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Assessment of indoor air quality in a primary school

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Abstract
Indoor air quality (IAQ) in schools is important as it directly affects the health, comfort, and learning ability of students and staff. This study assessed the IAQ in ten rooms at St. Peters Catholic Primary School, Sittingbourne, Kent, between February and March 2024. A portable uHoo business air quality monitor was used to assess ambient temperature, relative humidity, total volatile organic compounds (TVOC), formaldehyde, carbon monoxide (CO), carbon dioxide (CO_2), particulate matter ($PM_{2.5}$ and PM_{10}). The air quality index results revealed means of: temperature (18.45 ± 2.23 °C), relative humidity (57.59 ± 4.32%), CO (0.14 ± 0.11 ppm), CO_2 (737.20 ± 346.87 ppm), TVOC (2148.62 ± 5456.78 ppb), formaldehyde (18.68 ± 67.67 ppb), $PM_{2.5}$ (5.82 ± 2.31 μg/m^3), and PM_{10} (11.23 ± 2.71 μg/m^3). The results revealed variations in the diurnal variations in particulate matter ($PM_{2.5}$ and PM_{10}) during school hours and significant differences at 10.00 am break time (7.9 μg/m^3 and 13.3 μg/m^3), noon lunch time (7.8 μg/m^3 and 12.9 μg/m^3) and 3.00 pm end of school (7.5 μg/m^3, 12.5 μg/m^3). This study concludes that PM in this school is, primarily, driven by PM in the local area, not the school. All parameters were within permissible limits, except for TVOC. The school's management should adopt proactive measures, including routine IAQ assessments. This will allow the school to cultivate healthier environments that foster academic excellence.

Keywords Primary school · Indoor air quality · Formaldehyde · Particulate matter · Diurnal variations · Total volatile organic compounds

1 Introduction

Indoor air quality (IAQ) has emerged as a critical public health issue driven by increasing urbanisation, energy-efficient building designs, and the proliferation of indoor pollutants [1]. Indoor air pollution poses significant health risks, contributing to millions of deaths each year [2]. As awareness of such pollution increases, effective monitoring and control measures are being implemented to reduce these risks and promote healthier indoor environments [3].Globally, the development of IAQ guidelines has become increasingly important [4]. Real-time sensors represent a significant trend in monitoring indoor air quality [5, 6]. Unlike traditional fixed monitoring stations, these sensors provide dynamic spatiotemporal data that can effectively capture fluctuations in pollutant levels within indoor spaces [7]. The affordability and portability of real-time air quality sensors make them attractive for residential, school and commercial settings [8].

Indoor air pollution in schools is typically caused by a combination of familiar sources, including combustion, cleaning, and maintenance activities, as well as the emission of volatile organic compounds (VOCs) from building materials,

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furnishings, and biogenic sources [9]. The indoor air pollutants commonly present in schools include nitrogen and sulphur oxides, ozone, VOCs, polyaromatic hydrocarbons (PAHs), aldehydes, phthalates, and particulate matter (PM) [10]. Among these pollutants, PM is the most significant concern in terms of exposure to children because of its variety of sources, adverse health effects, and wide spatial and temporal variability [11]. Exposure to PM can result in an increase in cardiovascular and respiratory diseases, for NO_2 exposure may cause reduced lung development and respiratory infections, while formaldehyde and VOCs have been linked to a rise in asthma cases [12].

Children spend up to 70% of their time indoors, and indoor air pollutants in schools can pose a significant challenge [13]. Children's developing brains, lungs, and other organs make them biologically more vulnerable to air pollution than adults. Various health problems related to indoor air quality have been reported for school children. Some of these health effects can be long-term and have a lasting impact on a child's health later in life [14]. Symptoms related to air quality exposure, such as asthma and allergies, contribute to lost school days and poor attendance [15]. Additionally, symptoms related to poor environmental quality tend to decrease students' motivation, performance, and achievement rates.

The Schools' Air quality Monitoring for Health and Education project (SAMHE) provided an air quality monitor for over 1300 UK schools. Results indicate that relative humidity and $PM_{2.5}$ suggest that classrooms are influenced by weather and long-range events in addition to local activities. The 24 hour mean for $PM_{2.5}$ was 3.71 μg/m^3. Approximately 80% of indoor PM originated outdoors. Additionally after installing air filters in 300 classrooms a 29% reduction in PM levels was observed compared with nearby schools [16].

There has been growing research on issues impacting indoor air quality in schools predominantly in North America and Europe [17]. Several studies have reported on indoor air pollution in schools across the UK [16, 18, 19]. A latest study in London monitored thermal comfort, particulate matter (PM) and carbon dioxide (CO_2) in ten London primary schools, sampling sixty classrooms using standardised equipment to produce a comparable dataset [19]. The research aimed to understand the association between classroom air quality and various factors, including classroom volume, floor types, classroom locations, occupancy levels, ventilation rates, and different year groups. They found that the average concentrations of PM_1, $PM_{2.5}$, and PM_{10} in classrooms were 5 ± 2, 10 ± 2, and 29 ± 20 μg/m^3, respectively. During occupied hours, $PM_{2.5}$ levels were ~ 110% higher, and PM_{10} levels were 150% higher compared to non-occupied hours. PM_{10} levels almost doubled for wooden-floored classrooms compared with those with carpets.

Previous studies have generally concentrated on a few classrooms and a single pollutant. None have considered air quality across the school as a whole. The current study aimed to investigate the varying air pollution concentrations in all rooms (classrooms, hall, kitchen, and administrative office) of a primary school for the first time (with an age range of 4 to 11 years) in Sittingbourne, Kent in the United Kingdom.

2 Materials and methods

2.1 Study area

The study location was St. Peter's Catholic Primary School, situated in a residential area of Sittingbourne, Kent, United Kingdom (51° 20′ 4.1244″ N, 0° 43′ 29.91″ E), 50 m from the main traffic roads (see Fig. 1). The school is run by the Kent Catholic Schools Partnership, a form of multi-academy trust, and provides primary education for 211 students at the time of this study in 2024. The school was built in the 1960's and is single story. It is typical of many primary schools in the UK constructed at that time. Average outdoor temperature and humidity was 10 °C and 87% respectively.

All classrooms, the kitchen, the administrative office and the dining hall were included in the indoor air quality assessment. The school buildings are externally constructed of brick, internally insulated with plasterboard, and feature double-glazed windows and doors. Natural ventilation is achieved by opening windows and doors, as no air conditioning systems are installed.

No renovation activities occurred inside the school or in the surrounding area during the study period. Ten different rooms were selected for IAQ measurements — seven classrooms, the administrative office, the assembly/dining hall, and the kitchen — as shown in Fig. 2. Table 1 provides the details of the study rooms, their sampling dates and sizes.

Fig. 1 Indoor air quality study school (St. Peter's Catholic Primary School, Sittingbourne, Kent, 2024). Lat Long (51.334479, 0.724975) GPS coordinates 51° 20′ 4.1244″ N 0° 43′ 29.91″ E (Google Earth)

Fig. 2 Sampled site at St Peter's Catholic Primary School, Sittingbourne, showing floor plan and uHoo instrument location

2.2 Instrumentation

Indoor air quality measurements were carried out using a uHoo Aura portable indoor air quality monitor (serial number 34ffda055641383859482). A single portable uHoo air quality monitor was used to ensure consistent, reliable measurements. Using a single device eliminated intersensor variability and calibration differences that could bias results [20]. The study focused on temporal rather than spatial variations in indoor air quality; therefore, sequential sampling with one calibrated instrument was adequate. In small, mechanically ventilated spaces, air is typically well mixed and pollutant concentrations remain relatively uniform [21]. Using a single well-maintained device also enhanced data integrity and enabled greater control over calibration and instrument performance throughout the study period. This device measures multiple environmental parameters, including particulate matter ($PM_{2.5}$ and PM_{10}), temperature, relative humidity, total volatile organic compounds (TVOCs), carbon dioxide (CO_2), carbon monoxide (CO) and formaldehyde (HCHO).

