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Optimizing sensor placement in classrooms: a focus on temperature, relative humidity and CO₂

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ABSTRACT

In developed countries, people spend most of their time indoors; therefore, indoor environmental quality has a direct impact on human health. Assessing indoor conditions requires the continuous monitoring of several parameters. In this context, the present study aims to analyze the influence of sensor placement on the monitoring of CO₂ concentration, temperature and relative humidity in a primary school classroom. To this end, several sensors were installed in different locations within the classroom, and real-time data were collected for CO₂ concentration, temperature and relative humidity. The results showed that CO₂ measurements exhibited deviations from the mean ranging from 1% to 11% depending on sensor position, with the highest concentrations recorded near the students' working area. In contrast, deviations in temperature and relative humidity were minimal, ranging between 1–3% and 0–5%, respectively. It is concluded that the most appropriate location for sensor placement in this type of study is on the teacher's desk, as it allows for minimal interference with teaching activities, facilitates teacher supervision of the device, is positioned near the main emission source, ensures proper sensor operation, and yields representative data of the classroom environment in terms of CO₂, temperature and relative humidity.

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Sensors; schools; temperature; relative humidity; CO₂ concentration

Introduction

People spend approximately 75–90% of their time indoors (Klepeis et al., 2001). In this context, various symptoms have been associated with indoor air pollution in enclosed and poorly ventilated buildings characterized by low-quality materials and ventilation systems (Berenguer Subils, 2019). As several studies have shown, indoor pollutants can significantly affect human health (Stellman et al., 1998), particularly by impacting the respiratory and cardiovascular systems (Romero Placeres et al., 2006).

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Children are among the most vulnerable population groups with respect to poor indoor air quality (IAQ). They typically spend approximately 25–30% of their day in school. The available literature highlights the detrimental effects of indoor air pollution in schools on memory, attention, academic performance, and productivity (Barroso Martínez, 2018; Forero Garzon & Luengas Pinzón, 2021; Gascon & Sunyer, 2015; Hernández-Flórez et al., 2013; Palacios Espinoza & Espinoza Molina, 2014; Peña Brito, 2018; Pérez Silva et al., 2018; Ubilla & Yohannessen, 2017; Vargas Marcos & Gallego Pulgarín, 2005; Wargocki, 2016).

Numerous studies have investigated indoor environmental conditions in educational buildings. Those focusing on CO₂ concentrations have reported elevated concentrations in indoor spaces, influenced by architectural and design characteristics (Al-Hemoud et al., 2018; Barmparesos et al., 2018; Fang, 1998; Llabrés-Morey et al., 2024; Sivanantham et al., 2021; Zhong et al., 2017), the location and orientation of the school (PEP-Plataforma de Edificación Passivhaus & UBU-Universidad de Burgos, 2020; Sivanantham et al., 2021; Zomorodian et al., 2016), related health effects (Baloch et al., 2020; Madureira et al., 2015) and the regulatory frameworks (Genjo, 2022; McLeod et al., 2022; Singh et al., 2019). Ventilation has been identified as a key factor in maintaining adequate IAQ (Aguilar et al., 2022; de la Hoz-Torres et al., 2022; Di Gilio et al., 2021; Ding et al., 2023; Gil-Baez et al., 2021; Godwin & Batterman, 2007; Larsson & Olsson, 1992; Scheff et al., 2000; Tzoutzas et al., 2021).

Various monitoring devices are available to assess indoor air quality. Since the review by J.E. Thompson in 2016, notable advancements in sensor technologies have emerged (Thompson, 2016). While some limitations persist, there have been substantial improvements in data presentation and sensor quality. For example, Hernández-Gordillo et al. (2021) highlights significant progress in portable sensors, which are now more versatile and easier to deploy across different types of buildings (Hernández-Gordillo et al., 2021). These devices are increasingly affordable; however, they are typically limited to monitoring only two or three parameters (Coleman & Meggers, 2018).

Current standards for the use, quantity, and placement of sensors are often vague and do not consider several variables that can influence measurements, such as sensor specifications, proximity to airflow and/or occupants, HVAC systems, or the architectural and spatial characteristics of the monitored environment (Al Samam et al., 2022; Marín et al., 2025; Sá et al., 2024). According to ANSI/ASHRAE Standard 62.1, the breathing zone in occupied spaces is defined between 0.75 and 1.80 m above the floor and separated more than 0.6 m from walls or fixed air-conditioning units (ANSI/ASHRAE 62.1, 2010). ASTM D6245-07 recommends avoiding measurements near people, specifically maintaining at least 2 m of distance from any occupant (ASTM D6245-07, 2012). Taylor, based on LEED certification and Standard 62.1 (Taylor, 2005), suggests monitoring CO₂ concentrations between 0.90 and 1.80 m above the floor (Mahyuddin et al., 2014).

These standards emphasize selecting a representative measurement location to ensure reliable and stable readings – i.e. positions that are not directly influenced by air currents or too far from pollution sources. Therefore, they generally recommend placing sensors near the centre of the room, at a specified height, and away from HVAC flows (Bulińska et al., 2014; Mahyuddin et al., 2014; Pei et al., 2019; Waeytens & Sadr, 2018; Yang et al., 2021).

In Spain, UNE-EN ISO 16000-1 states that the centre of the room is the most suitable location, or alternatively, at least 1 m from any wall and between 1 and 1.5 m above the floor, avoiding corners, sunlit areas, ducts, drafts, or HVAC equipment (Asociación Española de Normalización y Certificación (AENOR), 2006).

However, placing sensors in accordance with these guidelines can be challenging due to technical or contextual limitations. These may include:

- The need for a power supply, which may constrain placement to locations near electrical outlets.
- Children's curiosity, which can interfere with accurate data collection if they handle the sensors.
- The requirement that sensors do not interfere with routine classroom activities.

As a result, it is common practice to install sensors in concealed areas or on the teacher's desk.

UNE 171330-2 specifies that the minimum number of sampling points (P) depends on the area (S) being measured and is calculated using the formula (Asociación Española de Normalización y Certificación (AENOR), 2008):

Equation 1: Sampling points according to UNE 171330-2.

$$P = 0,15 \times \sqrt{S}$$

where S = area (m^2).

According to this formula, classrooms exceeding $177 m^2$ require at least two sampling points. Therefore, in typical classrooms of approximately $50 m^2$, the use of a single sensor may be adequate.

Literature review

Previous studies have tested various sensor locations and demonstrated that CO_2 variability depends on both occupancy and spatial factors (Bulińska et al., 2014; Mahyuddin et al., 2014; Mahyuddin & Essah, 2024; Marín et al., 2025; Pei et al., 2019; Sá et al., 2024; Sørensen & Kristensen, 2024). N. Mahyuddin et al. found that while ventilation type can lead to variations in monitoring indoor CO_2 levels, these differences are generally not substantial (Mahyuddin et al., 2014). G. Pei et al. used simulations to estimate CO_2 distribution based on ventilation effects and human breathing; although some differences were noted within the breathing zone, they were minor, and the results are based on simulations (Pei et al., 2019). J. Waeytens and S. Sadr conducted CFD simulations in laboratory spaces to analyze the dispersion of volatile organic compounds (VOCs); they found that measurements taken far from the emission sources were not representative and highlighted the need for physical experiments to confirm airflow patterns (Waeytens & Sadr, 2018). S. B. Sorensen and K. Kristensen examined both total VOCs (TVOCs) and CO_2 , demonstrating that while both are affected by ventilation, TVOCs are also influenced by classroom activities (Sørensen & Kristensen, 2024).

