Wiley
Indoor Air
Volume 2024, Article ID 7888273, 15 pages
https://doi.org/10.1155/ina/7888273

WILEY

Research Article

Evaluation of Air Quality in a Primary School Classroom During Wintertime

Eleni Dovrou[1], **Christos Kaltsonoudis**[1], **Silas Androulakis**[1,2]
Ioannis Apostolopoulos[1], **Andrea Simonati**[1] and **Spyros N. Pandis**[1,2]

[1]*Institute for Chemical Engineering Sciences, Foundation for Research and Technology–Hellas (ICE-HT/FORTH), Patras, Greece*
[2]*Department of Chemical Engineering, University of Patras, Patras, Greece*

Correspondence should be addressed to Spyros N. Pandis; spyros@chemeng.upatras.gr

Received 12 August 2024; Accepted 10 December 2024

Academic Editor: Narayan Babu Dhital

The levels of gas and particulate pollutants were measured inside and outside of a primary school classroom located in a suburban area in the city of Patras, Greece, during wintertime to evaluate the indoor air quality, identify potential problems, and determine the effectiveness of ventilation. The Foundation for Research and Technology–Hellas (FORTH) mobile laboratory was deployed, and a switching valve system was used to obtain both indoor and outdoor measurements. The outdoor air was the main source of in-classroom pollutants, as the windows remained partially open. Ventilation of the classroom was achieved naturally through the windows, and it was continuous during school hours, maintaining the pollutant concentrations at low levels, with average fine particulate matter equal to 2.6 $\mu g\, m^{-3}$ and total aromatic and oxygenated volatile organic compound (VOC) levels in the order of 10 ppb. The levels of all measured pollutants were lower than the World Health Organization (WHO) safety limits, and they are not expected to affect the health of the students. Good air quality was observed within the classroom, showing the effectiveness of natural ventilation in this setting. Cleaning activities were a source of VOCs outside school hours, resulting in increases in the levels of VOCs of a few parts per billion. However, these concentrations were gradually reduced, and they did not reduce the indoor air quality the next school day. A box model was used to estimate an effective air exchange rate of 3.5 h^{-1} during school hours.

1. Introduction

Children spend at least 6 h per weekday in school and, on average, 4 h within a classroom [1, 2]. Indoor air quality affects the performance, learning ability, and health of students and teachers [2–7]. Poor in-classroom air quality impacts children more than adults, as they are still developing and have higher breathing rates [2–7]. The season, climate, and location of the school influence the exposure of children to pollutants [8–12].

There have been several studies of the levels of gas-phase pollutants in school areas and classrooms [12–23]. Pollutants, such as ozone (O_3), sulfur dioxide (SO_2), nitrogen oxides (NO_x), black carbon (BC), and individual volatile organic compounds (VOCs), have been measured. Several studies suggest a significant contribution of outdoor sources to indoor air quality [12–23]. In addition to outdoor air, the main indoor sources in a typical school classroom include emissions from humans, furniture, paints, glues, disinfectants, and cleaning products [13–17, 19, 20, 22–25]. Exposure of children to high pollutant levels or prolonged exposure to levels above the World Health Organization (WHO) guidelines can cause asthma, inflammation, and even permanent cell and tissue damage [12].

Particulate matter (PM), especially particulate matter with an aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$), has also been associated with adverse health effects, such as respiratory and cardiovascular inflammations [11, 12]. $PM_{2.5}$, including ultrafine particles, can reach the lower lungs and deposit there, eventually leading to oxidative stress [26, 27]. Within classrooms, the major PM source usually is outdoor air; however, the large number of children in a relatively small space for prolonged time periods results in the resuspension of particles from surfaces [11]. Increased particle levels are also associated with poor ventilation, especially observed during winter [11, 28, 29].

The indoor carbon monoxide (CO) limit set by WHO for 1-h average exposure is 31 ppm, while for 8-h average, it is 9 ppm [30]. Nitrogen dioxide (NO_2) and formaldehyde WHO limits for indoor exposure are 20.6 and 34 ppb, respectively [30–32].

Pollutant levels measured in school classrooms in past studies were 1–15 ppb for SO_2 [21], 0.3–14 $\mu g\,m^{-3}$ for BC [12], 2.8–9.5 ppb for acetaldehyde [14, 25, 33], 1.0–3.5 ppb for benzaldehyde [18], 0.03–3.5 ppb for benzene [12, 24], 0.03–7.5 ppb for toluene [18, 24, 34], 0.2–1 ppb for styrene [18], and 0.1 and 1.5 ppb for C9 aromatics [18]. Additional details about these past studies are provided in Table S1.