The sensor specifications of the uHoo Aura monitor are summarised in Table 2. The device employs a combination of microelectromechanical systems (MEMS), laser scattering, metal-oxide, electrochemical, and dual-channel NDIR sensing technologies to ensure high precision. The monitor automatically performs self-calibration every 24 hours and again after 168 hours of continuous operation, enhancing long-term measurement stability and accuracy.

Table 1 Details of the study rooms and sampling dates

Study room	Ventilation strategy	1st sampling date(d/m/y)	No of students	2nd Sampling date (d/m/y)	No of students	Room dimensions
Office	Window open (2)[b]	20/2/2024	(2)[a]	25/3/2024	(2)[a]	6.60 sqm
Dining and Assembly Hall	Door open (7)[b]	8/3/2024	200[c] (3)[d]	13/3/2024	203[c] (3)[d]	41.92 sqm
Kitchen	Window open (1)[b]	11/3/2024	(3)[a]	12/3/2024	(3)[a]	21.6 sqm
Reception class	Door open (7)[b]	21/2/2024	30 (3)[a]	22/2/2024	30 (3)[a]	17.68 sqm
Year 1	Door open (1)[b]	23/2/2024	30 (2)[a]	21/3/2024	29 (2)[a]	18.24 sqm
Year 2	Door open (1)[b]	26/2/2024	30 (3)[a]	20/3/2024	30 (3)[a]	17.76 sqm
Year 3	Door and window open(1)[b]	28/2/2024	29 (2)[a]	19/3/2024	29 (2)[a]	21.16 sqm
Year 4	Door open (7)[b]	29/2/2024	29 (4)[a]	18/3/2024	27 (4)[a]	21.16 sqm
Year 5	Door open (4)[b]	1/3/2024	26 (3)[a]	15/3/2024	30 (3)[a]	23.00 sqm
Year 6	Window open (7)[b]	4/3/2024	31 (3)[a]	14/3/2024	32 (3)[a]	21.00 sqm

[a]Number of staff in the room during the sampling period

[b]Average number of hours the window was opened during the sampled period

[c]Numbers of students in the dining hall for 1 h

[d]Number of staff in the dining hall during lunch

Sampling was done for 24 h daily from 8 to 8am the next day

Table 2 uHoo sensor specifications

Measure	Accuracy	Range	Limit of detection (LOD)	Technology
Temperature [°C]	± 0.5	− 40–85	–	Microelectromechanical systems (MEMS)
Relative humidity [%]	± 3%	0–100%	–	MEMS
$PM_{2.5}$ [μg/m^3]	± 10 μg/m^3 (0–100), ± 10% (100–1,000)	0–1000	1	Laser scattering
PM_{10} [μg/m^3]	± 25 μg/m^3 (0–100), ± 25% (100–1,000)	0–1000	1	Laser scattering
Carbon monoxide (CO) [ppm]	± 1 ppm (0–20), ± 5% (20–1,000)	0–1000	0.1	Electrochemical
Carbon dioxide (CO_2) [ppm]	± 30 ppm plus 3% of actual value	400–10,000	1	Dual-channel NDIR
Formaldehyde [ppb]	± 30 ppb (0–300), ± 10% (300–2,000)	0–2000	1	Electrochemical
Total VOCs [ppb]	± 15%	0–60,000	1	Metal-oxide

Prior to sampling, instruments were verified to ensure accurate readings. The monitor was positioned at a representative breathing height, away from doors and direct emission sources. Data were recorded at 1-min intervals, automatically stored in the cloud, and accessed via the uHoo Aura mobile and web applications.

2.3 Sampling

Sampling was conducted during February and March 2024, covering two monitoring rounds for each selected room. Each room was sampled continuously for 24 hours, after which the device was moved to the next room. No sampling was performed over weekends to maintain consistency with regular school occupancy patterns.

During each sampling session, contextual information was recorded, including: 1. Date and time of sampling; 2. Number of staff and students present; 3. Number of tables and chairs; 4. Number and duration of window and door openings; 5. Break times; and 6. Cleaning materials and schedules (see Supplementary Table S1).

Data were collected during regular school hours to reflect realistic exposure conditions. The ventilation strategies, number of occupants, and sampling dates for each room are summarised in Table 1.

2.4 Data analysis

The normality of the data was assessed using the Shapiro–Wilk test [22, 23]. A *p*-value greater than 0.05 indicated that the data followed a normal distribution, whereas a *p*-value less than 0.05 suggested a significant deviation from normality [24]. Given that most parameters were not normally distributed, non-parametric tests were utilised.

To evaluate differences in pollutant distributions among the sampled sites, a Kruskal–Wallis test was conducted [25]. Additionally, Spearman's correlation was employed to examine the relationships between temperature and relative humidity [26]. A two-tailed p-value of less than 0.05 was deemed statistically significant.

2.4.1 Ordinary least squares (OLS) linear regression

To explore the interrelationships among various pollutants, Ordinary Least Squares (OLS) linear regression was employed [27]. In this analysis, CO_2 was designated as the dependent variable. In contrast, the independent variables included TVOCs, $PM_{2.5}$, PM_{10}, CO, and HCHO. This approach enabled a comprehensive understanding of the interactions between these pollutants. The model was expressed as:

$$CO_2 i = \beta 0 + \beta 1\,(TVOCi) + \beta 2\,(PM2.5,i) + \beta 3\,(PM10,i) + \beta 4\,(COi) + \beta 5\,(HCHOi) + \varepsilon i$$

Prior to regression, all variables were screened for missing values and outliers. Variables showing skewed distributions were log-transformed to improve normality. Multicollinearity among predictors was assessed using the Variance Inflation Factor (VIF), with all values below the threshold of 5, indicating acceptable independence. The assumptions of linearity, homoscedasticity, and normality of residuals were rigorously examined through the use of residual plots, Q–Q plots, and the Breusch–Pagan and Shapiro–Wilk tests.

All statistical analyses were carried out using IBM SPSS Statistics v28.0 and R v4.2.2 (package glm) [28, 29].

3 Results

3.1 Descriptive result

Table 3 presents the hourly average data for all measured parameters. The room temperature averaged 18.45 °C, and the relative humidity averaged 57.59%. Moreover, the average concentration of TVOC was 2148.62 ppb, the CO_2 concentration average was 737.20 ppm, the CO concentration averaged 0.14 ppm, and the formaldehyde concentration averaged 18.68 ppb. In addition, $PM_{2.5}$ averaged 5.82 µg/m^3, and PM_{10} averaged 11.23 µg/m^3.

