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Development of a Portable Multi-Detector for Indoor Air Quality Monitoring in Schools: Preliminary Results About Formaldehyde Measurements

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Indoor air quality (IAQ) in schools is a major public-health concern, as pupils and staff spend extended periods in classrooms where air renewal, occupancy, and material emissions interact. A portable multi-detector was developed to monitor key indoor pollutants, namely carbon dioxide, particulate matter, total volatile organic compounds, and formaldehyde, using compact low-cost sensors integrated into an embedded acquisition system. The paper focuses on the description of the multi-detector and presents measurements obtained during a six-week campaign conducted in fourteen classrooms across five elementary schools under real operating conditions, with particular attention to formaldehyde data. Results show significant spatial and temporal variability of formaldehyde concentrations between classrooms, with median values ranging from 2 to 28 ppb. All measured concentrations remain below the WHO and ANSES short-term guideline (80 ppb), while only five classrooms exhibit median values below the French long-term guideline of 8 ppb. These findings highlight the relevance of multi-parameter monitoring for assessing exposure to indoor pollutants in school environments.

1. Introduction

Inadequate indoor air quality in schools affects health, comfort and learning conditions because pupils and teachers remain exposed for several hours each day. Sadrizadeh et al. (2022) reviewed classroom worldwide studies and showed that school environments frequently combine insufficient ventilation with exposure to particulate matter, carbon dioxide and gaseous pollutants. Continuous measurements performed directly in classrooms are therefore essential to correlate pollutant levels with occupancy, ventilation behavior and indoor emission sources, and eventually apply appropriate mitigation actions. This context supports a monitoring strategy that does not rely solely on carbon dioxide as a ventilation indicator but also on a variety of pollutants and environmental parameters to provide a more comprehensive understanding of indoor air quality dynamics.
Among indoor pollutants, formaldehyde, a colorless, corrosive, flammable gas with a pungent and suffocating odor, deserves particular attention due to its health effects, including respiratory irritation and potential long-term risks such as carcinogenicity (WHO, 2010). Consequently, a substantial body of literature addresses formaldehyde monitoring in indoor environments (Trocquet, 2023). For instance, Salthammer et al. (2010) identified formaldehyde as a major indoor pollutant emitted from wood-based products, furnishings, and coatings. In school settings, Tang et al. (2009) showed that concentrations are typically higher in newer buildings and during warmer periods, highlighting the role of material emissions and environmental conditions. Poulhet et al. (2014) further demonstrated that multiple emission sources can coexist within a single classroom, with a significant contribution from construction and furnishing materials. Then, while carbon dioxide remains relevant for tracking occupancy and air renewal, formaldehyde monitoring is required since it has specific emission sources that can persist independently of occupancy levels. Regulatory guidelines have been established to limit exposure to formaldehyde in indoor environments.
The World Health Organization (WHO) recommends a guideline value of 100 µg/m³ (approximately 80 ppb) for short-term exposure (i.e. over 30-minute periods at lifelong exposure), similarly to the French national agency ANSES. For a 2-hour exposure, ANSES recommends a maximum value of 50 µg/m³ (Trocquet, 2023), and the

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French government has established an annual average threshold of 10 µg/m³ (approximately 8 ppb) in public buildings, including schools (Decree n° 2011-1727, 2011). Although medium- or long-term exposure can be monitored using standard techniques such as passive samplers, continuous monitoring with high temporal resolution becomes essential to better understand short-term pollutant dynamics in classroom environments. The development of compact and low-cost sensors now enables the design of portable multi-parameter systems capable of tracking several pollutants simultaneously. Accordingly, the objective of this work is to develop and deploy a fast-response portable multi-detector in school environments. The following sections describe the developed device and present formaldehyde measurements obtained during a recent campaign conducted in several elementary schools in western France.