The maintenance of low indoor pollutant levels is often achieved via ventilation [35]. Previous studies have shown that although classrooms are regularly ventilated, mainly in-between classes during winter, ventilation may not be adequate [12, 35]. Natural ventilation (through the opening of windows) is often used in schools, followed by mechanical ventilation [1, 12]. The supply rate of outdoor air inside the classroom has a key role in the quality of air. Higher ventilation rates have been associated with healthier students and higher learning performance [1, 12, 36]. At the same time, natural ventilation through open windows, doors, or any tiny openings in the building envelope transfers both gas-phase pollutants and particles from the outdoor environment indoors. This can lead to high pollutant levels indoors if their concentrations outside the building are high. If the ventilation is interrupted, the pollutants are trapped indoors, and their levels decline slowly even if their outdoor levels decrease rapidly [1, 12, 36].

Previous studies have mainly focused on specific pollutants, investigating their levels and effects on children's learning ability and health [12–23]. Open questions remain, including (a) the evaluation of the classroom air quality by combining the measurements of gaseous and particulate pollutants; (b) the identification of in-classroom sources and the role of outdoor air in the pollutants' levels; and (c) the role of ventilation during classes, breaks, and prior to the beginning of the school in wintertime, when traditionally the windows remain closed due to the cold weather conditions.

The aim of this study is to characterize the air quality of a primary school classroom during wintertime by simultaneously measuring gas-phase and particulate pollutants. Winter is selected due to the restricted ventilation, the lower temperature and higher humidity levels, and the use of heating within the classroom and in houses close to the school area. Analysis of multiple pollutants' levels allows for the estimation of their sources and the factors influencing the classroom air quality and subsequently children's health.

2. Materials and Methods

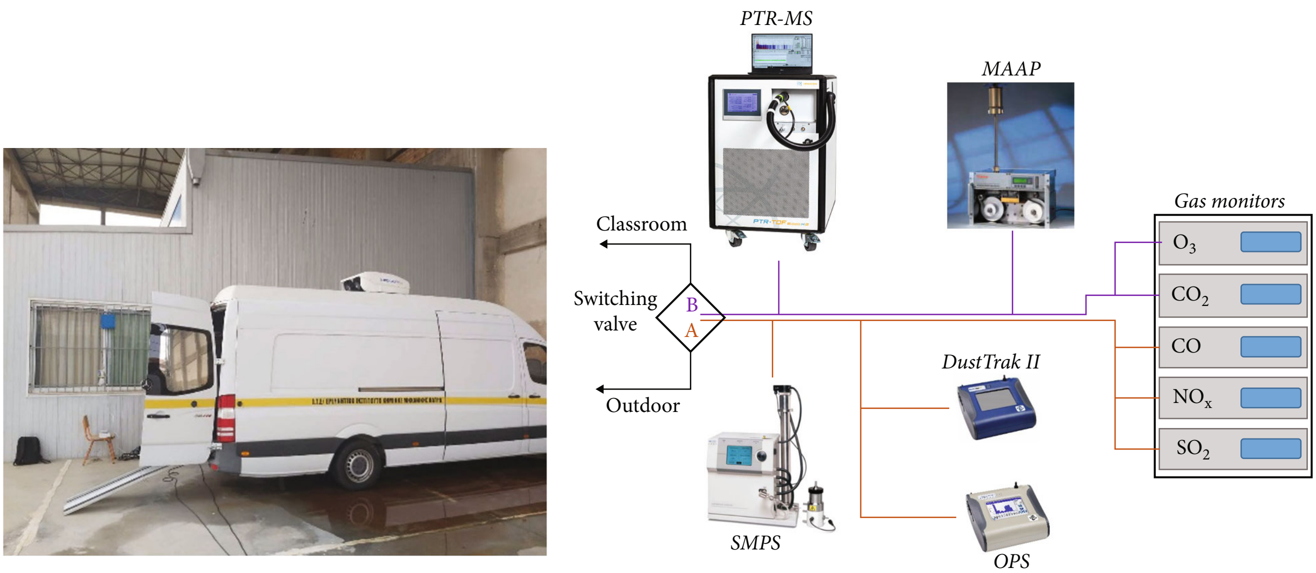
2.1. Location of Measurements. The Kastritsi primary school, located 8 km to the north of the city center of Patras, Greece, was selected for the air quality measurements. It is part of a school complex including a high school. The school is 1 km from the University of Patras main campus. The roads surrounding the school are not arterial, and they mainly accommodate the students, parents, and school personnel. A large school yard in front of the primary school is used by the students, and a smaller back yard is only accessed by the teachers. This smaller yard is protected by a shelter and contains a smoking area. The shelter surface was covered by concrete and was surrounded by grass.