Y. Yang used a mobile robotic station to measure CO₂ along a defined path, comparing results with those from fixed sensors; the mobile system recorded slightly higher values, but the difference was not significant and could be attributed to the robot's movement (Yang et al., 2021). S. Salam et al. conducted in situ measurements and simulations of IAQ parameters using multiple sensors placed throughout a space; their findings showed negligible variations in CO₂ and relative humidity, whereas temperature exhibited greater variability due to heat sources such as occupants, airflow, of HVAC systems (Al Samam et al., 2022). D. Marín et al. analyzed deviations between sensors of different specifications in classrooms and university spaces, confirming the influence of sensor type and placement; they found that the most reliable data came from sensors placed away from direct airflow (Marín et al., 2025).

In addition to studies focused on sensor placement, several recent investigations have examined indoor environmental quality in school buildings with explicit consideration of occupied and unoccupied periods. These works highlight the importance of distinguishing occupancy conditions when interpreting IAQ measurements and comparing results across studies.

Guidance documents such as the Reference Guide to Indoor Air Quality in Schools published by the U.S. Environmental Protection Agency clearly state that CO₂ concentration in classrooms is strongly linked to occupancy patterns and ventilation practices and recommend measurements within the occupied zone to ensure representativeness during teaching hours (US EPA, 2025).

Field studies conducted in educational buildings report that CO₂ levels typically increase during occupied periods and decrease to near-outdoor concentrations during breaks or unoccupied hours, particularly when natural ventilation is applied (Adekunle, 2021; Babich et al., 2023; Kuurola et al., 2023).

Several experimental investigations show that spatial differences between sensor locations are more pronounced during occupied hours, when occupant density and activity generate localized CO₂ gradients. In contrast, during unoccupied periods, CO₂ concentrations tend to become more homogeneous throughout the space, reducing the influence of sensor placement (Oldham & Kim, 2020; Sanguinetti et al., 2022).

With respect to thermal parameters, previous research indicates that temperature and relative humidity are less sensitive to short-term occupancy changes and are more influenced by sensor height, proximity to heat sources, and building envelope characteristics (Kuurola et al., 2023; Oldham & Kim, 2020). Similar trends were observed in the present work, where temperature and relative humidity exhibited lower spatial variability than CO₂ concentration.

Motivation and objectives

The motivation for this study arises from the growing need to ensure reliable measurements of indoor air quality in schools, where CO₂ concentration, temperature and relative humidity are key indicators of student comfort, ventilation and health. Although environmental monitoring has become widespread in recent years, uncertainties persist regarding how the quantity and, especially, the location of sensors affect the accuracy and representativeness of measurements. Given that regulations and technical guides offer general recommendations that are not always supported by specific experimental

evidence for classrooms, it is necessary to systematically evaluate whether the potential influence of sensor placement on recorded values.

The main objective of this study is to analyze the influence of sensor quantity and placement on the measurement of three key indoor environmental parameters in a classroom: CO₂ concentration, temperature and relative humidity. Additionally, the results are used to compare actual sensor performance with current regulatory recommendations. To this end, four sensors capable of monitoring CO₂, temperature and relative humidity were placed in different locations within a primary school classroom, based on its architectural layout. This study aims to identify how sensor placement affects measurement results and determine the most appropriate location for accurate and representative environmental monitoring.

Methodology

The study was conducted in a classroom of a primary school, which is located in the municipality of Palma, Spain, at a latitude of 39.57° N and a longitude of 2.65° E.

The city of Palma is characterized by a Mediterranean climate, with mild winters and warm summers. During the monitoring period in March, outdoor temperatures are typically moderate, allowing classrooms to operate without the need for active heating or cooling systems. These climatic conditions favour the use of natural ventilation through window and door opening, particularly during breaks, while windows are commonly kept closed during lessons to reduce outdoor noise. This climatic context is relevant for interpreting the indoor environmental measurements and the ventilation patterns observed during the study.

To further characterize the experimental conditions, [Figure 1](#) presents the outdoor temperature and relative humidity recorded during the monitoring period by nearby weather stations located within a distance of less than 2 km (Ecowitt, 2023). The data show mild and stable outdoor conditions throughout the study, essential for interpreting the indoor environmental measurements reported in the following sections.

The selected classroom is located on the third floor, has a rectangular shape with dimensions of 6.29 × 6.12 m and a ceiling height of 2.55 m. It has a single access door to the corridor and two sliding windows (1.20 × 1.50 m each) facing the street, as shown in [Figure 2](#).

The floor is finished with terrazzo tiles, while the walls are tiled up to mid-height and then rendered and painted, like the ceiling. The windows are made of aluminum with single glazing. The classroom is equipped with a ducted fan-coil HVAC system and four fluorescent light fixtures.

During the monitoring period, the classroom was occupied by 24 students aged 7–8 years and one teacher. The classroom also contained standard school furniture and equipment such as desks, chairs, cabinets, and whiteboards, as illustrated in [Figure 3](#) and summarized in [Table 1](#).

Sensor description

Indoor monitoring was carried out using a sensor capable of measuring CO₂ concentration (ppm), temperature (°C) and relative humidity (%), as shown in [Figure 4](#). The

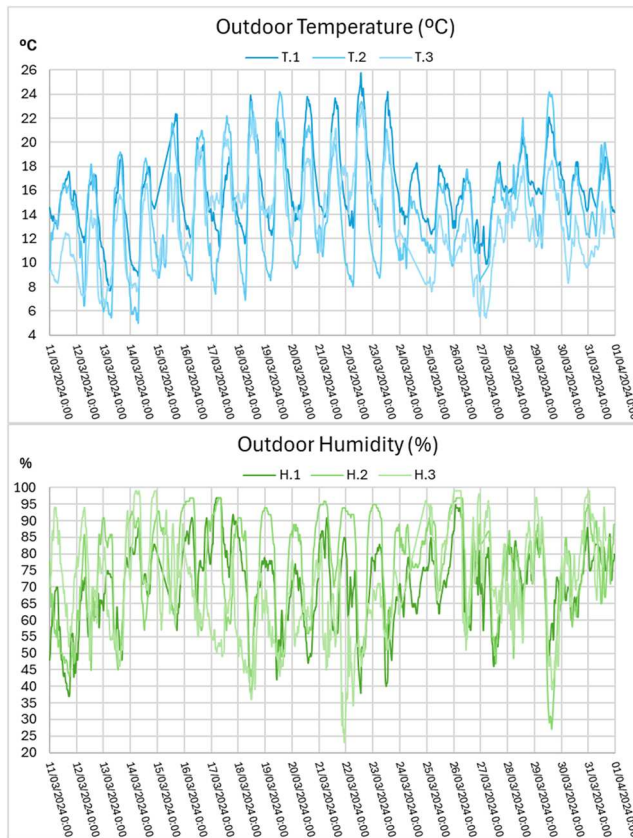


Figure 1. Outdoor conditions during the monitoring period.

sensor required a constant power supply and was connected to the school's Wi-Fi network, enabling data to be uploaded to a cloud platform every minute (ROBOTBAS, 2023), thereby facilitating subsequent analysis. CO₂ concentration was measured using a non-dispersive infrared (NDIR) sensor, while temperature and relative humidity were measured using environmental modules. The measurement ranges and accuracies are presented in Table 2 (ROBOTBAS, 2023).