2. Materials and methods

2.1 System overview

The developed prototype consists of a portable multi-detector designed for indoor air quality monitoring in school environments. It integrates sensors for carbon dioxide, particulate matter, total volatile organic compounds, and formaldehyde, combined with an embedded communication and acquisition system.
In addition to pollutant-specific sensors, environmental parameters such as temperature, relative humidity, light intensity, and acoustic levels are monitored to provide contextual information for interpreting pollutant dynamics. These parameters are known to influence both emission processes and sensor response, particularly formaldehyde, whose emissions are strongly affected by temperature and humidity conditions (Liang et al., 2016).
The sensing elements are integrated on a custom-designed printed circuit board (PCB) and interfaced with an embedded microcontroller (Arduino ESP32) responsible for data acquisition and transmission. The sensors provide electrical signals that are converted into physical quantities such as gas concentrations, temperature, and relative humidity. This configuration ensures consistent and directly interpretable measurements across the monitored environments. The developed prototype is shown in Figure 1.a.

2.2 Sensors

Table 1 presents the sensors selected for the prototype, along with their target parameters, measurement technologies, nominal ranges, interfaces, and main characteristics. The selected devices are supported by previous studies confirming their suitability for indoor air quality monitoring applications (McGarry et al., 2025; Zusman et al., 2020; Hong et al., 2023; Pei et al., 2023; Báthory et al., 2022).
In addition to the sensors listed in Table 1, a commercial Aranet4 Home device was used as a reference for carbon dioxide measurements, providing an independent benchmark to assess the performance of the integrated CO_2 sensor. Before field deployment, the sensors were used according to the manufacturers' calibration and operating recommendations.
A preliminary laboratory intercomparison was however performed using incense combustion as a common emission source. This test was not intended as a complete calibration because smoke and gaseous compounds were not perfectly homogeneously distributed, but it allowed the relative consistency and dynamic response of the multi-detectors to be assessed. For PM_{10}, the comparison with a TSI DustTrak aerosol monitor was limited to the concentration range relevant to the field observations, i.e., below 50 µg/m³, where differences remained within approximately 10%.
For luminosity and sound level, the mean inter-detector deviations were approximately 13% and 3%, respectively. The tVOC indicator showed a larger deviation of approximately 50%, which is consistent with the use of MOx-based sensors and with the non-uniform dispersion of volatile compounds during the incense test.
For formaldehyde, the SFA30 provides a factory-calibrated and lifetime-calibrated HCHO output, with integrated temperature and humidity compensation. According to the datasheet, its standard measurement range is 0–1000 ppb, with 1 ppb resolution, an accuracy of ±20 ppb or ±20% of the measured value, a repeatability of ±5 ppb or ±5% of the measured value, a response time below 2 min, and a long-term drift below 5 ppb or 5% of the measured value per year. Since no formaldehyde reference analyzer was available during this test, no additional absolute calibration was performed; the incense experiment was therefore used only as an intercomparison of the relative dynamic responses of the SFA30 sensors.
In the concentration range relevant to the classroom observations, i.e., below 40 ppb, the mean absolute inter-detector deviation was approximately 7 ppb. Long-term stability was also considered from sensor specifications and literature: the CO_2 Senseair Sunrise includes automatic baseline correction, the SGP40 VOC index relies on adaptive baseline processing, and PMS7003-based systems require periodic cleaning/maintenance after approximately 6–8 months of operation. These elements highlight the need to interpret compact-sensor measurements with consideration of accuracy, drift, environmental sensitivity, and maintenance requirements.

Table 1: Sensors selected for the portable multi-detector and their main characteristics

Sensor	Target	Technology	Nominal range	Interface	Accuracy/stability
Sunrise	CO_2	NDIR	400–10^4 ppm	I²C	±30 ppm ±3% m.v (measured value)
PMS7003	Particles	Mie scattering	0.3–10 µm	UART	75%
SGP40	TVOC	MOX	0–60 ppm	I²C	±15% m.v
SFA30	H_2CO	Electrochemical	0–5 ppm	I²C	±10%; drift<5ppb or 5% m.v/year
BH1750	Brightness	Photodiode	1–65,000 lx	I²C	±20% m.v
PCB Artist	Sound	MEMS	30–120 dB	Analog	±3 dB

2.3 Other components

Table 2 summarizes the main electronic components used for system integration, data acquisition, and communication within the portable multi-detector. The electronic system is implemented on a custom-designed printed circuit board developed using KiCad software. The PCB was fabricated and assembled in our laboratory workshop, where all components listed in Table 2 were soldered and integrated into a compact architecture. This approach ensures reliable electrical connections and facilitates the deployment of the device in real classroom environments. The embedded system is programmed using the Arduino development environment, which is also used for the configuration and testing of the ESP32 microcontroller. This platform enables the implementation of data acquisition routines, sensor communication protocols, and data transmission functions.