3.2 Diurnal differences between $PM_{2.5}$ and PM_{10}

The diurnal cycles of $PM_{2.5}$ and PM_{10} are presented in Figs. 3 and 4 below. During school hours, the highest concentrations were recorded at break time between 10 and 11 am, at lunchtime (noon), and when pupils were leaving in

Table 3 Hourly average statistics of all the parameter measurements

Parameters	Range	Minimum	Maximum	Mean	Standard deviation	Standard error	95% CI
Temperature (°C)	16.60	14.20	30.80	18.45	2.23	0.10	18.25–18.65
Relative humidity (%)	25.50	39.90	65.40	57.59	4.32	0.20	57.20–58.00
TVOC (ppb)	59,994.00	6.00	60,000.00	2148.62	5456.78	249.07	1659.22–2638.01
Carbon dioxide (ppm)	1985.00	401.00	2386.00	737.20	346.87	15.83	706.09–768.31
Carbon monoxide (ppm)	0.60	LOD	0.60	0.14	0.11	0	0.13–0.15
$PM_{2.5}$ (µg/m^3)	12.00	LOD	12.00	5.82	2.31	0.11	5.61–6.02
PM_{10} (µg/m^3)	12.00	6.00	18.00	11.23	2.71	0.12	10.98–11.47
Formaldehyde (ppb)	725.00	LOD	725.00	18.68	67.67	3.09	12.61–24.75

LOD (Below the limit of detection)

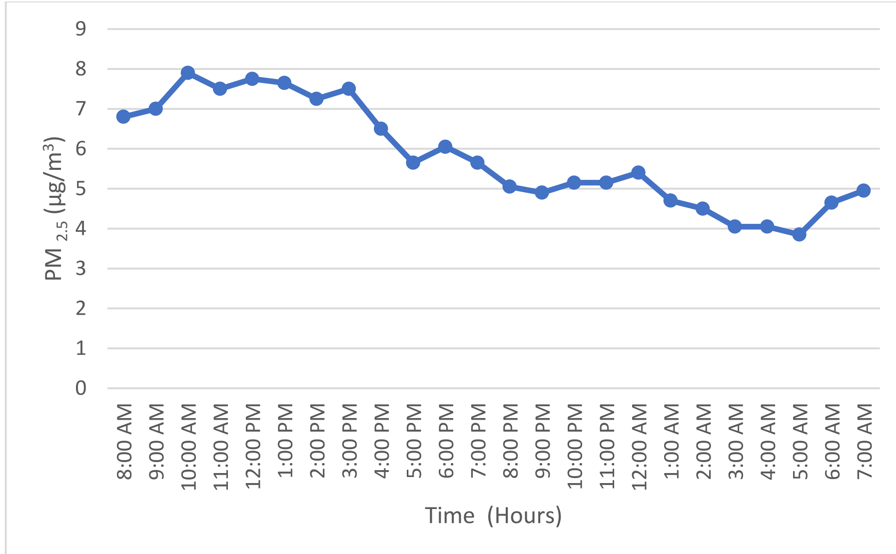

Fig. 3 Mean diurnal cycle of indoor $PM_{2.5}$ concentrations over 2 days

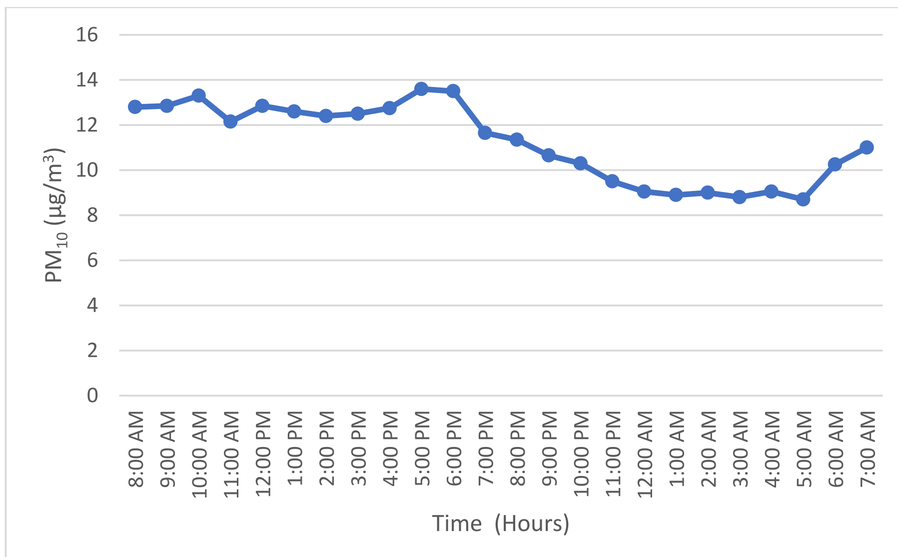

Fig. 4 Mean diurnal cycle of indoor PM_{10} concentrations over 2 days

the afternoon. Similarly, the results of $PM_{2.5}$ are similar to those of $PM_{10,}$ with the highest concentrations occurring during school hours at 10 am, 12 noon, and 3 pm.

3.3 Results of indoor air quality parameters between locations

3.3.1 Temperature

A comparison of the indoor temperatures between the rooms is shown in Fig. 5 below. A Kruskal–Wallis test indicated a significant difference in temperature across the ten rooms ($H(9) = 85.959$, $p < 0.001$). The median temperature levels were 19.55 °C for the office, 16.80 °C for the Dining Hall, 18.15 °C for the Kitchen, 19.65 °C for the Reception Class, 17.80 °C for Year 1, 18.05 °C for Year 2, 18.15 °C for Year 3, 17.65 °C for Year 4, 17.25 °C for Year 5 and 17.95 °C for Year 6 as shown in Fig. 5 below. A statistical analysis of the values across all rooms is provided in the supplementary information (Table S2).

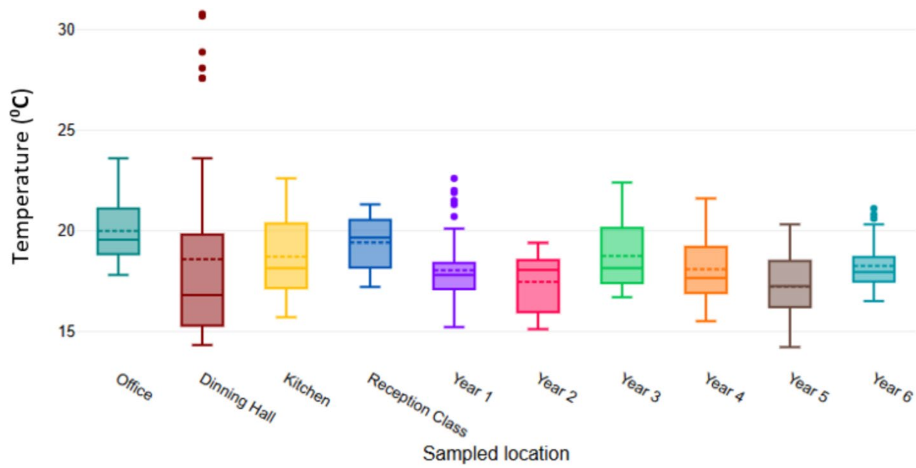

Fig. 5 Indoor temperature concentrations between rooms over 48 h at school. The midline of a box is the median of the data, dashed line in the box is the mean and the upper and lower limits are the third and first quartiles, respectively. The dots represent outliers

3.3.2 Relative humidity

A Kruskal–Wallis test indicated a significant difference in relative humidity (%) across the ten rooms ($H(9) = 64.967$, $p < 0.001$). The median relative humidity levels were 55.10% for offices, 58.25% for Dining Hall, 57.55% for Kitchen, 59.30% for the reception class, 55.35% for Year 1, 57.40% for Year 2, 59.10% for Year 3, 60.00% for Year 4, 59.90% for Year 5 and 57.75% for Year 6 as shown in Fig. 6 below. A statistical analysis of the values across all rooms is provided in the supplementary information (Table S3).