After sensor selection, a calibration process was undertaken by placing the sensors together in a controlled environment with stable ventilation and no human presence. Sensor readings were monitored for 24 h to assess deviations and reset the devices if necessary. The calibration was deemed acceptable when the measurements remained within a $\pm 10\%$ deviation range, which was achieved in this case, allowing for the use of the selected sensors.

Sensor deployment

Four sensors were deployed in the classroom, as shown in Figure 5, at different heights and locations, without interfering with the normal functioning of classroom activities:

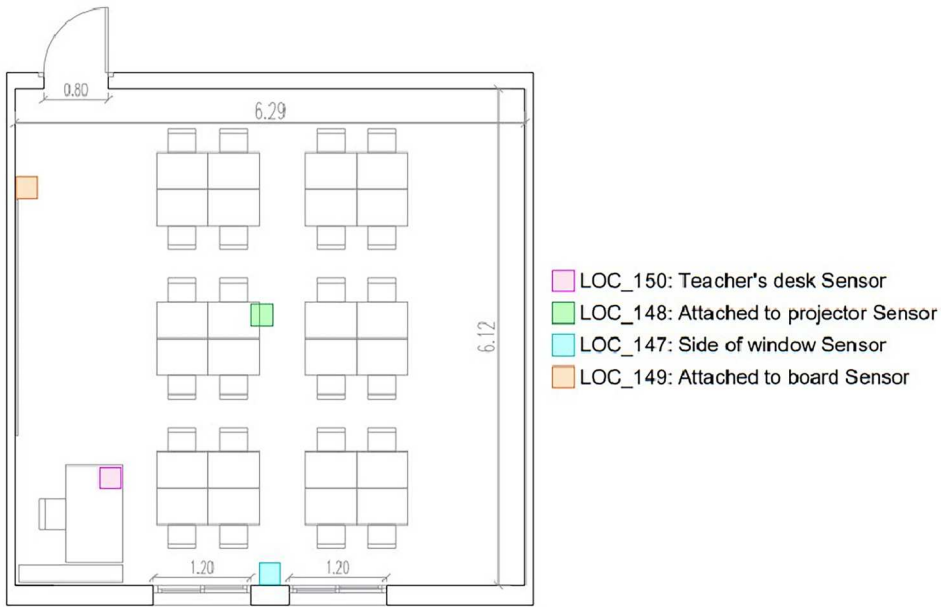
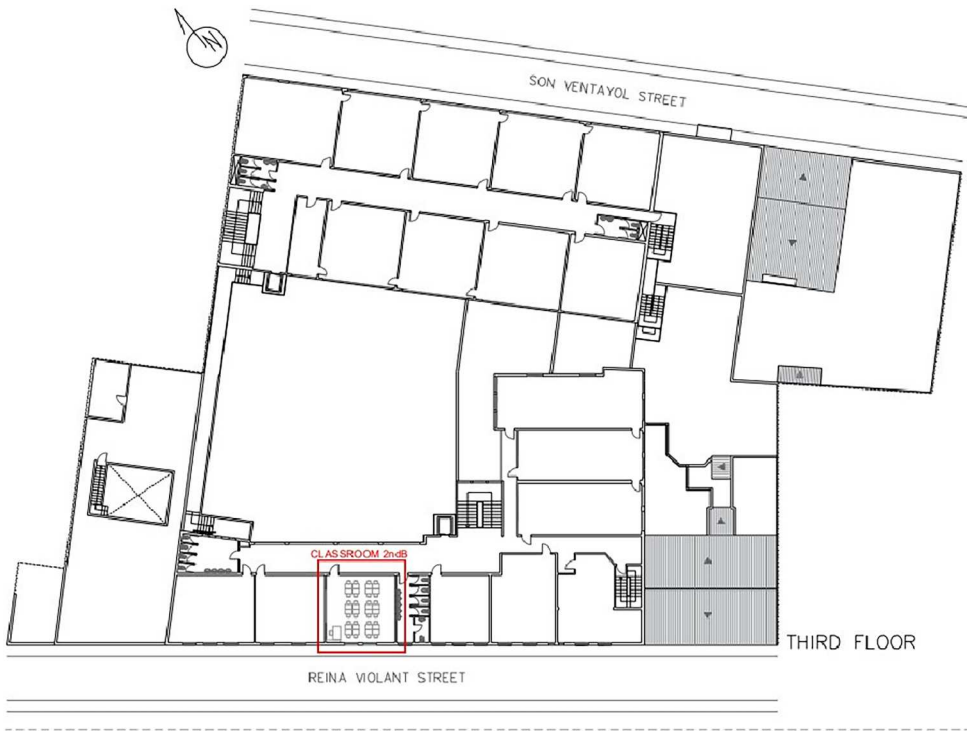


Figure 2. Location of classroom 2nd B on the 3rd floor and placement of sensors in the classroom.

- LOC_147: placed on an unused dehumidifier, 10 cm from the windows and 50 cm above the floor.
- LOS_148: suspended from the projection in the centre of the room, 2.30 above the floor.



Figure 3. Current status of classroom 2nd B.

Table 1. Characteristics and description of the classroom.

Characteristics	Classroom 2nd B
Area (m ²)	38.49
Volume (m ³)	98.16
Number of students	24 (7-8 years old)
Orientation	Northwest
School location	Urban centre with busy streets
Location of the classroom in school	3rd floor, below flat roof
Number of windows and surface(m ²)	2 × 1.80
Number of doors and surface (m ²)	1 × 1.64
Indoor materials	Terrazzo flooring. Ceramic tile walls up to 1.40 m, remaining walls and ceilings with plaster and plastic paint (no suspended ceiling). Aluminum windows with single pane glass. Laminated wood door.
Building characteristics	Structure of reinforced concrete columns and slabs. Ceramic brick façade without insulation, with exterior mortar finish and interior plaster rendering. Walkable flat roof without insulation, finished with tiles.
Services	Wall-mounted fan-coil unit with ducted outlets for hot and cold air conditioning, controlled from the classroom. Natural ventilation through opening doors and windows; no mechanical ventilation is available. Four fluorescent lights.

- LOC_149: mounted on the wall above the whiteboard, 2.10 m high and 90 cm from the door, located in the doorway airflow path.

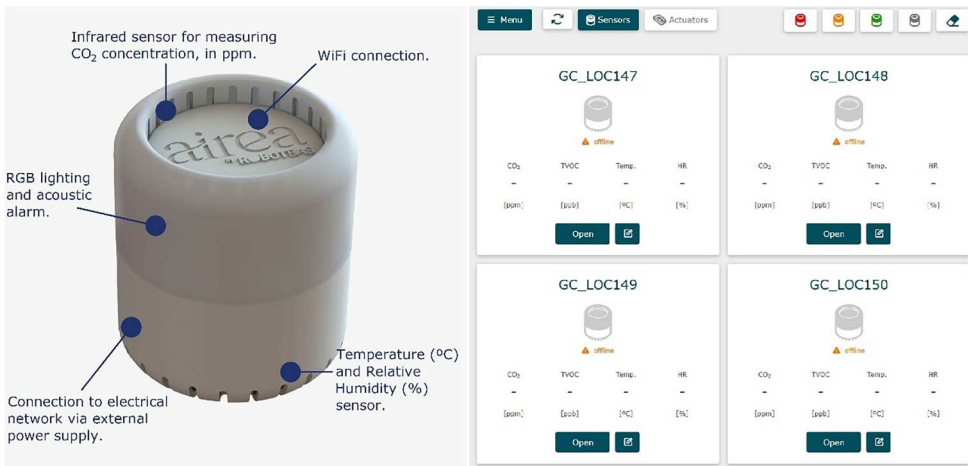


Figure 4. Device and sensor control platform.