Table 2: Main electronic components used for the multi-detector system

Component	Technology / Type	Interface	Role in system
Arduino µcontroller	Dual-core MCU	UART–SPI–I²C	Data processing and communication
W5500 Ethernet	Ethernet controller	SPI	Data transmission
MB102 Power supply	5 V / 3.3 V	-	System powering
µSD Data storage	Removable disk 1GB	SPI	Local data backup and redundancy
RTC Timer	Real-time clock	I²C	Timestamping of measurements
PCB	Printed circuit board	-	Electrical integration of all components

2.4 Data acquisition & transmission

Measurements are collected at one-minute resolution, allowing short-term variations and transient pollutant peaks to be detected. The ESP32 microcontroller acquires data from the sensors through I²C and UART protocols and can also communicate with external devices such as the Aranet4 Home through Bluetooth. The system is programmed in C++ using the Arduino environment and dedicated communication and sensor libraries. The acquired data are formatted as structured HTTP requests and transmitted via Wi-Fi or Ethernet to a Google Sheets interface through a webhook-based system. This solution was retained after testing an alternative Firebase-based approach, which introduced synchronization issues and occasional data loss or duplication. Google Sheets is used as a central storage and processing interface, enabling data organization, visualization, and integration with other deployed sensor platforms.

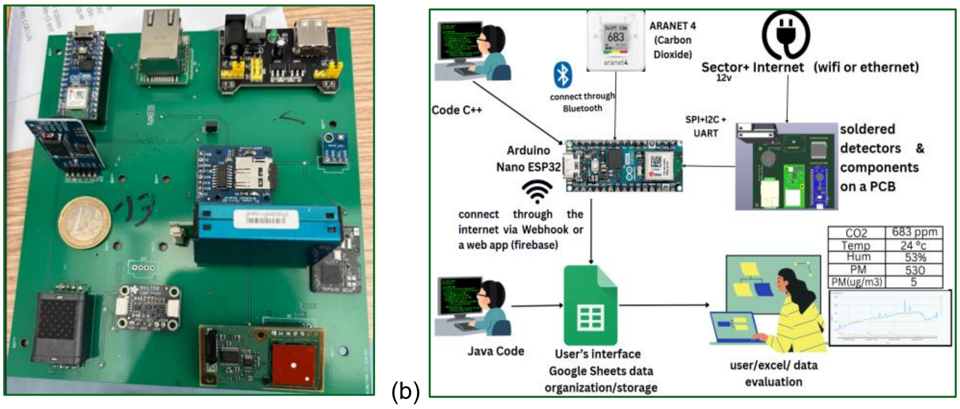
(a)  (b)

Figure 1: a: Portable multi-detector prototype (COFRA V2.0) integrating gas sensors, environmental sensors and communication modules on a custom-designed PCB. b: Data acquisition and transmission architecture of the multi-detector system, including sensor interfacing, embedded processing, wireless communication, and cloud-based data storage.

2.5 Deployment conditions and measurement overview

The multi-detector system was deployed in several elementary school environments during a measurement campaign conducted between 2 February and 24 March 2026, corresponding to six consecutive weeks of monitoring. Measurements were carried out in fourteen classrooms from five schools located in the Ille-et-Vilaine department (Brittany, France), under real operating conditions. Each multi-detector, based on an Arduino platform, was installed in a single classroom and operated autonomously with a measurement frequency of one minute. Data from each device was transmitted independently using dedicated webhook addresses, allowing real-time collection and storage of measurements in separate data streams associated with each classroom.
To support data interpretation, contextual information was collected in collaboration with teachers through a daily reporting form. This included occupancy periods, air renewal actions (e.g., by window opening), teaching activities, and other relevant events such as cleaning periods. The combination of high-resolution measurements and contextual data provides a detailed description of indoor air quality conditions and enables the identification of short-term variations and differences between classrooms over time.