The examined classroom was facing the back yard and was selected due to its easier access and its restriction to the children. The classroom was 7 (width), 8 (length), and 4 m (height) and was used by 20 first-grade children. The distance between this classroom and the smoking area was 6 m, and the road was approximately a 10 m distance. The road was at a higher level (3.5 m) than the classroom.

The classroom was selected using three main criteria: (1) accessibility so that the Foundation for Research and Technology–Hellas (FORTH) mobile laboratory could be next to it without obstructing main roads and the school's activities, (2) safety and constant access to the mobile laboratory, and (3) permission by the school and parents to conduct measurements. The selected school and classroom met all three criteria. The existence of a smoking area nearby did not affect the air quality of the classroom, as discussed in the results, due to its distance from it and its infrequent use.

Within the primary school, the selected classroom is adjacent to the events room, and the main door of the classroom leads to this room (Figure S3). Thus, painting and crafts activities, usually taking place in the events room at noon, can directly affect the classroom studied. The students also participate in painting and crafting activities once a week inside the classroom. During these periods, the windows remained partially open. Additional activities occur either in the events room or in the front yard of the school. During breaks, all the students are either in the front yard, if the weather allows it, or in the hallways and the events room. All the windows remained open during the breaks to allow for natural ventilation and circulation of air, following the guidelines of the Greek Ministry of Education.

2.2. Instrumentation. The FORTH mobile laboratory [37] was used to transport and host the instrumentation used for the air quality measurements (Figure 1(a)). A proton transfer reaction mass spectrometer (PTR-MS, Ionicon Analytik) was used to measure VOCs. The sampling flow rate was 0.5 L min^{-1}, and the drift tube operated at 600 V at a constant pressure of 2.2–2.3 mbar (detailed information in [38]). A scanning mobility particle sizer (SMPS) (classifier model 3080, differential mobility analyzer (DMA) model 3081, condensation particle counter (CPC) model 3787, TSI), with a sheath flow rate of 5 L min^{-1}, sample flow rate of 1 L min^{-1}, and size range from 10 to 710 nm, was used to measure the particle number size distribution. Additionally, an optical particle sizer (OPS model 3330, TSI) and an aerosol monitor DustTrak II (DT, model 8530, TSI) were used to measure the size distribution and concentration of larger particles. A multiangle absorption photometer (MAAP model



(a) (b)

Figure 1: (a) Photograph of the FORTH mobile laboratory outside of the examined classroom and (b) schematic of the instrumentation and their connections.

2012, Thermo Fisher Scientific) was used to measure BC mass loadings. Gas monitors were used to measure O_3 (Model 400E, API Teledyne), SO_2 (Model 100EU, API Teledyne), CO and carbon dioxide (CO_2) (Model 300E, API Teledyne), and NO_x (Model T360, API Teledyne).

All the instruments used in the present study were calibrated prior to their deployment in the school. Specifically, all the gas monitors were calibrated using gas cylinders for each reference compound. The particle monitors were evaluated by verifying their corresponding flows, probes, pressure, and accuracy as instructed by the manufacturer. Finally, the PTR-MS performance was also evaluated during test experiments in the laboratory.

2.3. Measurements. The measurements lasted a week and started on the afternoon of January 12, 2023 (Thursday), and were completed on the afternoon of January 19, 2023 (Thursday). Patras is located in the Ionian Sea, and its winters are mild (Figure S4). However, January is usually the coldest month of the year. Even in this coldest period of the year, the minimum temperature exceeds 2°C, and the maximum temperature can reach or even exceed 20°C. The city and its meteorological conditions are representative of the larger Greek cities, which are located at the coast and include more than three-quarters of the population.