3.3.3 Total volatile organic compounds

A Kruskal–Wallis test indicated a significant difference in total volatile organic compounds (TVOC) across the ten rooms ($H(9) = 106.481$, $p < 0.001$). The median TVOC levels were 920.00 ppb for offices, 758.00 ppb for dining hall, 249.00 ppb for kitchen, 564.50 ppb for the reception class, 1473.73 ppb for Year 1, 1760.50 ppb for Year 2, 1433.00 ppb for Year 3, 1376.00 ppb for Year 4, 2010.00 ppb for Year 5 and 1342.50 ppb for Year 6 as shown in Fig. 7 below. A statistical analysis of the values across all rooms is provided in the supplementary information (Table S4).

3.3.4 Carbon dioxide

A Kruskal–Wallis test indicated a significant difference in carbon dioxide (CO_2) concentration (ppm) across the ten rooms ($H(9) = 38.998$, $p < 0.001$). The median carbon dioxide (CO_2) concentrations were 660.88 ppm for the office, 577.00 ppm for dining hall, 475.50 ppm for kitchen, 573.00 ppm for the reception class, 636.50 ppm for Year 1,

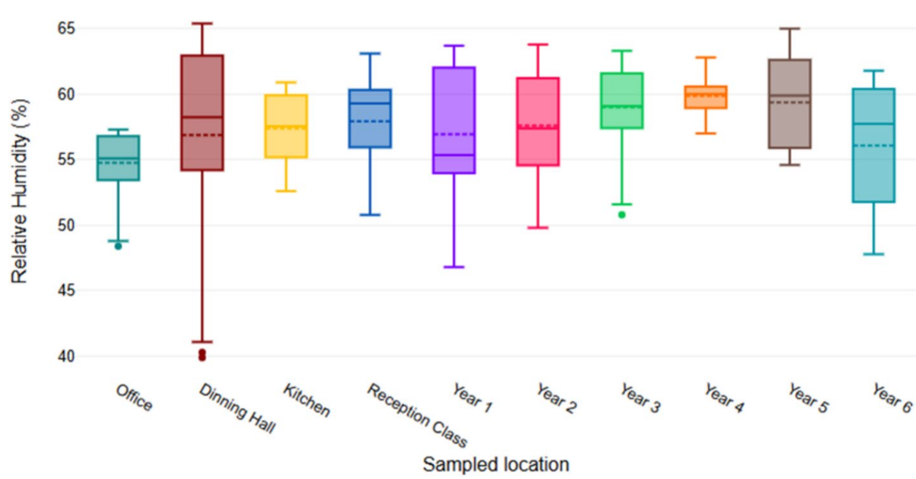

Fig. 6 Indoor relative humidity between rooms in the school. The midline of a box is the median of the data, dashed line in the box is the mean and the upper and lower limits are the third and first quartiles, respectively. The dots represent outliers

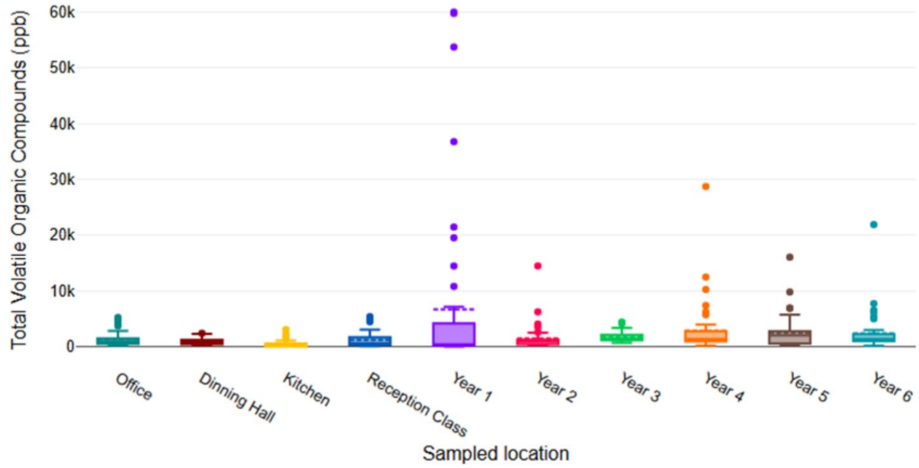

Fig. 7 Indoor TVOC concentrations between rooms in the school. The midline of a box is the median of the data, dashed line in the box is the mean and the upper and lower limits are the third and first quartiles, respectively. The dots represent outliers

596.00 ppm for Year 2, 718.00 ppm for Year 3, 589.00 ppm for Year 4, 523.00 ppm for Year 5 and 575.00 ppm for Year 6 as shown in Fig. 8 below. A statistical analysis of the values across all rooms is provided in the supplementary information (Table S5).

3.3.5 Carbon monoxide

A Kruskal–Wallis test indicated a significant difference in carbon monoxide (CO) ppm across the ten rooms ($H(9) = 78.679$, $p < 0.001$). The median carbon monoxide (CO) concentrations were 0.10 ppm for the office, 0.17 ppm for Dining Hall, 0.15 ppm for Kitchen, 0.10 ppm for the Reception Class, 0.10 ppm for Year 1, 0.10 ppm for Year 2, 0.20 ppm for Year 3, 0.20 ppm for Year 4, 0.10 ppm for Year 5 and 0.20 ppm for Year 6 as shown in Fig. 9 below. A statistical analysis of the values across all rooms is provided in the supplementary information (Table S6).

3.3.6 $PM_{2.5}$ concentrations

A Kruskal–Wallis test indicated a significant difference in $PM_{2.5}$ concentration across the ten rooms ($H(9) = 24.601$, $p = 0.03$). The median $PM_{2.5}$ concentrations were 6.00 μg/m^3 for the office, 5.00 μg/m^3 for the Dining Hall, 5.00 μg/m^3 for the Kitchen, 5.00 μg/m^3 for the Reception Class, 6.00 μg/m^3 for Year 1, 6.00 μg/m^3 for Year 2, 6.00 μg/m^3 for Year 3, 5.50 μg/m^3 for Year 4, 6.50 μg/m^3 for Year 5 and 7.00 μg/m^3 for Year 6 as shown in Fig. 10 below. A statistical analysis of the values across all rooms is provided in the supplementary information (Table S7).

