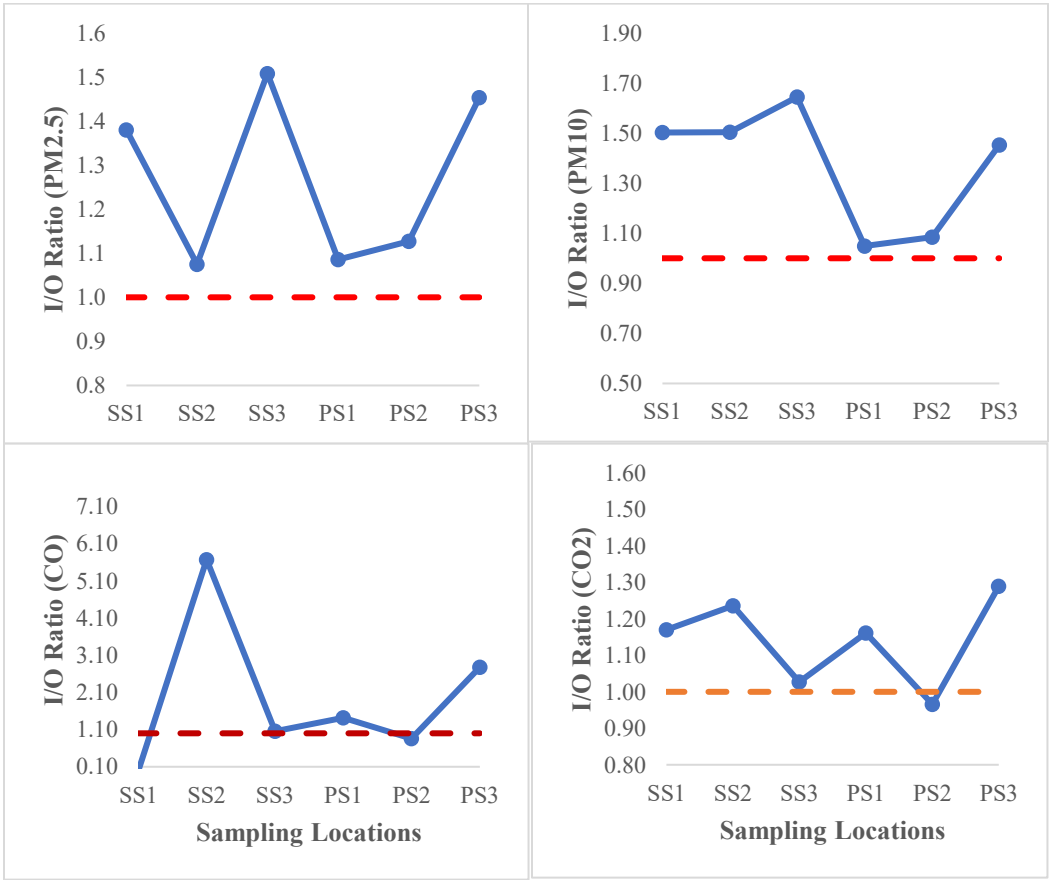


Figure 4. Indoor-to-Outdoor (I/O) Ratios

Correlation between Microclimate and Pollutant Levels

To evaluate the influence of environmental conditions on air quality, a Pearson correlation analysis was conducted between microclimate variables (temperature and relative humidity) and pollutant concentrations. The results of the influence of environmental conditions on air quality presented in Table 3 reveal significant relationships across nearly all the measured parameters. Relative humidity displayed a consistent and significant inverse relationship with particulate matter. Both the indoor and outdoor RHs were strongly negatively correlated with the concentrations of $PM_{2.5}$ and PM_{10}. Indoor RH correlated with $PM_{2.5}$ at -0.527 and with PM_{10} at -0.487 ($p<0.01$). The outdoor RH showed even stronger negative associations with indoor particulates ($PM_{2.5}$: -0.540; PM_{10}: -0.510). These findings suggest that drier conditions facilitate the suspension and accumulation of dust particles in the school environment. Conversely, RH was positively correlated with gaseous pollutants. Indoor RH was significantly positively correlated with CO (0.386) and CO_2 (0.436). Temperature exhibited the opposite trend to that of humidity, generally showing positive correlations with particulate matter and negative correlations with gases. Indoor temperature was positively correlated with $PM_{2.5}$ (0.344) and PM_{10} (0.368). The outdoor temperature followed a similar trend, showing positive correlations with all the particulate categories. The temperature was significantly negatively correlated with the concentration of indoor gases. Specifically, the indoor temperature correlated negatively with CO (-0.239) and CO_2 (-0.359) at the 0.01 significance level.