Table 2. Sensor characteristics.

Parameters	Range	Accuracy
CO ₂ (ppm)	400-10000 ppm	±50 ppm
Temperature (°C)	5-45°C	±1°C
Relative Humidity (%)	0-100%	±5%

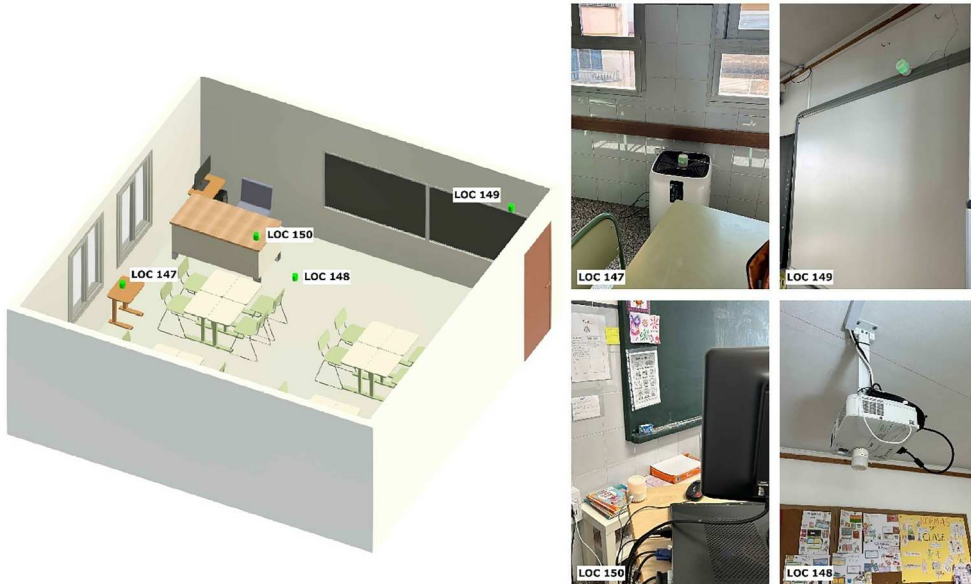


Figure 5. Sensor placement.

- LOC_150: placed on the teacher’s desk, approximately 60 cm from adjacent walls and 80 cm above the floor.

According to regulatory guidelines and commonly accepted recommendations, temperature, relative humidity, and CO₂ sensors should preferably be installed away from heat sources, doors, windows, and walls, as these locations may be affected by transient conditions.

In the present study, sensor locations were selected based on a combination of practical, safety-related, and methodological criteria. First, sensor placement was constrained by the availability of nearby power supply points, as the devices required a continuous electrical connection to ensure uninterrupted data recording. Second, locations were chosen to guarantee safe use in a primary school environment, minimizing the risk of accidental contact or tampering by students and avoiding interference with normal classroom activities.

Although some sensors were intentionally placed near windows, doors, walls, or heat-emitting equipment, these locations reflect common sensor installation scenarios in real educational settings and allow the evaluation of potential measurement biases introduced by proximity to ventilation openings, airflow paths, or thermal sources.

Therefore, the adopted deployment strategy enables the assessment of how typical, although non-ideal, placement scenarios may influence the recorded values. This approach is consistent with the objective of the study to analyze the influence of sensor number and placement in real classroom environments.

Data analysis

Monitoring was conducted from 11 to 31 March 2024. The sensors continuously recorded CO₂ concentration, temperature and relative humidity, with all data stored in the cloud. These data were then processed to examine the variability in indoor environmental parameters across the different sensor locations.

No specific ventilation protocol was imposed on the teacher during the monitoring period. As such, the data reflects typical classroom use during regular school hours (see [Table 3](#)).

Based on discussions with the teacher and a review of the class schedule, it was confirmed that windows and doors were generally opened at the beginning of the day and subsequently closed due to seasonal conditions. To reduce outdoor noise, windows and doors were kept closed during lessons and reopened during breaks and lunchtime. Therefore, only natural ventilation was available, as no mechanical ventilation system was in place. The HVAC system remained unused during the measurement period due to mild outdoor temperatures that did not require heating or cooling.

Table 3. Schedule.

Time	Monday	Tuesday	Wednesday	Thursday	Friday
9:00	Start of classes				
9:00–10:30	Classes				
10:30–11:00	Playtime 1st–6th				
11:30–13:00	Classes				
13:00–15:00	Lunch and playtime				
15:00–17:00	Classes				
17:00	End of classes				

Results

Figures 6–8 present the time series of CO₂ concentration, temperature and relative humidity, respectively. In each figure, occupied and non-occupied periods are clearly distinguished. Complete 24-hour profiles for these parameters are provided in Supplementary Figures S.M.1 and S.M.2.

CO₂ concentration

Figure 9 shows that sensor LOC_150 consistently recorded higher CO₂ concentrations than the remaining sensors throughout the monitoring period. This sensor is located on the teacher's desk, close to the main occupied zone of the classroom. The remaining sensors (LOC_147, LOC_148, and LOC_149) exhibited similar CO₂ concentration profiles, with lower average values than LOC_150.

Temperature

Temperature measurements in Figure 10 showed comparable temporal trends across all sensor locations. However, higher temperatures were recorded at LOC_148 and LOC_149, while LOC_147 and LOC_150 presented nearly identical temperature values.

Relative humidity

Relative humidity measurements (Figure 11) followed similar temporal patterns at all sensor locations. Lower relative humidity values were observed at LOC_148 and

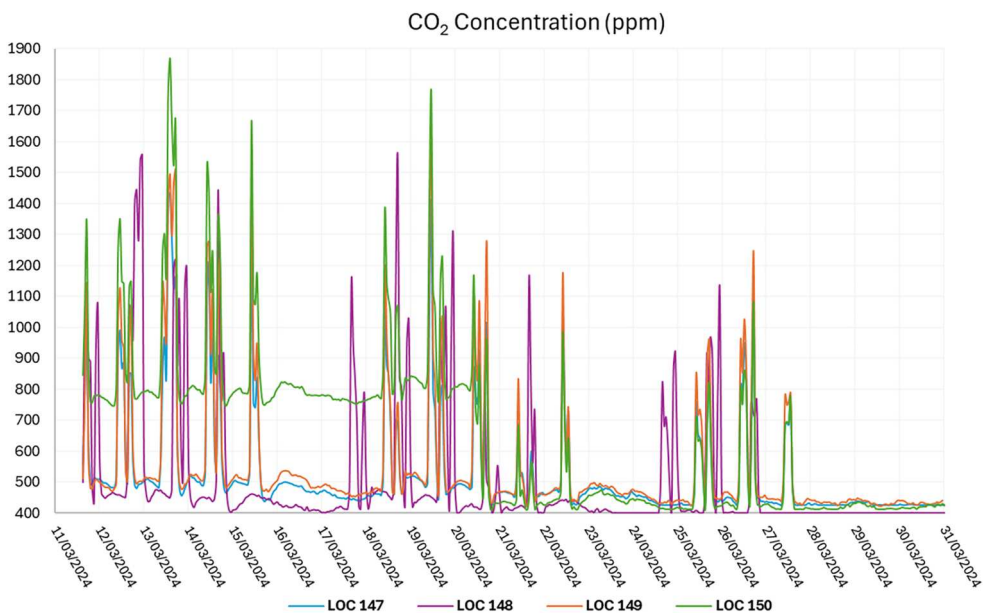


Figure 6. CO₂ concentration (ppm).