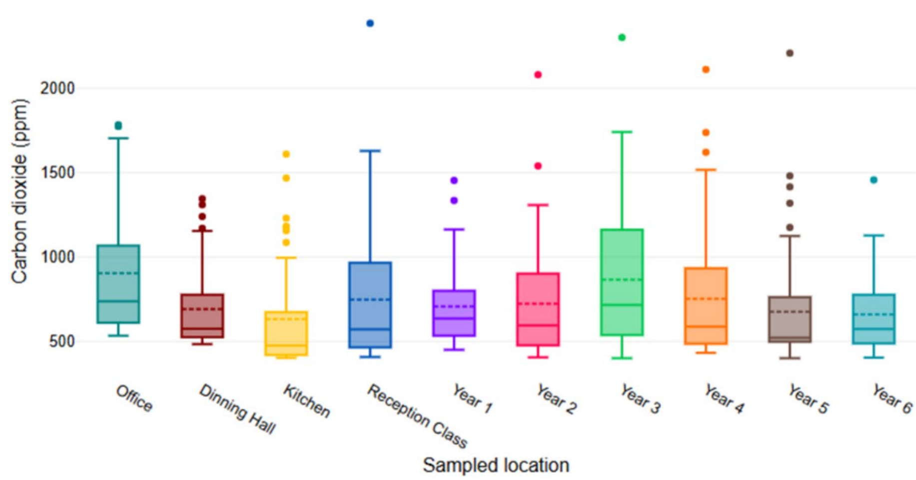

Fig. 8 Indoor CO_2 concentrations between rooms at the schools. The midline of a box is the median of the data, dashed line in the box is the mean and the upper and lower limits are the third and first quartiles, respectively. The dots represent outliers

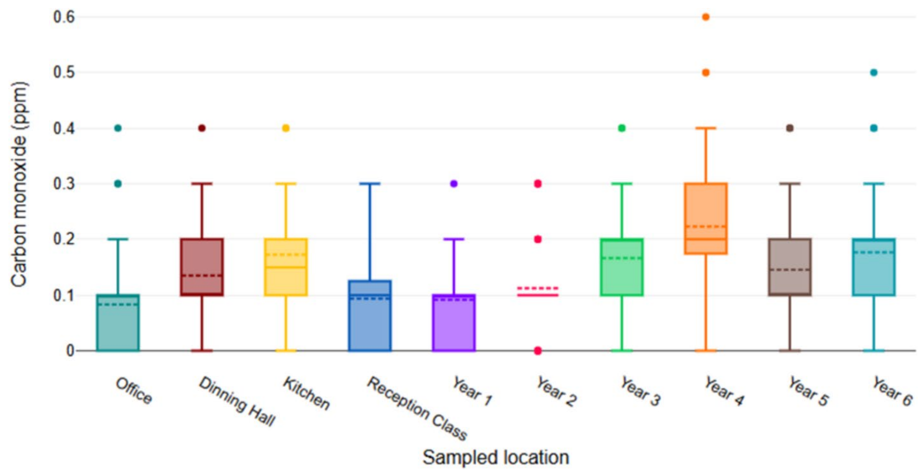

Fig. 9 Indoor carbon monoxide concentrations between rooms in the school. The midline of a box is the median of the data, dashed line in the box is the mean and the upper and lower limits are the third and first quartiles, respectively. The dots represent outliers

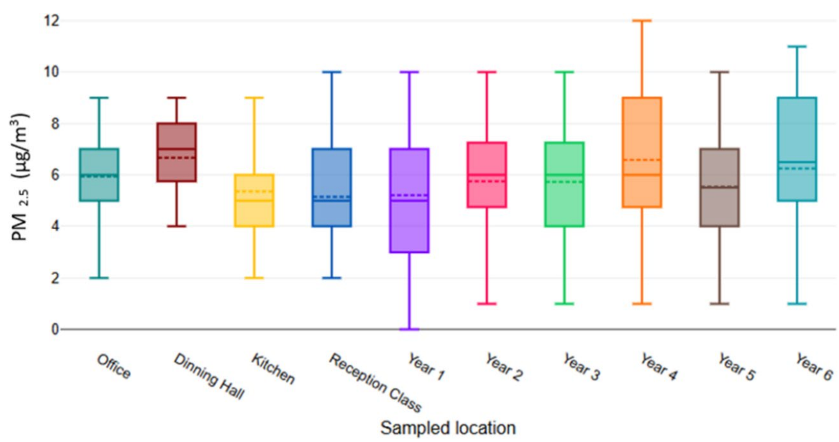

Fig. 10 Indoor $PM_{2.5}$ concentrations between rooms in the school environment. The midline of a box is the median of the data, dashed line in the box is the mean and the upper and lower limits are the third and first quartiles, respectively. The dots represent outliers

3.3.7 PM_{10} concentrations

A Kruskal–Wallis test indicated a significant difference in PM_{10} concentration across the ten rooms ($H(9) = 34.676$, $p < 0.001$). The median PM_{10} concentrations were 11.00 µg/m^3 for the office, 12.00 µg/m^3 for the Dining Hall, 10.50 µg/m^3 for the Kitchen, 12.00 µg/m3 for the Reception Class, 10.00 µg/m^3 for Year 1, 11.00 µg/m^3 for Year 2, 11.00 µg/m^3 for Year 3, 12.00 µg/m^3 for Year 4, 12.00 µg/m^3 for Year 5 and 12.00 µg/m^3 for Year 6 as shown in Fig. 11 below. A statistical analysis of the values across all rooms is provided in the supplementary information (Table S8).

3.3.8 Formaldehyde

A Kruskal–Wallis test indicated a significant difference in formaldehyde concentration across the ten rooms ($H(9) = 67.770$, $p < 0.001$). The median formaldehyde concentrations were 9.70 ppb for the office, 0 ppb for Dining Hall, 0 ppb for Kitchen, 1.00 ppb for the reception class, 0 ppb for Year 1, 0 ppb for Year 2, 0 ppb for Year 3, 13.00 ppb for Year 4, 2.00 ppb for Year 5 and 4.50 ppb for Year 6 as shown in Fig. 12 below. A statistical analysis of the values across all rooms is provided in the supplementary information (Table S9).

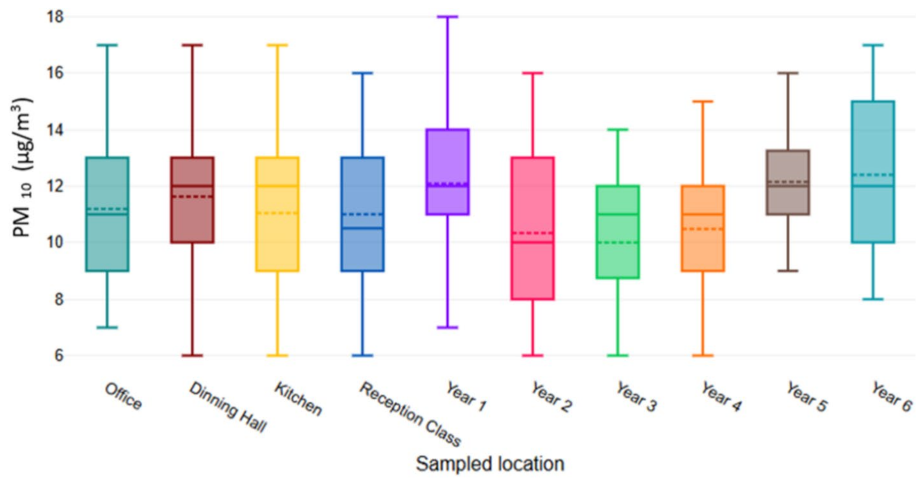

Fig. 11 Indoor PM_{10} concentrations between rooms in the school environment. The midline of a box is the median of the data, dashed line in the box is the mean and the upper and lower limits are the third and first quartiles, respectively. The dots represent outliers