Table 3: Correlations between Microclimate and Pollutant Levels

Microclimate Variable	$PM_{2.5}$i	PM_{10}i	COi	CO_2i	$PM_{2.5}$o	PM_{10}o	COo	CO_2o
Indoor RH	-0.527**	-0.487**	-0.386**	0.436**	-0.445**	-0.411**	0.250**	0.254**
Indoor Temp	0.344**	0.368**	-0.239**	-0.359**	0.230**	0.322**	-0.093*	-0.216**
Outdoor RH	-0.540**	-0.510**	-0.358**	0.427**	-0.307**	-0.362**	0.118**	0.123**
Outdoor Temp	0.308**	0.314**	-0.181**	-0.252**	0.166**	0.330**	0.166**	-0.029

i=indoor, o=outdoor, ** Correlation is significant at the 0.01 level; * at the 0.05 level

Thermal Comfort and Heat Stress Analysis

The spatial distributions of the THI and HI values across the sampling sites are presented in Figure 5. The Indoor THI values, ranked from lowest to highest mean, were recorded as follows: PS2 (28.3) < PS3 (28.4) < PS1 (28.8) < SS2 (28.8) < SS3 (28.9) < SS1 (29.1). On the basis of the THI classification scale, all the classrooms fall within the "Uncomfortable" (26–29) to "Severe heat discomfort" (>29) zones. Specifically, site SS1 exceeded the threshold for severe discomfort. Given that the "Optimal learning zone" is defined as 19–26, every sampled classroom significantly exceeds the reference value for a productive learning environment. The indoor HI values, ranked from lowest to highest, were as follows: PS2 (29.2) < PS3 (29.3) < PS1 (29.8) < SS2 (29.8) < SS3

(29.9) < SS1 (30.1). All the calculated mean HI values fell within the "Caution" (27–32°C) category.

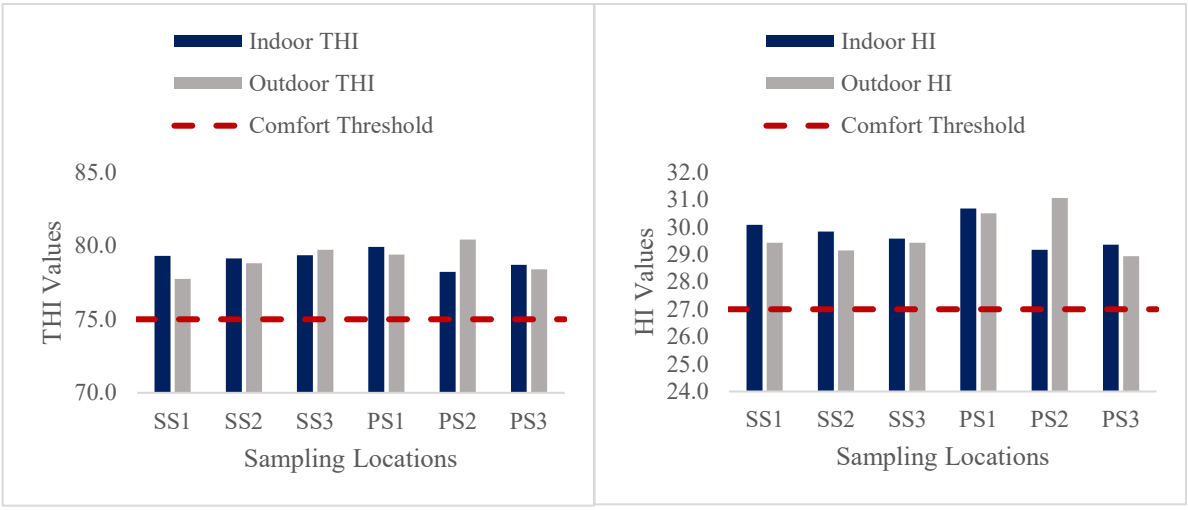


Figure 5: THI and HI values across sampling locations

Assessment of Non-carcinogenic Health Risk

The results of the potential for non-carcinogenic health effects resulting from exposure to particulate matter ($PM_{2.5}$ and PM_{10}) are presented in Figure 6. An HQ value below the threshold reference of 1.0 indicates that adverse non-carcinogenic health effects are unlikely, whereas values exceeding 1.0 suggest a potential health risk. For the indoor environments, the HQ values were ranked as follows: SS2 (0.296) < PS1 (0.320) < PS2 (0.377) < SS1(0.384) < SS3 (0.417) < PS3 (0.441). All the calculated HQ values for $PM_{2.5}$ remained below the unity threshold (HQ < 1). However, notably, the outdoor HQ at site SS3 reached 0.625, the highest among all the measured locations, reflecting the influence of ambient air quality on the total risk profile of secondary students. The indoor HQ values for PM_{10} were ranked as follows: PS (0.261) < PS2 (0.289) < SS2 (0.296) < PS3 (0.338) < SS (0.384) = SS3 (0.417). Like those for $PM_{2.5}$, all the HQ values for PM_{10} across both primary and secondary school sites were less than 1.0. Across all the sampling sites, the HQ values for both $PM_{2.5}$ and PM_{10} did not exceed the critical risk threshold of 1.0. This finding indicates that, on the basis of the current sampling period and exposure parameters, students are not at immediate risk of chronic non-carcinogenic health effects from particulate matter inhalation.