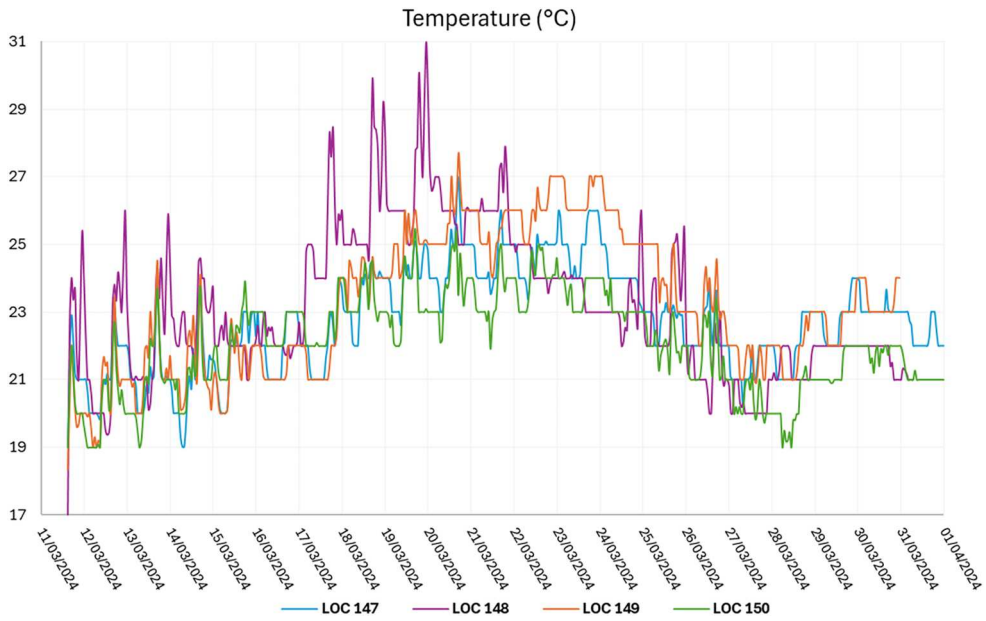


Figure 7. Temperature (°C).

LOC_149, whereas LOC_147 and LOC_150 showed slightly higher and nearly overlapping values.

Figure 12 summarizes the dispersion of the three parameters across sensor locations. The largest dispersion was observed for CO₂ concentration, particularly at LOC_150.

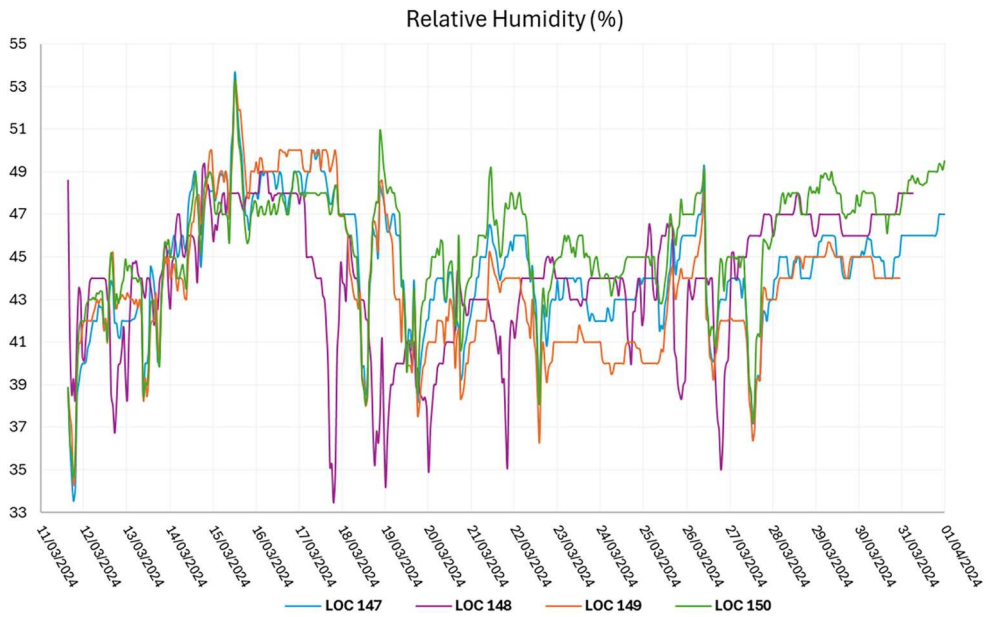


Figure 8. Relative Humidity (%).

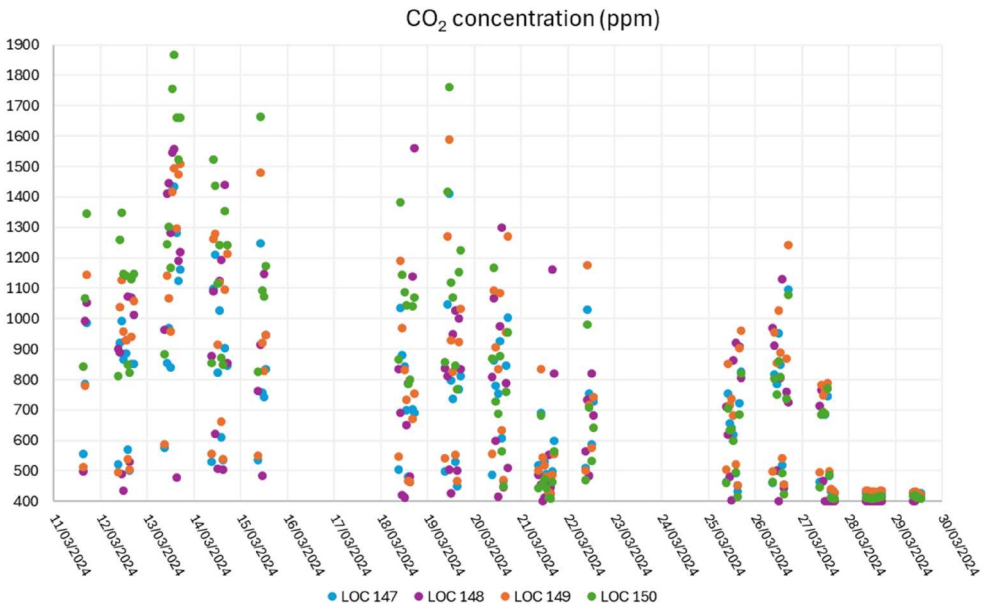


Figure 9. CO₂ concentration (ppm) during occupied period.