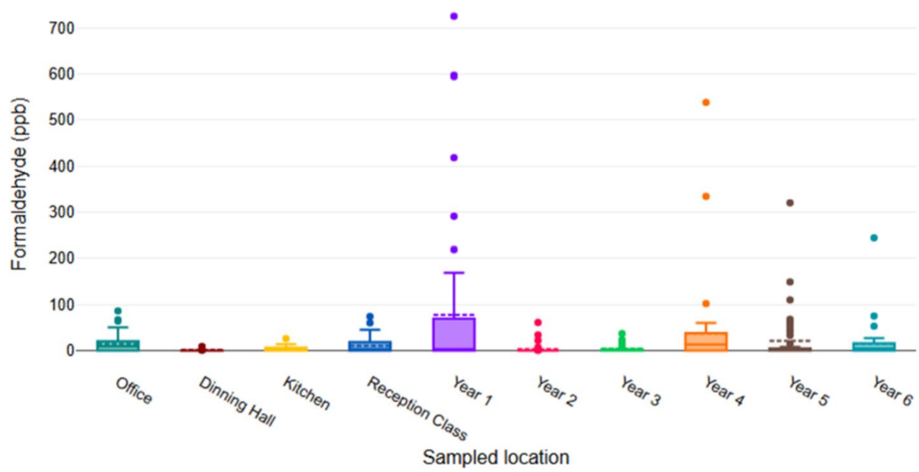

Fig. 12 Indoor formaldehyde concentration between rooms in the school. The midline of a box is the median of the data, dashed line in the box is the mean and the upper and lower limits are the third and first quartiles, respectively. The dots represent outliers

3.3.9 Spearman correlation

The Spearman correlation coefficient between the indoor temperature and the indoor relative humidity was significant ($p < 0.01$). A weak negative association was found between the indoor temperature and relative humidity (Spearman $r = -0.170$, $p < 0.01$).

3.4 Linear regression model

In order to explore the interrelationships among various pollutants, a multiple regression was conducted, with relative humidity, PM2.5, PM10, TVOCs, carbon monoxide and formaldehyde as the predictors, with levels of carbon dioxide as the dependent variable. Overall, the results showed the utility of the predictive model was significant, $F(7472) = 49.00$, $R^2 = 0.42$, $p < 0.001$. Some of the predictors explain a large amount of the variance between the variables (42%). The results showed that $PM_{2.5}$, temperature and relative humidity were significant positive predictors of carbon monoxide ($\beta = 0.20$, $t = 5.29$, $p < 0.001$, $\beta = 0.59$, $t = 13.64$, $p < 0.001$ and $\beta = 0.29$, $t = 7.34$, $p < 0.001$ respectively). The results showed that PM_{10} ($\beta = -0.00$, $t = -0.007$ $p = 0.994$, TVOCs, $\beta = -0.18$, $t = 1.65$ $p = 0.100$), CO $\beta = -0.01$, $t = 0.358$ $p = 0.721$ and formaldehyde $\beta = -0.08$, $t = -0.783$ $p = 0.434$) were not significant predictors of CO_2.

Table 4 Recommended levels of indoor air quality parameters according to World Health Organisation

Parameters	Optimum or recommended levels	References
Temperature (°C)	18 °C to 24 °C	[32, 33]
Relative humidity (%)	40%–60%	[32, 33]
TVOC (ppb)	Below 500 ppb	[32, 33]
Carbon dioxide (ppm)	Below 800 ppm	[32, 33]
Carbon monoxide (ppm)	Below 17.5 ppm	[32, 33]
$PM_{2.5}$ (μg/m^3)	Below 15 μg/m^3	[32, 33]
PM_{10} (μg/m^3)	Below 45 μg/m^3	[32, 33]
Formaldehyde (ppb)	Below 40 ppb	[32, 33]

4 Discussion

The present study aimed to analytically compare the indoor air quality parameters in 10 rooms of a primary school and identify any significant changes using uHoo Aura portable monitors [30, 31]. The World Health Organisation (WHO) air quality recommended levels are shown in Table 4 [32].

Studies have shown that workplaces, including classrooms, should be maintained at a 'reasonable' temperature, even if there is no legal minimum or maximum temperature. A periodic temperature check is necessary, and government guidelines on workplace temperatures, which require a 'reasonable' indoor temperature, should be followed, particularly in classrooms where people are not performing physical work. The guidance states a minimum of 16 °C, but there are no guidelines for maximum temperature. This study reported the mean temperature within the school to be 18.45 °C ± 2.23, as shown in Table 3. Previous studies have reported that the comfortable temperature for 11–to 16-year-old children in the temperate climate of England is 16.5 °C during winter [34] and 19.1 °C during summer [35]. Furthermore, the comfort temperature for 7–11-year-old children is 20.5 °C during spring [36].

The thermostat of the chosen school studied was set at 19 °C during the school period; for countries with temperate or colder climates, such as the United Kingdom, 18 °C has been proposed as a safe and well-balanced indoor temperature to protect the health of the general population during cold seasons, including the school environment [37–39]. This study revealed significant differences in median temperatures between the office and kitchen, compared with those of the other rooms in the school, as shown in Fig. 5. Although not exceeding 20 °C, the higher temperature could be attributed to equipment in the locations, such as printers and other heat-generating equipment, as well as cooking appliances in the kitchen.

Table 3 presents the relative humidity in the rooms, with a mean of 57.59% ± 4.32. This finding aligns with other studies [40–43]. The WHO reported that a humidity level between 40 and 60% is ideal for indoor rooms, as this balances the moisture levels in the air and keeps occupants safe from harm [44, 45]. If the relative humidity exceeds 60%, measures should be implemented to decrease the level because it could begin to affect the occupants. A high indoor relative humidity of more than 60% can lead to problems such as mould growth and condensation on windows. Increased respiratory symptoms and the spread of viruses and bacteria can also occur in high-humidity environments.

The relative humidity of every rooms was ideal. Moreover, Fig. 6 shows a significant difference in relative humidity between the rooms, which could be attributed to the state of the rooms during the study. However, all the relative humidity readings were below 60%.

Particulate matter can be naturally occurring or human-derived. This study has shown that the permissible levels of particulate matter were attained for both $PM_{2.5}$ (15 μg/m^3) and PM_{10} (45 μg/m^3). Table 3 shows that the particulate matter concentrations were negligible, with mean levels of $PM_{2.5}$ of 5.82 μg/m^3 ± 2.31 and PM_{10} of 11.23 μg/m^3 ± 2.71. While differences existed in PM $_{2.5}$ and *PM* $_{10}$ across the rooms possibly due to factors like room size, usage, ventilation, all particulate levels were within safe limits. Figures 3 and 4 present the diurnal profiles of particulate matter concentrations within the school. The highest particulate matter PM $_{2.5}$ concentrations were at 10 am (break time), noon (lunchtime) and 3 pm (after school). However, the highest particulate matter (PM_{10}) concentrations were observed at 10 am (break time), noon (lunchtime), and 3 pm to 6 pm (after school). Significant differences were detected between the locations, as shown in Figs. 10 and 11, but none exceeded the recommended levels of $PM_{2.5}$ (< 15 μg/m^3) and PM_{10} (< 45 μg/m^3). The PM levels in this study are below the World Health Organisation's (WHO) daily limit, as shown in Table 4.