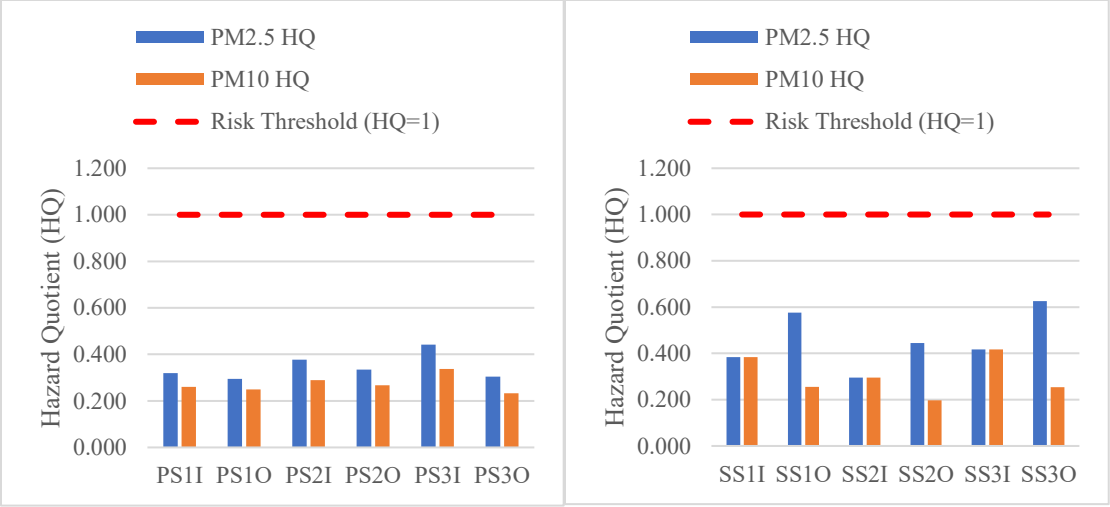


Figure 6: Non-Carcinogenic health risks for primary and secondary schools

Baseline Population and Environmental Characteristics

A comprehensive analysis of the study population's socio-demographic and environmental backgrounds between the primary and secondary school cohorts is presented in Supplementary Tables S2–S4.

Socio-Demographics: Secondary school students represented a higher age profile (69.0% aged 10–12 years) and a higher proportion of female participants (61.7%) than did the primary school group, where males predominated (84.3%) (Table S2; $p<0.001$). Socioeconomic status also varied, with secondary school families occupying both the lowest (< ₦50,000) and highest (> ₦200,000) income brackets more frequently than primary school families did (Table S2).

School Infrastructure: Secondary schools were primarily public institutions (84.0%) characterized by a high reliance on natural ventilation via window opening (86.0%) and less frequent cleaning (89.0% cleaned only once or twice weekly). Conversely, primary schools utilized more mechanical ventilation through electric fans (60.0%) and maintained a universal three-week cleaning schedule but reported a 100% prevalence of visible mould (Table S3; $p<0.001$).

Household Factors: Domestic exposure risks were notably higher for secondary school students, who reported significantly higher rates of household smoking (26.0%) and the use of biomass/kerosene cooking fuels (17.0%) than primary school students did (7.0% and 3.0%, respectively) (Table S4; $p<0.001$).

Prevalence of Respiratory Symptoms among Students

The comparative prevalence of respiratory symptoms between secondary and primary school students is presented in Table 4. These results indicate a distinct contrast in the symptomatic profiles of the two cohorts. A highly significant disparity was found in cough prevalence ($\chi2=51.34$, $p<0.001$), with 58.0% of secondary school students reporting a cough compared to 10.0% of primary school students. This 58.0% prevalence in secondary schools strongly aligns

with the higher reliance on natural ventilation (86.0%) and the subsequent infiltration of outdoor $PM_{2.5}$ noted in previous sections. Similarly, chest pain was significantly more prevalent in the secondary school cohort (40.0%) than in the primary cohort (16.0%) ($\chi2$ =14.29, p<0.001), further suggesting an elevated respiratory burden in the secondary school microenvironment. Conversely, the prevalence of phlegm was significantly higher in primary schools (54.0%) than in secondary schools (30.0%) ($\chi2$=11.82, p=0.001). This higher rate among primary students may be linked to the 100% prevalence of visible mould in primary classrooms (Table S3), as mould exposure is a well-documented trigger for excess mucus and phlegm production in younger children. Interestingly, the prevalence of wheezing was identical in both groups at 25.0% ($\chi2$ =0.00, p=1.000

Table 4: Prevalence of respiratory symptoms in schools (N=200)

Symptom (Yes)	Secondary (n=100)	Primary (n=100)	Total (n=200)	$\chi2$	p-value
Cough	58 (58.0%)	10 (10.0%)	68 (34.0%)	51.337	<0.001*
Chest Pain	40 (40.0%)	16 (16.0%)	56 (28.0%)	14.286	<0.001*
Phlegm	30 (30.0%)	54 (54.0%)	84 (42.0%)	11.820	0.001*
Wheezing	25 (25.0%)	25 (25.0%)	50 (25.0%)	0.000	1.000

Factors associated with respiratory symptoms

Bivariate analyses were conducted to determine the relationships among student demographics, classroom environmental factors, and the prevalence of respiratory symptoms, and the details are presented in Tables S5–S7. The incidence of coughing was significantly associated with nearly all measured variables (p<0.05). Notably, students in classrooms that rely on natural ventilation (window opening) reported a higher prevalence of cough (84.5%) than those with mechanical ventilation did (Table S5; $\chi2$ =16.99; p<0.001). Furthermore, coughing was significantly more frequent among students from public schools (86.2%), those in classrooms with tiled floors (60.3%), and those in environments where sanitation occurred only once or twice weekly (Table S5). Unlike the use of coughing, the use of ventilation was not significantly associated with chest pain (Table S6; p=0.463). However, significant associations were found with sanitation frequency ($\chi2$ =20.70, p<0.001), visible mould ($\chi2$ =12.50, p<0.001), and classroom crowding ($\chi2$ =7.84, p=0.005). Students in overcrowded classrooms and those in spaces cleaned only twice weekly were significantly more likely to report thoracic discomfort (Table S6). Like chest pain, the type of ventilation was not a significant driver of phlegm production (Table S7; p=0.266). The presence of phlegm was most strongly associated with sanitation frequency ($\chi2$=17.81, p<0.001) and visible mould ($\chi2$ =6.04, p=0.014). Specifically, 70.2% of the students who reported phlegm were in classrooms cleaned three times weekly, and 69.0% were in classrooms where mould was present (Table S7).