We categorize the reported values into three periods: (1) the school hours, which correspond to 8:00 until 13:30 local time (LT), as the students are allowed to enter the classroom at 8:00; (2) the cleaning period, which is from 13:35 to 16:15; and (3) the nonschool hours, which correspond to the rest of the day. The classroom windows were opened prior to the beginning of classes for ventilation (7:45–8:30 or 9:00) and during the last two classes (11:30 or 12:00–13:30). During the rest of the day, most of the windows remained closed, with the exception of one window that remained half open. The windows were also opened during breaks that lasted 20 (first break), 15 (second break), and 10 min (third break). During the nonschool hours, a window remained partially open.

All instruments were used for both in-classroom and outdoor measurements, and Teflon and copper tubing were used for the sampling. The instruments were sampled alternatively in-classroom and outdoor air (Figure 1(b)). Valve A was connected with the SMPS, OPS, DustTrak, SO_2, NO_x, and CO monitors, while valve B was connected with the PTR-MS, MAAP, O_3, and CO_2 monitors. Switching was achieved by combining a three-way stainless steel Swagelok valve (1/4 inch) and a servomotor, controlled by an Arduino Uno. The switching took place every 6 min, and it was synchronized with the SMPS scanning cycles. The first minute was discarded, and the following 5 min were used in the analysis. The CO_2 levels were used to confirm the correct switching during school hours.

The FORTH mobile laboratory was placed outside of the classroom under the shelter and within 50 cm of the classroom window (Figure 1(a)). The instrumentation was placed securely inside the mobile laboratory. To avoid overheating the instruments, a fan was placed inside the mobile laboratory.

3. Results and Discussion

3.1. Meteorology. Elevated in-classroom and outdoor temperature levels were observed during the day, with in-classroom temperatures reaching values of 25°C (Figure 2). The outdoor levels peaked at noon, reaching values of 20°C. The relative humidity decreased during the day, with indoor values being lower than outdoors. The in-classroom levels varied from 33% to 43%. Outdoor relative humidity ranged from 40% to 68%.

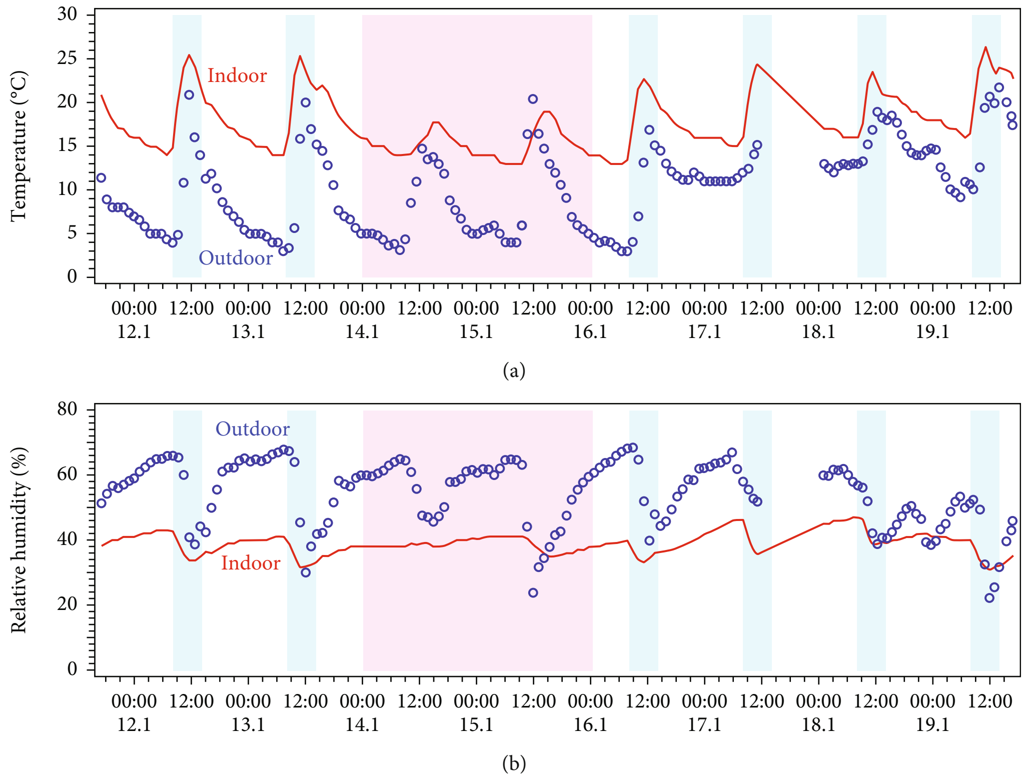


FIGURE 2: Indoor (red line) and outdoor (blue symbols) values of (a) temperature and (b) relative humidity during the campaign in the Kastritsi school. The light blue shading represents the school hours and the pink shading represents the weekend.