Within the rooms in the schools, the mean total volatile organic compound (TVOC) content was 2148.62 ppb ± 5456.78 ppb, as shown in Table 3; this was too high. TVOCs are emitted as gases from certain liquids, including chemicals, some of which have short- and long-term adverse health effects. It has been reported that TVOC concentrations are higher indoors than outdoors. Sources of TVOC include paints, paint strippers, cleaning supplies, disinfectants, building materials, office equipment such as copiers, printers, correction fluid, craft materials used in schools, permanent markers, glue, and photographic solutions [46–48]. Most of these products can release organic compounds when used and stored to some degree. One of the primary reasons TVOCs are built indoors is a lack of ventilation. Increasing ventilation when TVOC levels are high can lower TVOC levels indoors in schools [49].

Figure 7 illustrates significant differences between the rooms, which are attributed to the reasons mentioned earlier. TVOC concentrations over 2200 ppb are reported to be unhealthy and could result in both short-term and long-term effects. The recommended TVOC level should be below 500 ppb as recommended by World Health Organisation as shown in Table 4. Elevated readings of total volatile organic compounds (TVOCs) and several significant outliers were noted in the sampled classrooms. To better understand these findings, we sought to identify potential sources and contributing mechanisms. In primary schools including St Peters Primary school, likely indoor sources include episodic activities (such as the use of art and craft solvents, markers, and class cleaning events), furniture (including adhesives and laminates), cleaning and disinfection activities, as well as chemical storage. Additionally, transient infiltration of outdoor emissions played a role. It is important to consider that instrument or sampling artifacts, such as sensor drift, calibration errors, or transient cross-sensitivity, can also result in misleading peaks. Our field campaign employed sequential room-by-room monitoring, rather than fully simultaneous multi-point sampling, which means that brief peaks may indicate temporal events rather than persistent spatial differences. Therefore, we recommend follow-up targeted speciation using sorbent/thermal desorption sampling and Gas Chromatography-Mass Spectrometry (GC–MS), alongside corroborative colocated real-time sensors to differentiate between episodic emissions, persistent sources, and measurement artifacts. The absence of continuous outdoor monitoring limits our ability to quantify indoor–outdoor gradients during high-TVOC episodes.

Carbon dioxide has long been used as an indicator of good indoor air quality, primarily due to its association with ventilation. When carbon dioxide levels are high, this may indicate that the space is not well-ventilated. The mean CO_2 concentration in the school rooms was 737.20 ppm ± 346.87, as shown in Table 3. The ideal level of CO_2, which should be less than 800 ppm, is needed to reduce the risk of lung inflammation. This finding in the study is consistent with previous studies in educational settings, where the CO_2 concentration was less than the proposed level of 800 ppm [50].

However, Fig. 8 shows significant differences in median CO_2 concentrations across the rooms. The office had a median concentration of CO_2 that was higher than that of the kitchen, years 5 and 6, and the reception area. This could be due to the office's activities and the size of the room. Although the CO_2 level in the office was below the acceptable limit (see Table 4), no action was needed.

The primary source of exposure to CO in schools is the use of cooking or other fuel-burning appliances. The mean CO concentration in the school rooms was 0.14 ppm ± 0.11 ppm, as shown in Table 3. The optimal level should be 17.5 ppm, as shown in Table 4. There were significant differences between the rooms with varying CO concentrations, but none exceeded an unacceptable level, as shown in Fig. 9.

The mean formaldehyde concentration in the school rooms was 18.68 ppb ± 67.67 ppb, as shown in Table 3. The optimal level should be below 40 ppb, as shown in Table 4. There were significant differences in formaldehyde concentrations between the rooms and the office, particularly in year four and at the other locations, as shown in Fig. 10. However, none of the concentrations exceeded the recommended level. Two significant sources of formaldehyde emissions are building materials and furniture. A similar study conducted in two schools in France over several weeks reported formaldehyde concentrations below 40 ppb, with formaldehyde concentrations ranging from 25.6 to 33.8 ppb in the first school and 14.7 to 26.8 ppb in the second school [51]. Furniture, flooring and painting accounted for the emissions.

4.1 Interrelationships among various pollutants

The Ordinary Least Squares (OLS) linear regression model identified temperature, relative humidity, and $PM_{2.5}$ as the most strongly associated variables with indoor CO_2 concentrations in this study. The positive association between CO_2 and temperature/humidity likely reflects confounding with occupancy (occupied rooms tend to be warmer, more humid, and have higher CO_2). The positive association with $PM_{2.5}$ may reflect co-occurrence of occupancy/activity sources (resuspension, indoor activities) or shared temporal patterns (times of day when rooms are occupied). However, model diagnostics reveal multicollinearity and residual autocorrelation, and several predictors have heavy tails; therefore results should be interpreted as indicative associations to guide further targeted studies rather than definitive causal estimates [52].

Follow-up analyses using mixed-effects and time-series approaches and incorporating occupancy/ventilation data are recommended in future research.

The empirical evidence presented in this study establishes a significant link between indoor CO_2 concentrations and concurrent thermal and particulate parameters within primary school classrooms. The identified positive correlations between CO_2 levels and both temperature and relative humidity indicate that elevated CO_2 concentrations occur during periods of increased occupancy and inadequate ventilation. This finding aligns with existing literature on indoor air quality in educational settings. Previous research has similarly documented that CO_2 levels exceeding 1000 ppm can signal insufficient air exchange, which may adversely affect both comfort and cognitive performance [53–55]. Thus, this study contributes to the understanding of how indoor environmental factors influence air quality and learning conditions in schools.

The observed significant effect of $PM_{2.5}$ on CO_2 concentrations may be indicative of shared temporal patterns rather than a direct causal relationship. In educational settings, classroom activities such as movement, cleaning, or the resuspension of dust can elevate $PM_{2.5}$ levels, particularly during periods of high occupancy, leading to coinciding spikes in CO_2 concentrations. This co-variability between particulate matter and ventilation parameters has been documented in similar educational contexts [56, 57], suggesting that a complex interplay of factors influences the dynamics of indoor air quality.

The sporadic exceedances of total volatile organic compounds (TVOCs), which sometimes significantly surpass permissible levels, can be attributed to the off-gassing of materials, the use of certain cleaning products, or insufficient purge ventilation after various indoor activities. These observations align with prior research findings related to post-occupancy assessments of low-ventilation classrooms [58, 59]. Such insights underscore the critical need for improved ventilation strategies and the careful selection of materials and cleaning agents in indoor environments to mitigate health risks associated with airborne pollutants.

Although the multivariable model accounted for approximately 42% of the variance in CO_2 concentrations, the presence of multicollinearity and autocorrelated residuals suggests that the underlying relationships may be more complex than represented. Future research should employ mixed-effects or time-series models to address repeated measures, autocorrelation, and room-level heterogeneity adequately. Additionally, incorporating direct occupancy counts, ventilation rates, or CO_2-based air exchange measurements would substantially enhance the model's interpretability and support more robust causal inferences.

The findings underscore that, despite the apparent maintenance of school buildings, instances of inadequate ventilation can occur frequently and coincide with heightened levels of indoor pollutants. The implementation of continuous indoor air quality (IAQ) monitoring, coupled with adaptive ventilation management and effective material source control, is essential for achieving compliance with World Health Organisation (WHO) indoor air quality standards and fostering healthier educational environments.

This study evaluated the indoor air quality (IAQ) of St. Peter's Catholic Primary School, Sittingbourne, Kent, between February and March 2024, using a multi-parameter uHoo Aura air quality monitor. The results showed that most IAQ parameters, including particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), and formaldehyde (HCHO), were within the WHO (2021) recommended limits. However, elevated concentrations of total volatile organic compounds (TVOCs) and sporadic increases in carbon dioxide (CO_2) were observed during school hours, particularly at times of high occupancy and limited ventilation. These findings indicate that, although the school generally maintains acceptable IAQ conditions, inadequate ventilation and indoor emission sources occasionally compromise air quality, potentially affecting comfort, health, and learning performance.