Impact of Particulate Matter (PM) Risk on Respiratory Health

The relationships between aggregated environmental particulate risk and the frequency of respiratory symptoms were evaluated and are shown in Supplementary Tables S8 and S9**.** Statistical analysis revealed that students in "High-Risk" PM environments experienced a significantly higher prevalence of cough (58%) and chest pain (40%) than did those in "Low-Risk" environments (0% and 16%, respectively) (Table 11; $p<0.001$). Interestingly, the prevalence of Phlegm was higher in the low-risk group (54%) than in the high-risk group (30%), suggesting that factors other than PM, such as the 100% prevalence of mould found in primary schools (Table S3), may be the primary drivers of mucus production. No significant difference was observed for wheezing ($p=1.000$). Binary logistic regression confirmed that high environmental PM levels are potent predictors of respiratory distress (Table S9). Total PM risk demonstrated a highly significant association with coughing ($p<0.001$), with the model indicating an exceptionally high (infinite) odds ratio, suggesting that high PM exposure is a near-universal precursor for coughing in the sampled population. Furthermore, students in high-PM-risk classrooms were 2.74 times more likely to report chest pain (OR = 2.74; 95% CI: 1.53–4.90; $p=0.001$). Consistent with the prevalence data, the regression model revealed that high PM risk was associated with lower odds of phlegm (OR = 0.29; $p<0.001$), reinforcing the conclusion that while particulate matter drives airway irritation (cough and pain), biological contaminants likely drive productive symptoms (phlegm) in this study context.

Multivariate predictors of respiratory symptoms

Table 5 presents the logistic regression analysis model, which evaluates the "total PM risk" alongside specific classroom factors (ventilation and sanitation) while adjusting for potential confounders, including age, sex, income, floor material, and mould presence. According to the univariate analysis, high total PM risk was a near-perfect predictor of coughing among students ($p<0.001$). In the multivariate step, the model yielded a massive adjusted odds ratio for PM risk ($p < 0.001$), confirming that particulate matter concentration is the absolute primary driver of cough in this cohort. While Class Ventilation (Window Opening) showed an increased likelihood of coughing in both the crude (OR = 1.70) and adjusted (AOR = 1.82) models, the association did not reach statistical significance ($p=0.476$), suggesting that the actual concentration of pollutants is a more potent trigger than the ventilation method itself. Sanitation frequency emerged as the most significant predictor of phlegm production. Students in classrooms with the lowest cleaning frequency (Sanitation 1) were 5.54 times more likely to report phlegm (AOR = 5.54; 95% CI: 1.35–22.80; $p = 0.018$). Interestingly, high PM risk showed an inverse relationship in the crude model for phlegm, further reinforcing the hypothesis that phlegm in this population is more closely tied to hygiene and biological factors (such as the 100% prevalence of mould in primary schools) than to particulate concentrations alone. Regarding chest pain, high PM risk significantly increased the odds in the crude analysis (OR = 2.74; $p = 0.001$). In the adjusted model, the impact of sanitation frequency reached near-significance; students in classrooms with the poorest sanitation had nearly three times the odds of experiencing chest pain (AOR = 2.93; 95% CI: 0.99–8.65; $p = 0.052$).

Table 5: Logistic Regression Analysis of Environmental Predictors for Respiratory Symptoms

Symptom	Predictor Variable	Crude OR (95% CI)	p-value	Adjusted OR (95% CI) †	p-value
Cough	Total PM Risk (High)	High/Inf.*	<0.001	High/Inf.*	**<0.001**
	Class Ventilation (2)	1.70 (0.49 – 5.95)	0.407	1.82 (0.35 – 9.50)	0.476
	Age (1)	—	—	1.28 (0.37 – 4.46)	0.704
	Age (2)	—	—	0.80 (0.36 – 1.77)	0.579
	Gender (Male)	—	—	0.53 (0.18 – 1.56)	0.247
Phlegm	Total PM Risk (High)	0.29 (0.15 – 0.56)	<0.001	High/Inf.*	1.000
	Sanitation (1)	4.68 (1.25 – 17.51)	0.022	5.54 (1.35 – 22.80)	**0.018**
	Sanitation (2)	8.52 (1.61 – 45.01)	0.012	6.40 (0.93 – 44.21)	0.060
Chest Pain	Total PM Risk (High)	2.74 (1.53 – 4.90)	0.001	High/Inf.*	1.000
	Class Ventilation (2)	1.69 (0.74 – 3.89)	0.143	1.72 (0.67 – 4.31)	0.372
	Sanitation (1)	2.65 (0.95 – 7.37)	0.062	2.93 (0.99 – 8.65)	**0.052**

COR: crude odds ratio (univariate); AOR: adjusted odds ratio (multivariate). †Adjusted for age, gender, income, floor material, and mould. *Statistical Note: "High/Inf." and p=1.000 in the adjusted model indicate "perfect prediction" (quasicomplete separation), where the PM risk variable is strongly associated with the outcome that the model cannot calculate a stable numerical AOR alongside other variables. Bold indicates statistical significance at $p<0.05$.