3. Results and Discussion

3.1 Global formaldehyde distribution

Figure 3 presents the distribution of formaldehyde concentrations across the monitored classrooms during occupied periods only. These periods correspond to teaching hours (8:00–12:00 and 13:00–15:30), excluding weekends, holidays, and Wednesdays when no classes are held, ensuring that the analysis reflects actual occupancy conditions. The results show marked variability between classrooms, with median concentrations ranging from 2 to 28 ppb. All measured concentrations remain below the WHO and ANSES short-term guideline (80 ppb), while only five classrooms out of fourteen exhibit median values below the French long-term guideline of 8 ppb. The observed inter-classroom variability may be explained by several combined factors, including classroom use, ventilation strategy, building characteristics, furnishing and material emissions, storage of teaching materials, cleaning practices, and environmental conditions such as temperature and relative humidity. Since these factors were not independently controlled during the field campaign, the measured differences should be interpreted as the result of combined indoor emission and dilution processes rather than the effect of a single isolated source.

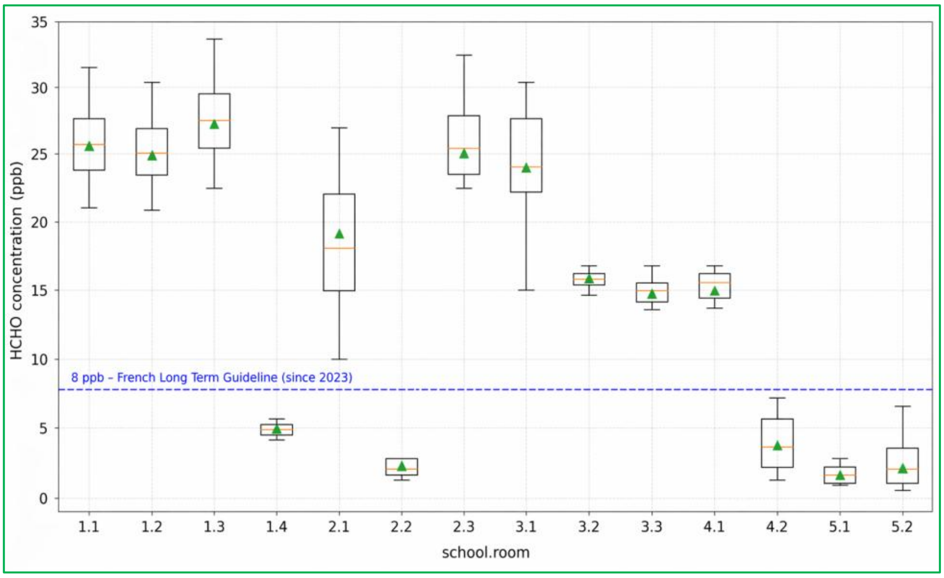


Figure 3: Distribution of formaldehyde concentrations across monitored classrooms in occupied periods; ----: French Long-Term Guideline since 2023; Box: interquartile range 25th–75th percentiles; —— :median; ▲: mean; —— : 5th and 95th percentiles.

3.2 Temporal evolution of formaldehyde concentrations

The temporal evolution of formaldehyde concentrations measured in one school, where four classrooms were instrumented, is presented in Figure 4. In contrast to Figure 3, this representation includes the full measurement period, encompassing both occupied and unoccupied periods, including nights, weekends, and holidays. The time series reveals distinct behaviors between classrooms. Classroom 1.1 maintained moderate to elevated HCHO levels, typically between 20 and 35 ppb, with recurrent short-term increases. This classroom corresponds to a young children's, aged 2-3 years, classroom also used for nap periods, where painting, creative activities, glues, paper/cardboard materials, coatings, and stored educational materials can contribute to material-related indoor emissions. In contrast, Classroom 1.4, corresponding to an upper primary school classroom grade with pupils aged 9–10 years, showed much lower concentrations, often below 10 ppb and occasionally close to zero. The school is equipped with a dual-flow mechanical ventilation system, which contributes to the decrease in HCHO concentrations observed during school time by enhancing air renewal and dilution. Conversely, during unoccupied periods, when air renewal is reduced or absent, HCHO concentrations can increase again, particularly in rooms where material-related indoor emission sources are present. This pattern suggests that the observed HCHO dynamics are governed by combined effects of internal emission sources, classroom use, material characteristics, and ventilation conditions, rather than by direct emissions from occupants alone. Consequently, the higher concentrations observed in some classrooms may reflect sustained indoor emissions combined with variable dilution over time.