3.2. CO_2. Previous studies have reported that in-classroom CO_2 levels in suburban and light-density urban areas varied from 400 to 4000 ppm, while outdoor levels ranged from 300 to 700 ppm [1, 39, 40]. Figure 3 shows the CO_2 concentrations during the campaign. During school hours, the in-classroom CO_2 levels were on average 520 ppm, while the outdoor concentration was 460 ppm. The 60 ppm difference between in-classroom and outdoor CO_2 levels is attributed to the presence of the students in the classroom and the resulting CO_2 emissions. After school hours, the in-classroom CO_2 levels decreased and remained at a constant level close to the outdoor concentration.

During classes, when all students are within the classroom, the CO_2 levels reach peak concentrations of up to 600 ppm without reaching alarming levels. The natural ventilation prevented the accumulation of in-classroom CO_2, and its levels did not reach 5000 ppm, which is considered the limit above which students' performance may deteriorate significantly [4].

3.3. Gas-Phase Pollutants. In-classroom average CO levels during school hours were 0.6 ppm, while the average outdoor concentration was also 0.6 ppm. The similar in-classroom and outdoor CO levels (Figure 3) indicate efficient indoor and outdoor air exchange and a lack of significant indoor sources. The CO concentrations in the classroom remained below the indoor WHO guidelines. The strong correlation ($R^2 = 0.98$) of in-classroom to outdoor CO levels indicates that the outdoor air was the main source of CO. Increased CO levels were mainly observed before the beginning of classes, at the end of the classes, and during non-school hours. The increased traffic around the school due to the drop-off and pick-up of children led to an increase in CO by approximately 0.1 ppm. During nonschool hours, CO reached values up to 1 ppm, mainly due to residential biomass burning and traffic. However, even these peak levels are considered relatively low.

Outdoor O_3 levels remained relatively low during this wintertime period, with a maximum of 50 ppb during the campaign (Figure 4). The same trend was observed for indoor O_3 levels in general. During school hours, the outdoor O_3 levels were higher compared to the in-classroom levels by 2 ppb, by 6 ppb during the cleaning period, and by 10 ppb during the nonschool hours. The lower in-classroom values are likely due to surface O_3 reactions [41, 42]. The similarity of the trends indicates the influence of outdoor air on indoor O_3 levels. The in-classroom concentrations were below the indoor WHO guidelines.

Due to technical issues with the SO_2 monitor, we were able to collect measurements only for 3 days (Figure 4). The outdoor levels were elevated compared to in-classroom levels by an average of 0.3 ppb, with average in-classroom levels equal to 0.4 ppb and outdoor levels of 0.7 ppb. The small difference in SO_2 levels could be due to the role of air exchange between the outdoor and indoor environments at periods of elevated SO_2. The in-classroom concentrations presented a similar pattern to the outdoor levels, indicating that the outdoor air was the main source of SO_2 in the classroom.