Discussion

The findings of this study reveal significant spatial heterogeneity in air quality across the sampled primary and secondary schools. The discovery that indoor particulate matter ($PM_{2.5}$ and PM_{10}) and gaseous pollutants (CO_2 and CO) vary significantly across locations suggests that the school microenvironment is not a monolithic space (Sahu and Gurjar, 2020). Instead, it represents a complex intersection of site-specific outdoor ambient conditions and indoor occupancy patterns. The higher variability observed in secondary schools (SS3) than in primary schools indicates that older student populations or larger building volumes may introduce more complex pollutant dynamics. These fluctuations are often driven by increased physical activity and specific student behaviours, such as the resuspension of dust particles through movement (Zhou et al., 2021). Furthermore, the particulate matter concentrations in this study significantly exceeded the 24-hour guidelines established by the National Environmental Standards and Regulations Enforcement Agency (NESREA, 2011) and the World Health Organization (WHO, 2021). Such exceedances are common in rapidly growing African urban centers; for instance, long-term monitoring in Addis Ababa similarly revealed that $PM_{2.5}$ levels consistently violate WHO safety thresholds, posing severe public health risks (Kumie et al., 2021). In the Nigerian context, these findings align with observations in Lagos, where $PM_{2.5}$ levels across various locations frequently reach "unhealthy" air quality index (AQI) categories (Suriano et al., 2025). Chronic exposure in school settings, similar to the risks identified in Akure's health centers, can lead to reduced lung function, exacerbated asthma, and increased absenteeism (Abulude et al., 2024). Since children have higher breathing rates relative to body mass, the high PM levels at SS3 and PS1 are particularly alarming. These localized spikes mirror broader regional concerns where infrastructural challenges often

hinder the closure of critical data gaps (Olise, 2025). Consequently, localized assessments such as those in Kano and Akure emphasize that current PM levels necessitate more robust, site-specific air quality management to protect vulnerable populations (Abulude et al., 2024; Nafisa and Gana, 2025). While CO_2 levels in this study generally remain below the common ASHRAE threshold of 1,000 ppm for poor ventilation, the outliers identified in the boxplots suggest significant periodic spikes. These spikes are concerning because even "low-level" inhalation exposure to CO_2 , often found in indoor environments, has been shown to negatively impact human health and psychomotor performance (Azuma et al., 2018). Specifically, such elevated concentrations are linked to "Sick Building Syndrome" (SBS) symptoms, including drowsiness, headaches, and impaired cognitive performance during lessons (Azuma et al., 2018; Mokhtar et al., 2025). The relationship between classroom air and occupant health is well documented in literature works; for instance, a study of schools in New York revealed a direct correlation between higher CO_2 concentrations and increased reporting of health symptoms among teachers, emphasizing that even subtle increases in CO_2 can degrade the indoor environment (Muscatiello et al., 2015). In the context of the school microenvironment, these periodic fluctuations may create "perceived" poor air quality that triggers physical discomfort and reduced concentration among both students and staff (Mokhtar et al., 2025). The observed trend of higher indoor CO_2 concentrations than outdoor levels align with the findings of international studies in urban school and university settings, where inadequate ventilation frequently traps metabolic CO_2 (Sahu and Gurjar, 2020). These findings are further supported by research indicating that even at levels previously considered acceptable, periodic CO_2 spikes are linked to "Sick Building Syndrome" and diminished psychomotor performance (Azuma et al., 2018; Mokhtar et al., 2025). Locally, the finding that secondary schools exhibit higher PM variability than primary schools agree the findings of previous studies in Nigerian urban centers, such as Lagos and Kano, which attributed such spikes to high-traffic proximity and the "re-suspension" of dust driven by increased student mobility (Nafisa and Gana, 2025; Suriano et al., 2025; Zhou et al., 2021). These elevated concentrations are persistent across African metropolitan areas; for example, long-term monitoring in Addis Ababa consistently reveals that the $PM_{2.5}$ concentrations exceed the WHO safety thresholds (Kumie et al., 2021). However, the consistent indoor-outdoor temperature overlap suggests a "leaky" building envelope—a common feature in tropical school architecture. Unlike temperate climates, where mechanical HVAC systems provide a thermal buffer (Muscatiello et al., 2015), the local school microenvironment remains highly susceptible to outdoor ambient conditions. This vulnerability is compounded by broader regional infrastructural challenges and data gaps that often hinder effective air quality management in Nigeria (Abulude et al., 2024; Olise, 2025). The I/O ratios for $PM_{2.5}$ and PM_{10} across the sampling sites were consistently above 1.0, suggesting that schools, particularly secondary schools (SS3), act as reservoirs for particulate matter. The primary driver is likely mechanical resuspension, where student movement on unpaved or dusty floors kicks up settled dust, keeping particles airborne (Tian et al., 2014). In secondary schools, higher student density and more vigorous physical activity typically led to higher resuspension rates than they do in primary schools, a phenomenon further influenced by ambient factors such as indoor humidity (Cho et al., 2021). These findings align with local studies in Nigeria by Owoade et al. (2013), who reported that indoor PM levels in public buildings often exceed outdoor levels because of poor floor maintenance and high occupancy. Internationally, these findings are similar to those in Barcelona, Spain, where school classrooms had I/O ratios >1.0 due to "human cloud" effects—the shedding of skin cells, clothing fibres, and resuspended road dust (Amato et al., 2014).