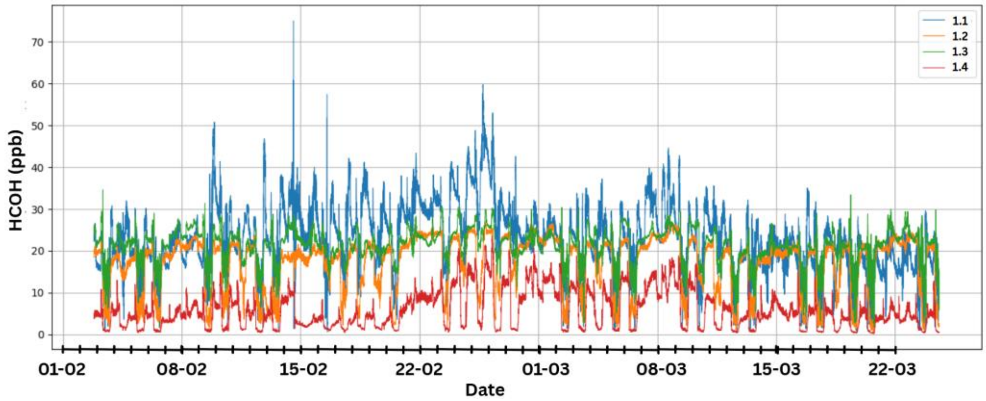


Figure 4: Minute-resolution formaldehyde concentrations in four classrooms of one school (Feb.-Mar 2026)

3.3 Correlation analysis

The correlations between formaldehyde and other measured parameters were calculated for the occupied periods only using a homemade Python code, based on the Pearson correlation coefficient (Pearson, 1896). Table 3 presents the results for one representative classroom per school. Similar trends are observed across the selected classrooms. Relative humidity shows the highest correlations, reaching r = 0.85, while temperature and tVOCs exhibit none to strong correlations (up to r = 0.65). In contrast, moderate correlations are found with CO_2 ($r \leq 0.45$), and negligible values are observed for PM_{10} and sound levels. These results highlight that formaldehyde variations are mainly associated with environmental conditions, although the strength of these relationships varies between classrooms. These correlations should be interpreted as statistical associations only and do not imply direct causation.

Table 3: Pearson correlation coefficients between formaldehyde (HCHO) and environmental parameters for representative classrooms during occupied periods

Parameter	1.1	2.3	3.1	4.1	5.1	Interpretation
CO_2	0.45	0.35	0.40	0.30	0.35	Moderate
Temperature	0.25	0.45	0.50	0.20	0.65	Moderate to strong
tVOCs	0.65	0.55	0.35	0.10	0.00	None to strong
Relative Humidity	0.35	0.60	0.65	0.70	0.85	Moderate to very strong
PM_{10}	0.05	0.00	0.00	0.00	0.05	Negligible
Sound (dB)	0.02	0.05	0.10	0.00	0.20	None to weak
Luminosity	0.10	0.15	0.20	0.00	0.10	None to weak

4. Conclusion

This study presented the development and deployment of a portable multi-detector for indoor air quality monitoring in schools, with a focus on formaldehyde. The six-week campaign conducted in fourteen classrooms provided high-resolution measurements under real operating conditions. A preliminary laboratory intercomparison confirmed the consistency of the relative dynamic response of the detectors, while also highlighting the need to consider sensor-specific accuracy, drift, and calibration limits. The field results showed marked spatial and temporal variability of HCHO concentrations between classrooms. Although all measured values remained below the WHO short-term guideline, most classrooms exceeded the French long-term reference value, emphasizing the relevance of continuous monitoring in school environments. The observed differences appear to result from combined effects of room characteristics, ventilation practices, classroom use, material-related emissions, and environmental conditions. Correlation analysis suggested associations between HCHO and parameters such as relative humidity and temperature; however, these relationships should be interpreted as statistical associations rather than direct causal links. Overall, this work demonstrates the usefulness of multi-parameter monitoring for investigating indoor air quality in schools and supports the need for further sensor characterization and reference calibration to improve the interpretation of formaldehyde measurements

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