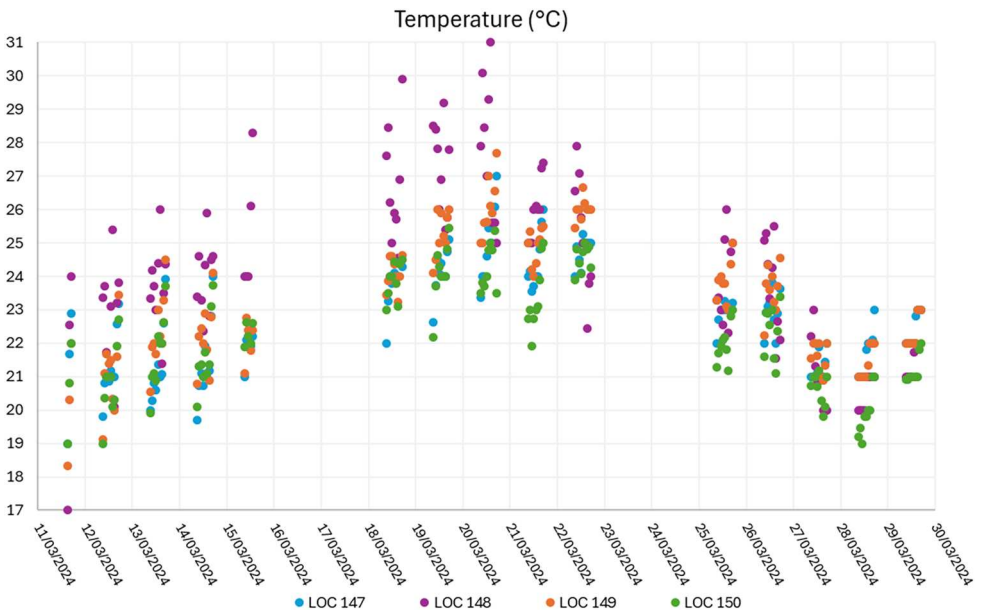


Figure 10. Temperature (°C) during occupied period.

Temperature variability was more pronounced at LOC_148 and LOC_149, while relative humidity exhibited the lowest dispersion among all parameters.

Table 4 presents the overall mean values, mean values during occupied hours, and modal values for CO₂ concentration, temperature, and relative humidity at each sensor

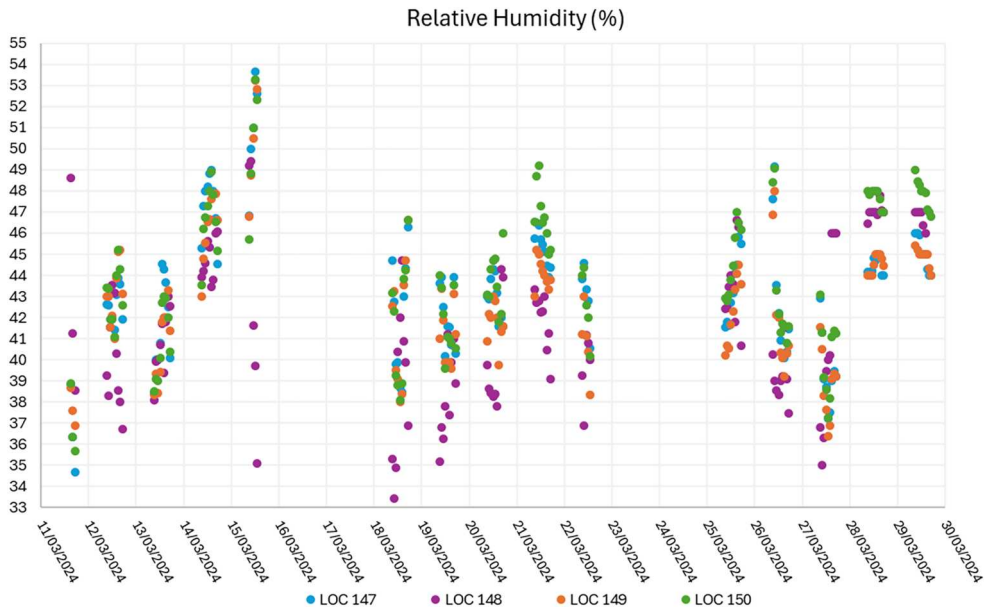


Figure 11. Relative Humidity (%) during occupied period.

location. During occupied hours, LOC_150 registered the highest average CO₂ concentration, whereas temperature and relative humidity values remained within a relatively narrow range across all sensors.

Based on the occupied-hour mean values, an overall average was calculated for each parameter. Table 5 shows this total average and the percentage deviation of each sensor relative to that value. Temperature exhibited the smallest deviations between sensor locations, followed by relative humidity. CO₂ concentration showed the highest variability, with a maximum deviation of 11%.

Table 4. Mean and modal values for CO₂, temperature (T) and relative humidity (RH), by sensor location.

Sensor	LOC 147	LOC 148	LOC 149	LOC 150
MEAN values				
CO ₂ (ppm)	519.23	499.28	549.66	643.43
T (°C)	22.76	22.37	22.08	22.10
RH (%)	44.51	42.33	41.54	45.58
Mean values (occupied hours)				
CO ₂ (ppm)	703.81	739.02	773.05	847.22
T (°C)	22.78	23.63	23.31	22.30
RH (%)	43.37	40.63	42.74	44.06
Modal values				
CO ₂ (ppm)	426.00	400.00	441.00	411.00
T (°C)	23.00	22.00	22.00	23.00
RH (%)	44.00	44.00	44.00	47.00
Modal values (occupied hours)				
CO ₂ (ppm)	426.00	400.00	–	411.00
T (°C)	21.00	21.00	22.00	21.00
RH (%)	44.00	47.00	45.00	48.00

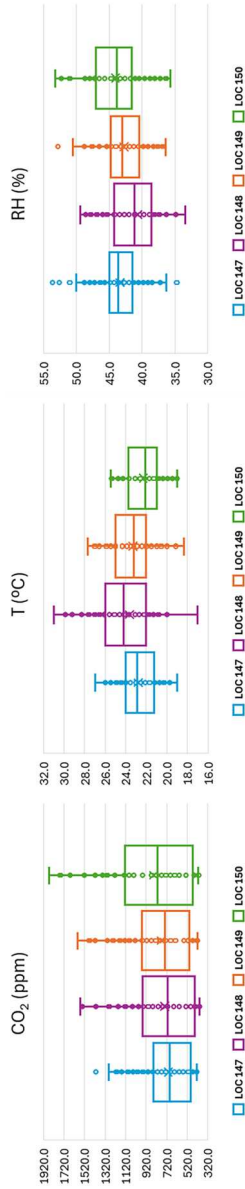


Figure 12. Dispersion plots of CO₂ (ppm), Temperature (°C) and Relative Humidity (%).

Discussion

Influence of sensor location and occupancy on CO₂ measurements

The results demonstrate that CO₂ concentration is the parameter most affected by sensor location, particularly during occupied periods. The highest values recorded by LOC_150 indicate that sensors placed within the occupied zone, close to the main emission source (i.e. occupants), tend to capture higher and potentially more representative CO₂ concentrations.

Although LOC_150 does not strictly comply with the positioning guidelines outlined in the introduction, specifically regarding height and central placement, its proximity to occupants explains the higher recorded values. In contrast, LOC_147, which is also close to the occupied area but located near windows, recorded lower CO₂ concentrations. This suggests that exposure to outdoor airflow and natural ventilation can significantly influence measured CO₂ levels, even when sensors are positioned near occupants.