Furthermore, the significant indoor accumulation observed here reinforces the findings of Blondeau et al. (2005), who demonstrated in a study of French schools that while outdoor air significantly influences indoor chemistry, indoor-generated particles and a lack of effective filtration can lead to indoor concentrations that consistently outpace outdoor baselines. Interestingly, some international studies in highly industrialized cities report I/O ratios <1.0 for PM because outdoor ambient pollution is so extreme that it dwarfs indoor sources (Zhou et al., 2021). The CO I/O ratio showed the most dramatic fluctuation, specifically the peak of 5.71 at SS2. This high ratio is rarely the result of poor ventilation alone; it almost certainly points to localized indoor combustion. This could be attributed to the proximity of the sampling site to school laboratories using gas burners, kitchen areas using biomass/gas for mid-day meals, or even the use of small gasoline generators near classroom windows (Abulude et al., 2018). This spike is consistent with studies in low-income urban areas where "point sources" significantly skew indoor air profiles. However, it contradicts studies in modern, HVAC-equipped schools in the U.S. or Europe, where CO I/O ratios typically hover at approximately 1.0 because of the absence of indoor combustion (Honan et al., 2024). The CO_2 ratio (which can reach 1.29) serves as a proxy for ventilation efficiency. Since humans are the main source of CO_2 indoors, a ratio >1.0 confirms that the rate of CO_2 production by students exceeds the rate of removal by fresh air. The peaks at PS3 and SS2 suggest that these classrooms are "under-ventilated," which is likely due to closed windows for security or noise reduction. While these levels indicate a need for improved air exchange to protect student health and cognitive function (Sadrizadeh et al., 2022), these values are relatively modest compared with those reported by Blondeau et al. (2005), where airtight, energy-efficient buildings often see CO_2 I/O ratios exceeding 3.0. The lower ratios in this study suggest that the "leaky" nature of Nigerian school architecture—designed for passive tropical ventilation—actually helps prevent massive CO_2 buildup, even if it fails to filter out incoming or resuspended dust. This study revealed a strong, significant inverse relationship between the RH and particulate matter concentration. High humidity increases the moisture content of airborne particles, causing them to undergo hygroscopic growth (Hinds and Zhu, 2022). As particles become heavier, they settle out of the air more rapidly through dry deposition (Piu et al., 2014). Conversely, drier conditions with low RHs decrease the particle mass and reduce the cohesive forces between dust particles on the floor, facilitating the mechanical resuspension mentioned in the previous sections (Cho et al., 2021). These findings are consistent with observations by Ochei and Emmanuel (2018**)** regarding Harmattan dust haze in northern Nigeria, where low relative humidity and high dust loading coincide to create hazardous respiratory conditions. Internationally, this aligns with Asbach et al. (2016)**,** who reported that low humidity levels in public buildings significantly increase the mobility of "dust clouds". However, this contradicts the findings of some studies in extremely humid coastal regions where very high RHs (>80%) can actually correlate positively with PM because of the formation of secondary organic aerosols. In contrast to particulates, RH was positively correlated with gaseous pollutants. This relationship is likely driven by ventilation behaviour. On days with high relative humidity (often coinciding with rain), teachers and students are more likely to close windows and doors to keep the interior dry or warm. This reduction in air exchange leads to the accumulation of metabolic CO_2 and any indoor-generated CO. This finding is consistent with the findings of Sadrizadeh et al. (2022), who reported that "envelope tightening" due to outdoor weather conditions was the primary driver of increased levels of indoor gaseous pollutants. It was also observed that temperature exhibited the opposite trend to that of humidity, with positive correlations with particulates and negative correlations with gases. As the air warms, convection currents can keep smaller particles suspended for longer

periods. This is exacerbated in "leaky" tropical buildings where high outdoor temperatures also indicate dry, dusty periods (Akande and Adebamowo, 2010). The negative correlation between temperature and CO_2 is a classic indicator of buoyancy-driven ventilation. Compared with a slightly cooler outdoor morning, higher indoor temperatures can create a "stack effect," where warm air rises and escapes through high windows or vents, pulling in fresh air and diluting gas concentrations. In temperate climates, temperature often correlates positively with CO_2 because high temperatures lead to the use of air conditioning and the sealing of buildings (Blondeau et al., 2005). The contradiction in our findings highlights the unique "passive" nature of Nigerian school architecture, where heat often prompts the opening of windows, thereby improving gas dilution despite the heat (Ogunsote et al., 2011; Xi et al., 2025). The recorded indoor THI values in this study indicated that people using the classrooms are outside the "Optimal Learning Zone" (19–26). The primary driver of these elevated values is the thermal lag of building materials and inadequate structural shading (Amankwaa et al., 2025). In many Nigerian schools, high solar gain through uninsulated roofing and the lack of specialized "cool roof" technologies lead to indoor temperatures that mirror or exceed outdoor conditions (Akande and Adebamowo, 2010). Research into educational psychology and environmental health suggests that for every degree Celsius above 25°C, there is a measurable decline in student concentration, memory recall, and mathematical problem-solving ability (Zhu et al., 2016). At site SS1 (THI 29.1), students are likely to experience cognitive fatigue, as the body diverts metabolic energy toward thermoregulation rather than cognitive processing. The mean heat index (HI) values fall into the "Caution" category (27–32°C). While not yet in the "Extreme Caution" or "Danger" zones, consistent exposure to the "Caution" level in a crowded classroom can lead to heat exhaustion, headaches, and dehydration. This is particularly critical for younger students in primary schools (PS1–PS3), whose surface-area-to-mass ratio makes them more susceptible to rapid heat gain than adults are (Sadrizadeh et al., 2022). These findings are significantly higher than those of thermal comfort studies in European schools (Blondeau et al., 2005), where the challenge is typically maintaining warmth. However, these findings align with those of studies in Southeast Asia and Brazil, where the temperatures of classrooms frequently exceed 28°C, leading to the recommendation of increased ceiling heights and high-volume low-speed (HVLS) fans to improve evaporative cooling (Buonocore et al., 2020). The trend showing higher discomfort in secondary schools than in primary schools likely reflects occupancy density. Older students have a higher metabolic rate, generating more internal heat gain within the same classroom volume, a factor noted by Ogunsote et al. (2011) and as a primary failure in standardized Nigerian school designs that use the same prototypes for both age groups.