4.2 Comparing indoor and outdoor air quality in schools

A study by Handy et al. (2025) examined $PM_{2.5}$ concentrations in UK schools and found that indoor levels often exceed outdoor levels. Indoor $PM_{2.5}$ is primarily affected by activities such as cleaning, the use of certain classroom materials, and inadequately maintained ventilation systems. In contrast, outdoor $PM_{2.5}$ largely arises from traffic emissions and industrial activities. The study highlights the importance of evaluating both indoor and outdoor air quality to assess environmental health risks in schools and recommends measures such as effective ventilation and air purification to reduce the adverse health impacts of indoor pollution [60].

Moreover, an observational study across 24 UK schools over 10 days found significant disparities in air quality, with average indoor air quality indices (AQIs) approximately 44% higher than the city-wide average. Notably, only 27% of schools had indoor AQIs consistent with the city-wide average; 59% exceeded it, while 14% were below. Furthermore, rural schools had slightly higher indoor AQIs than urban ones. Regarding specific pollutants, the primary indoor contaminants were volatile organic compounds (VOCs), which can cause eye, nose, and throat irritation, and particulate matter (PM_{10}), which can aggravate respiratory and cardiovascular conditions. Additionally, 33% of schools had average walk-exposure AQIs above the city average, with the highest being 7 times the lowest. Altogether, these results indicate a need for targeted interventions, such as enhanced ventilation, to reduce indoor air pollution in schools [61].

In addition to particulate matter assessments, a study by Wood et al. (2024) indicates that daily average CO_2 levels in UK classrooms typically remain below the recommended threshold of 800 ppm for adequate ventilation. This suggests that indoor air quality is generally maintained within acceptable limits, thereby potentially minimizing health risks associated with poor ventilation [62].

A study by Pulimeno et al. (2020) found that approximately 85% of students were exposed to $PM_{2.5}$ and PM_{10} concentrations exceeding the World Health Organization's safe thresholds. Exposure to these particulate matter pollutants is associated with respiratory and cardiovascular problems, suggesting that indoor air quality may continue to pose significant health risks despite adequate ventilation measures [63].

These studies emphasize the critical need to evaluate both indoor and outdoor air quality when assessing environmental health risks in educational settings. Since outdoor air quality can significantly influence indoor conditions, implementing effective ventilation systems and air purification technologies is essential to mitigate indoor pollutant concentrations and safeguard students' health.

4.3 Recommendation

To improve IAQ in primary school environments, the implementation of proactive ventilation management and source control measures is recommended. Enhancing natural ventilation through scheduled window and door openings during and after classes can significantly reduce CO_2 accumulation. Additionally, replacing conventional cleaning products and teaching materials with low-VOC alternatives, along with conducting purge ventilation after cleaning activities, can mitigate VOC exposure. Regular IAQ monitoring using portable multi-sensor devices should be incorporated into school management practices to detect pollutant peaks and assess intervention effectiveness. Training programmes for staff and students on IAQ awareness and ventilation behaviour would further reinforce sustainable air management practices indoor and outdoors.

4.4 Limitations

While the study provides valuable baseline data, it is subject to certain limitations. The research was conducted at a single school during a limited winter–spring period (February to March 2024), thereby excluding potential seasonal variations. Ventilation rates were inferred indirectly from CO_2 levels rather than measured directly, and outdoor air quality influences were not continuously monitored. Furthermore, the uHoo Aura monitor, though reliable, is subject to sensor drift and cross-sensitivity, and its measurements were not validated against reference-grade instruments. These factors introduce uncertainty and suggest that the observed pollutant associations should be interpreted as indicative rather than definitive. This study acknowledges several limitations that should be considered. First, the monitoring strategy employed a sequential measurement design, wherein indoor environmental parameters were collected room by room rather than simultaneously across all sampling locations. While this approach enabled us to cover a wider range of microenvironments with limited equipment, it introduces a potential temporal bias, as environmental conditions can fluctuate significantly over time. Consequently, the observed differences between rooms may partially reflect short-term temporal variations rather than true spatial distinctions. Future research would benefit from parallel, multi-sensor deployments that allow for simultaneous monitoring, thereby facilitating a better isolation of spatial variability.

Second, the study did not incorporate outdoor measurements of environmental conditions such as ambient temperature, humidity, or pollutant concentrations. In the absence of paired outdoor data, it becomes challenging to fully understand the contributions of outdoor infiltration, seasonal variations, or meteorological factors to the indoor environment. This limitation also constrains our ability to quantify indoor–outdoor gradients or assess how building characteristics influence pollutant penetration. Future work that incorporates continuous outdoor monitoring would enhance the comparability of results and provide a more comprehensive context for interpreting indoor measurements within broader environmental dynamics.

4.5 Future research

Future research should expand the temporal and spatial scope of IAQ assessment to include multi-seasonal monitoring across diverse school types and urban contexts. Integrating simultaneous indoor–outdoor sampling would clarify pollutant source contributions, while the use of mixed-effects or time-series models could better account for repeated measures and temporal variability. Incorporating real-time occupancy and ventilation data would improve model robustness and causal interpretation. Additionally, investigating the relationships between IAQ parameters and student health or cognitive performance could provide more substantial evidence for policy action. Overall, maintaining good indoor air quality is vital to supporting student wellbeing and academic success. Schools should adopt continuous IAQ monitoring and ventilation improvement strategies as integral components of healthy learning environments.

5 Conclusion

This study assessed the indoor air quality (IAQ) at St. Peter's Catholic Primary School in Sittingbourne, Kent, United Kingdom, from February to March 2024, utilising a uHoo Aura air quality monitor. The findings revealed that while temperature, humidity, particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), and formaldehyde (HCHO) levels remained within the World Health Organisation (WHO) recommended limits, the concentrations of total volatile organic compounds (TVOCs) and carbon dioxide (CO_2) occasionally surpassed permissible thresholds. This was particularly evident during periods of high classroom occupancy and limited ventilation. These results underscore that even in comparatively well-maintained school environments, inadequate ventilation and the presence of indoor emission sources can significantly impact IAQ, with potential effects on student comfort, health, and cognitive performance.

The study emphasises the critical need to integrate indoor air quality (IAQ) management into school operations. This can be accomplished through proactive ventilation strategies, the use of low-emission materials and cleaning products, and regular IAQ monitoring. While the research was confined to a single site and a brief monitoring period, it offers valuable baseline data for similar educational settings across the United Kingdom. Future studies should adopt multi-seasonal and multi-site approaches, incorporate direct measurements of ventilation and occupancy, and utilise advanced statistical or time-series modelling to capture pollutant dynamics more effectively. Sustaining improvements in IAQ is vital for creating healthier and more effective learning environments.

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Data availability Data is provided within the manuscript.

Declarations

Ethics approval and consent to participate All experimental protocols were approved by Nottingham Trent University Ethics review board. The study was conducted in accordance with the applicable ethical guidelines established by Nottingham Trent University, as well as relevant international standards for research. The study was approved by Nottingham Trent University Ethics Committee. Informed consent was obtained from all subjects involved in the study and the head of the school.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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