The remaining sensors (LOC_148 and LOC_149), despite differences in height and location, showed comparable CO₂ values, indicating limited spatial variability under the monitored conditions. This finding suggests that in classrooms with stable occupancy and ventilation patterns, CO₂ gradients may be moderate, except in locations strongly influenced by either occupants or airflow paths.

Although the classroom operated without HVAC during the monitoring period, the differences observed in temperature and relative humidity cannot be attributed solely to the proximity of windows or doors. In particular, the higher temperature and lower relative humidity values recorded by sensor LOC_148 are consistent with its location at approximately 2 m above the floor, above the occupied zone and close to internal heat sources such as the projector and lighting fixtures. Under these conditions, localized heat accumulation and vertical thermal stratification may occur, especially during the final hours of the school day, even when CO₂ concentrations are effectively diluted by ventilation.

In contrast, sensors LOC_147 and LOC_149 were located closer to openings such as windows and the door, where air infiltration may occur even when these openings remain closed, potentially leading to lower temperatures and higher relative humidity. This indicates that temperature and relative humidity are more sensitive to sensor height, internal heat gains, and local airflow effects than to ventilation-driven mixing alone.

Comparison between CO₂, temperature, and relative humidity

Compared to CO₂ concentration, temperature and relative humidity exhibited lower sensitivity to sensor position. Temperature was the most spatially uniform parameter, as

Table 5. Overall mean and percentage deviation of each sensor from the total average.

Total average (with occupancy)	% Deviation				
	LOC 147	LOC 148	LOC 149	LOC 150	
CO ₂ (ppm)	765.78	8%	3%	-1%	-11%
T (°C)	23.01	1%	-3%	-1%	3%
RH (%)	42.70	-2%	5%	0%	-3%

confirmed by the minimal percentage deviations shown in [Table 5](#). Slightly higher temperatures at LOC_148 and LOC_149 can be attributed to their elevated positions and proximity to heat-emitting equipment.

Relative humidity showed modest spatial variability and remained within a narrow range across all sensor locations. Lower relative humidity values were observed at LOC_148 and LOC_149, corresponding to areas with higher temperatures. In contrast, LOC_147 and LOC_150 recorded slightly higher relative humidity values, likely influenced by occupant presence and localized moisture generation. The sensor placed on the desk (LOC_150) recorded the highest average relative humidity, reflecting its proximity to occupants.

Comparison with previous studies

The observed influence of occupancy and ventilation on CO₂ concentration is consistent with findings reported in previous experimental and numerical studies on indoor environmental quality in classrooms and similar environments. Numerous studies have shown that CO₂ levels are strongly governed by occupant distribution, activity, and airflow patterns, while temperature and relative humidity tend to be more spatially homogeneous (Mahyuddin et al., 2014; Mahyuddin & Essah, 2024; Pei et al., 2019; Sørensen & Kristensen, 2024; Waeytens & Sadr, 2018; Yang et al., 2021).

[Table 6](#) summarizes key results from reviewed studies investigating sensor placement and IAQ monitoring. In line with this literature, the present study confirms that sensors located near the breathing zone provide reliable CO₂ measurements under steady occupancy conditions. Differences between sensor locations are reduced when ventilation is effective, particularly during periods when windows and doors are opened.

In addition, recent studies IAQ studies in school buildings corroborate the interpretation of the present results, showing that spatial variability in CO₂ concentration is most pronounced during occupied hours and becomes significantly reduced during unoccupied periods or breaks due to ventilation effects (Adekunle, 2021; Babich et al., 2023; US EPA, 2025). This pattern is consistent with the monitored classroom, where higher CO₂ variability was associated with occupancy, while more homogeneous conditions were observed during non-occupied periods.

In contrast, temperature and relative humidity have been reported to be less sensitive to occupancy and more influenced by sensor position and local thermal conditions (Kuurola et al., 2023; Oldham & Kim, 2020). In line with these findings, the present study confirms that sensor placement has a greater impact on CO₂ measurements during occupied periods than on temperature and relative humidity.

Implications for IAQ monitoring in classrooms

Considering the classroom as a space characterized by stable occupancy, fixed schedules, and repetitive activities, the results indicate that spatial differences between sensors are generally limited, particularly for CO₂ concentration. This supports existing recommendations for placing sensors within the occupied zone to obtain representative measurements.

Table 6. Results of the reviewed studies.

Reviewed study	Authors	Year	Key findings
<i>Sensor Location Methodology for Improved IEQ Monitoring in Working Environments</i>	S. Al Samman M. Eftekhari D. Coakley C. Angelopoulos V. Dimitriou	2020	Real-time monitoring (CO ₂ , PM _{2.5} , PM ₁₀ , CH ₂ O, TVOCs, T and RH) with CFD under varying occupancy and ventilation scenarios. Median CO ₂ and RH values showed minimal ventilation, while T values varied by $\pm 5^{\circ}\text{C}$. Sensor location significantly influenced readings due to airflow and occupant proximity. Representative sensor placement was validated through simulations.
<i>The Reliability of CO₂ Measurements Using Low-Cost Sensors: A Study of Sensor Positioning and Ventilation Strategies in Classrooms</i>	D. Marin A. Alegría-Sala L. Canals Casals M. Macarulla J. Fonollosa	2025	Measurements across 22 sessions over five months in primary schools and universities (T, RH, CO ₂ and VOC). Variations of up to 80 ppm (CO ₂) and 1°C (T) observed, especially with natural and cross ventilation. Mechanical or no ventilation resulted in negligible dispersion. Sensor position and ventilation strategy had a greater impact than sensor specifications. Suggested 100 ppm correction for unfavourably located sensors.
<i>The spatial distribution of carbon dioxide in rooms with particular application to classrooms</i>	N. Mahyuddin H. B. Awbi M. Alshitawi	2014	CO ₂ concentrations in four university classrooms with varying ventilation conditions. Differences of 150-200 ppm were observed between 0.20 and 1.80 m heights, with higher concentrations at greater heights. Natural and mechanical ventilation significantly reduced differences to <5%. When sensors were placed uniformly at 1.80 m, discrepancies ranged from 2 to 8%.
<i>Spatial distribution of CO₂ Impact on the indoor air quality of classrooms within a University</i>	N. Mahyuddin E.A. Essah	2024	CO ₂ concentration reflects the dynamic relationship among the variation of occupancy of occupants, their activity levels and occupancy periods. CO ₂ at breathing height provided reliable data under steady occupancy. In fully enclosed rooms or during long classes, CO ₂ levels rose rapidly, especially in the occupied zone.
<i>Effect of sensor position on the performance of CO₂-based demand controlled ventilation</i>	G. Pei D. Rim S. Schiavon M. Vannucci	2019	CFD simulations evaluated sensor placement under displacement and mixing ventilation systems. Differences of up to 800 ppm (CO ₂) were found from floor to ceiling under displacement ventilation, reduced to 400 ppm with increased air exchange. Under mixing ventilation, differences were <150 ppm, reduced to <50 ppm with higher air change rates.
<i>Experimentally validated CFD analysis on sampling region determination of average indoor carbon dioxide concentration in occupied space</i>	A. Bulińska Z. Popiołek Z. Buliński	2014	Identification of representative CO ₂ measurement zones using sensors and CFD. Suitable locations included central room areas regardless of height, near emission sources, or near internal doors and at least 40 cm away from walls. Unsuitable locations included areas near windows, HVAC outlets, or directly above emission sources. Study conducted with a single occupant.
<i>Incorporating SLAM and mobile sensing for indoor CO₂ monitoring and source position estimation</i>	Y. Yang J. Liu W. Wang	2021	Indoor air monitoring using a mobile robotic sensor system. Differences between fixed and mobile measurements were <20 ppm near the pollution source. Mobile sensing

(Continued)

Table 6. Continued.