In this study, all HQ values for $PM_{2.5}$ and PM_{10} were less than 1.0, indicating a low hazard to individuals using the classrooms when adjusted for inhalation rates and exposure frequency, and these values do not pose an immediate chronic non-carcinogenic threat. The primary reason the HQ remained below 1.0 despite high raw concentrations could be the exposure duration factor. Students are typically exposed to the classroom environment for approximately 6–8 hours a day, 180–200 days a year. This intermittent exposure "dilutes" chronic daily intake (CDI) compared with residential or industrial settings where exposure is more continuous (US EPA, 2011). These results are similar to the findings of Obanya et al. (2018) in Lagos, Nigeria, where the HQ values for particulates in public spaces were found to be less than 1.0, although they were significantly greater than those at rural control sites. In contrast, studies in highly polluted industrial hubs such as Delhi, India, and China have frequently reported $PM_{2.5}$ HQ values exceeding 2.0 or 3.0 for school children (Mbazima, 2022). These findings suggest that the air quality in these Nigerian

schools, while "uncomfortable", as revealed by the THI values, is significantly safer from a chronic toxicological standpoint than that in schools in industrialized countries. The high outdoor HQ (0.625) at site SS3 reported in this study contradicts the general trend where indoor environments are usually riskier because of resuspension. This is primarily because site SS3 is located near a major market along a highway, a spatial factor that significantly elevates the baseline risk for secondary students through the infiltration of traffic-related emissions. These observations are consistent with those of Kaewrat et al. (2021), who demonstrated that in open-air or naturally ventilated classrooms, the indoor air quality and subsequent human health risk are inextricably linked to the proximity of outdoor pollution sources, such as biomass burning or traffic. Despite the lower absolute concentrations in some primary schools, PS3 had a relatively high indoor HQ. This reflects the physiological reality that younger children have higher inhalation rates per unit of body weight, meaning that they absorb a higher dose of pollutants than secondary school students under similar conditions do (Sadrizadeh et al., 2022). Furthermore, Kaewrat et al. (2021) emphasised that because children have smaller lung surface areas and develop immune systems, their calculated health risk from particulate matter ($PM_{2.5}$ and PM_{10}) is often significantly higher than that of adults in the same environment, even when concentrations appear moderate.

To provide a holistic view of the school-home exposure continuum, this study synthesizes the socio-demographic and infrastructural data with observed health outcomes. This study revealed a sharp contrast in cough incidence between secondary schools and primary schools. This disparity is directly linked to school infrastructure. On-site assessment revealed that secondary schools (84.0% public) rely almost exclusively on natural ventilation (86.0%). While this prevents CO_2 buildup, it allows for the high-volume infiltration of outdoor $PM_{2.5}$ and Harmattan dust. These findings are in agreement with those of Blondeau et al. (2005), who reported that in "leaky" buildings, the indoor air quality mirrors the outdoor ambient environment. However, these findings contradict studies in developed nations where mechanical filtration in schools usually severs the link between outdoor dust and indoor respiratory symptoms (Sadrizadeh et al., 2022). Conversely, primary school students reported significantly higher rates of phlegm (54.0% vs. 30.0%). This is statistically linked to the 100.0% prevalence of visible mould in primary classrooms. Mould spores are potent biological irritants that cause the goblet cells in the airway to overproduce mucus (phlegm). These results are similar to the findings of Obanya et al. (2018) and Eghomwanre et al. (2025), who reported that dampness in older school buildings was a strong predictor of mucus-related symptoms among students. This study also revealed that the lower cleaning frequency in secondary schools (89.0% cleaned only once or twice weekly) exacerbated the particulate issue. Infrequent cleaning allows for the accumulation of a "dust reservoir" on floors. As secondary students are more physically active, they trigger higher rates of mechanical resuspension, as supported by the findings of Cho et al. (2021). The implication is that current hygiene practices in these schools are insufficient to break the cycle of pollutant exposure, directly contributing to the high prevalence of mucus-related respiratory distress among younger groups. This underscores a critical gap in school environmental management, where "dry" cleaning methods may involve inadvertently recirculating allergens rather than removing them. It was also observed that secondary school students face a "double burden" of exposure, with significantly higher rates of household smoking (26.0%) and biomass/kerosene fuel use (17.0%). The high prevalence of cough in this group is likely not just a result of the classroom environment but also a synergistic effect of poor school air and domestic combustion byproducts. This "cumulative exposure" model is a hallmark of low-income urban settings in Nigeria (Abulude et al., 2018). The most striking finding