Reviewed study	Authors	Year	Key findings
	Y. Cao H. Li		enabled precise, real-time CO ₂ monitoring using a single sensor instead of multiple fixed ones.
<i>Computer-aided placement of air quality sensors using adjoint framework and sensor features to localize indoor source emission</i>	J. Waeytens S. Sadr	2018	CFD-based simulations to optimize sensor number and placement for identifying emission sources. Inappropriate placements included areas affected by airflow obstructions or furniture. Suitable locations were identified based on space characteristics and sensor coverage.

However, the use of multiple sensors provides additional insight into spatial variability, especially for temperature and relative humidity, revealing gradients that may not be captured by a single measurement point. Therefore, while appropriate sensor placement is essential for reliable indoor environmental monitoring, deploying multiple sensors enhances the robustness of IAQ assessments and supports better-informed decisions regarding ventilation management and occupant comfort in school classrooms.

Building on this discussion, the results of the present study allow a direct evaluation of the main research objective, which was to analyze the influence of both the number of sensors and their spatial distribution within the classroom on the measurement of three key indoor environmental parameters: CO₂ concentration, temperature, and relative humidity.

The experimental deployment of four multiparameter sensors at different locations within a primary school classroom, defined according to the architectural layout of the space, its typical use, and occupant distribution, made it possible to assess how sensor placement affects recorded values. The findings show that in classrooms with stable occupancy patterns, regular schedules, and repetitive activities, the effect of sensor location on CO₂ measurements is moderate, with the most representative values obtained when sensors are placed within or close to the occupied zone.

At the same time, the results highlight that relying on a single sensor may overlook relevant spatial gradients in temperature and relative humidity, particularly in areas influenced by heat sources, wall proximity, or airflow patterns. In this sense, the use of multiple sensors provides a more comprehensive representation of the indoor environmental conditions and improves the reliability of assessments used to evaluate compliance with existing standards.

Overall, this discussion confirms that while current guidelines for sensor placement are generally suitable for educational environments with stable operating conditions, the strategic deployment of multiple sensors strengthens indoor environmental quality monitoring by reducing uncertainty and supporting more robust ventilation and comfort optimization strategies in school classrooms.

Conclusions

This study examined the influence of both sensor number and spatial placement on the monitoring of indoor air quality parameters in a primary school classroom under real operating conditions. Through in situ measurements of CO₂ concentration, temperature,

and relative humidity, the work provides experimental evidence on how sensor deployment strategies affect the representativeness and reliability of indoor environmental data in educational environments.

The results indicate that sensor placement has a parameter-dependent impact on measurement outcomes. Among the monitored variables, CO₂ concentration proved to be the most sensitive to sensor location, exhibiting a maximum deviation of 11% between measurement points during occupied periods. This spatial variability is primarily associated with occupant distribution, local emission sources, and airflow patterns within the classroom. In contrast, temperature and relative humidity showed substantially lower spatial variability, with deviations limited to $\pm 1^\circ\text{C}$ and $\pm 3\%$, respectively, indicating a relatively homogeneous distribution of these parameters across the classroom under the stable operating conditions observed during the monitoring period.

These findings highlight that spatial heterogeneity in classrooms cannot be generalized across all IAQ parameters. While CO₂ concentration reflects localized conditions linked to human presence and ventilation effectiveness, thermal parameters are more strongly influenced by building characteristics, sensor height, and proximity to heat-emitting elements. As a result, the relevance of sensor placement depends not only on the physical location of the device but also on the specific parameter being monitored and the intended use of the collected data.

A particularly relevant outcome of this study is the performance of the sensor located on the teacher's desk (LOC_150). Although this position does not strictly comply with normative recommendations regarding central placement and standardized installation heights, it consistently recorded the highest CO₂ concentrations and the values most representative of students' exposure within the breathing zone. From a practical and operational perspective, this location also offers several advantages: it avoids direct contact with walls and floors, minimizes the risk of accidental manipulation, does not interfere with classroom activities, and allows supervision by teaching staff. These characteristics make it a technically robust and contextually appropriate option for sensor deployment in real classroom settings.

From a monitoring strategy standpoint, the results suggest that in classrooms characterized by stable occupancy patterns, regular schedules, and predominantly natural ventilation, the use of a single well-positioned sensor may be sufficient to obtain representative CO₂ measurements. This finding has important implications for the design of cost-effective indoor air quality monitoring programmes in schools, particularly in contexts where sensor deployment is constrained by economic, infrastructural, or operational limitations. In such cases, prioritizing sensor placement within or near the occupied zone may offer a reasonable balance between monitoring accuracy and implementation feasibility.

At the same time, the deployment of multiple sensors provided additional insight into the spatial variability of temperature and relative humidity. While differences in these parameters were less pronounced than for CO₂, the multi-sensor approach revealed localized gradients related to sensor height, proximity to heat sources, and interactions with the building envelope. These spatial patterns would not have been captured using a single measurement point, highlighting the added value of multi-sensor configurations when a comprehensive assessment of thermal comfort and moisture distribution is required. This emphasizes the need to balance simplicity and spatial resolution when selecting monitoring strategies for different IAQ objectives.

Beyond the technical and methodological implications, this study reinforces the broader importance of reliable indoor environmental monitoring in educational buildings. Indoor air quality, thermal comfort, and humidity levels are closely linked to students' health, cognitive performance, comfort, and overall well-being. Accurate and representative measurements are therefore essential to support informed decisions regarding ventilation management, classroom operation, and potential interventions aimed at improving indoor conditions in schools.

Several limitations of the study should be acknowledged. The experimental analysis was conducted in a single classroom with a specific architectural configuration, occupancy profile, and ventilation strategy, which may limit the direct generalization of the results to other educational settings. The monitoring period was limited in duration, and only four sensor locations were evaluated. Additionally, mechanical ventilation systems, varying occupancy densities, alternative classroom layouts, and seasonal variations were not considered and may influence the magnitude and nature of spatial variability in IAQ parameters.

Nevertheless, focusing on a single classroom enabled a controlled and economically viable experimental setup. The selected classroom is considered representative of a typical teaching environment in Palma due to its dimensions, construction characteristics, age, and internal organization, which are common in many educational buildings in similar climatic contexts. Within this framework, the findings provide experimentally grounded evidence that complements existing guidelines and contributes to a better understanding of practical sensor deployment under real classroom conditions.

Overall, this study demonstrates that informed decisions regarding both the number and placement of sensors are essential for reliable IAQ assessment in schools. While generalized recommendations provide a useful starting point, experimental evaluation under realistic conditions is necessary to identify placement strategies that balance accuracy, practicality, and cost-effectiveness. Future research should extend these findings by investigating a wider range of classroom typologies, climatic conditions, ventilation strategies, and longer monitoring periods, as well as different age groups and occupancy patterns, to further refine recommendations for optimal sensor placement in educational environments.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve the readability and language of the manuscript. After using this tool/service, the author(s)

reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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