in this study is that “High PM Risk” acted as a near-perfect predictor for coughing ($p < 0.001$), yielding an exceptionally high adjusted odds ratio. This suggests that in the sampled urban school environments, high particulate matter exposure is not merely a risk factor but the absolute primary driver of the cough reflex. High concentrations of PM, especially $PM_{2.5}$, are small enough to penetrate deep into the alveolar regions of the lungs, triggering the cough reflex through the stimulation of rapid-adapting receptors (RARs) in the airway mucosa (Xing et al., 2016). The fact that students in high-PM-risk environments were 2.74 times more likely (Crude OR = 2.74; $p = 0.001$) to report chest pain—a finding that reached a state of "perfect prediction" in the adjusted model—suggests that particulate exposure causes not just minor irritation but significant pulmonary inflammation. This "perfect prediction" aligns with the ESCAPE study in Europe, which revealed a linear relationship between $PM_{2.5}$ and respiratory symptoms in children (MacIntyre et al., 2014). The implication is that the biological threshold for respiratory defense is overwhelmed by the mass of inhaled particles, particularly in schools where natural ventilation allows for unfiltered ambient dust infiltration. Without lowering the concentration of indoor particulates, medical interventions will likely remain ineffective, as the environment serves as a constant trigger for bronchial inflammation.

Furthermore, while high PM risk was associated with a dry irritant cough, sanitation frequency was the dominant predictor for phlegm production. Students in poorly cleaned classrooms (Sanitation 1) were 5.54 times more likely to produce phlegm (AOR = 5.54; 95% CI: 1.35–22.80; $p = 0.018$). This distinction is critical; while PM triggers a mechanical or chemical cough, phlegm (mucus production) appears more closely tied to hygienic and biological factors, such as the 100% prevalence of mould in primary schools (Hill et al., 2022). These findings support those of Obanya et al. (2018) in Lagos, where “dampness” and “infrequent sweeping” were more closely linked to productive coughs (phlegm) than to dry wheezing. Finally, the study revealed that while window opening (natural ventilation) was associated with a greater likelihood of symptoms (AOR = 1.82), it remained statistically non-significant when adjusted for PM levels ($p = 0.476$). This indicates that the ventilation method itself is secondary to the pollutant load it facilitates. If outdoor air is high in PM_{10}, especially during the harmattan, windows become a liability rather than a benefit. This contrasts with studies in cleaner environments where increased ventilation is almost always associated with improved health outcomes (Blondeau et al., 2005), highlighting the unique environmental challenges faced by schools in rapidly urbanizing tropical regions.

Conclusion

This study provides a critical spatio-temporal assessment of air quality and thermal comfort parameters and determines the respiratory health risks in the urban school microenvironment in Benin City. The findings of this study reveal significant spatial heterogeneity in air quality across the sampled primary and secondary schools. The particulate matter concentrations in this study significantly exceeded the 24-hour guidelines of both national and international standards. While the chronic non-carcinogenic health risk remained below the unity threshold of 1.0, the “uncomfortable” to “severe” heat stress levels across all the schools indicate a significant failure in thermal buffering. Furthermore, the study identifies a distinctly high indoor PM concentration, particularly in secondary schools, which acts as a “perfect predictor” for dry cough among students. In contrast, the prevalence of phlegm is not driven by particulates but by the frequency of cleaning and the presence of visible mould in the classrooms, which explains why primary

school students in “low-PM” but “high-mould” environments suffer more from productive mucus symptoms. Without targeted structural and policy interventions, the school environment will continue to impair the physiological well-being and, by extension, the academic potential of the student population. To address the significant respiratory health risks identified in this study, a multi-faceted policy approach that integrates infrastructure upgrades, improved sanitation protocols, and rigorous environmental monitoring is needed. Schools must prioritize the paving of assembly grounds and walkways to reduce particulate resuspension, while the Ministry of Education should implement seasonal ventilation guidelines and provide mechanical filtration to mitigate the risks associated with natural ventilation during high-pollution periods such as Harmattan. Furthermore, a national “School Damp-Proofing Program” is essential for eliminating biological triggers through roof repairs and anti-fungal treatments, complemented by a shift from dry-sweeping to standardized daily wet-mopping. Finally, the institutionalization of bi-annual respiratory screenings and the deployment of low-cost air quality sensors will empower school administrators with the real-time data and medical oversight necessary to protect students from chronic environmental hyper-responsiveness.

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Author Contributions

AFE: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Validation, Writing—original draft, and Writing. MOA: Formal analysis, Validation, Supervision, Writing—review & editing. All authors read and approved the submitted version.

Ethical Approval

Ethical approval for this study was obtained from the Health Research Ethics Committee of University of Benin Teaching Hospital (Protocol Number: ADM/E22/A/VOL.VII/1486549125537). Written informed consent was obtained from the school principals and the parents/guardians of all participating students before data collection."

Consent to Participate: Informed consent was obtained from all individual participants included in the study.

Consent to Publish

The authors affirm that the participants provided informed consent for the publication of the research findings.

Competing Interests

The authors declare no conflicts of interest

Data availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

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