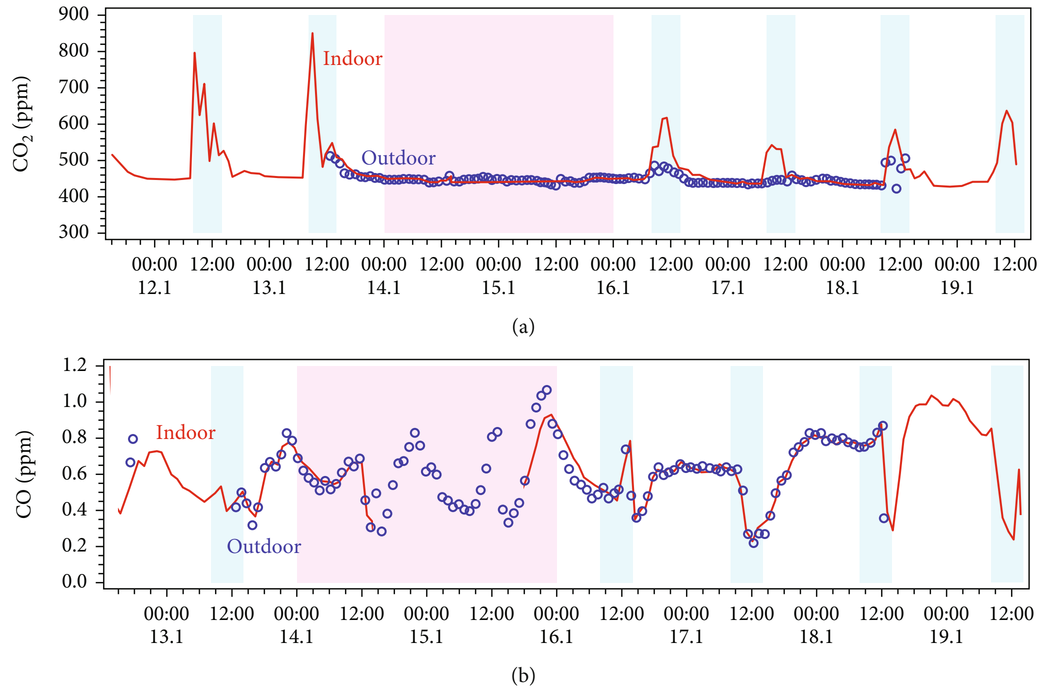


FIGURE 3: Indoor (red line) and outdoor (blue symbols) concentrations of (a) CO_2 and (b) CO during the campaign. The light blue shading represents the school hours and the pink shading represents the weekend.

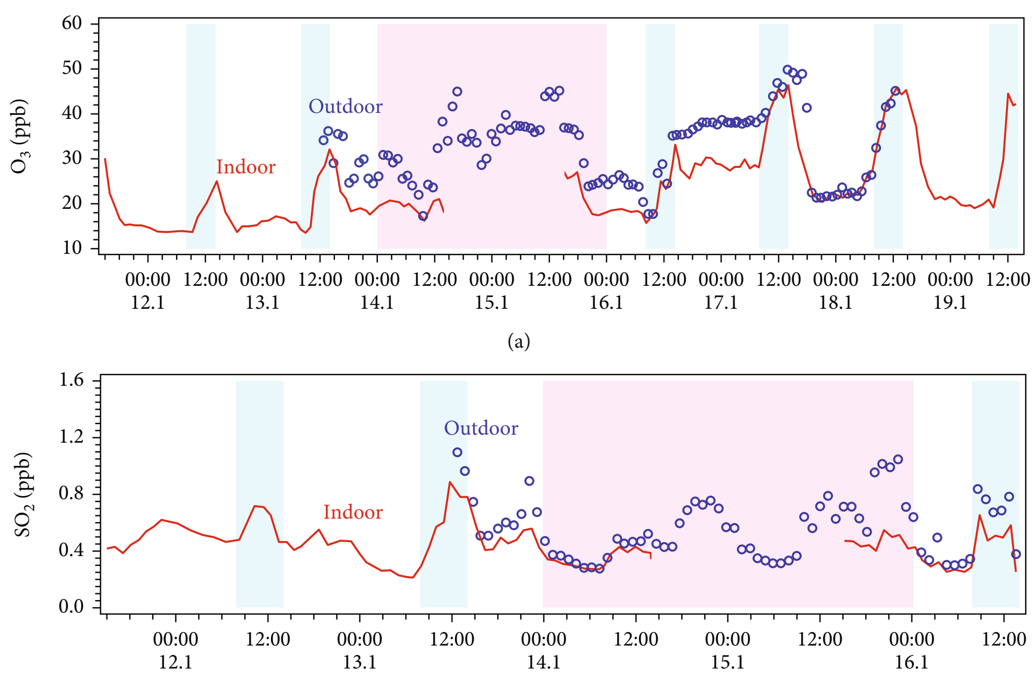


FIGURE 4: Indoor (red line) and outdoor (blue symbols) concentrations of (a) O_3 and (b) SO_2 for the duration of the campaign. The light blue shading represents the school hours and the pink shading represents the weekend.

The same indoor and outdoor levels during school hours were observed for NO_2 (Figure 5). Increased outdoor concentrations during school hours were followed by a significant decrease during nonschool hours. The in-classroom concentrations followed the same pattern as the outdoor concentrations, indicating that the outdoor air was the main source of indoor NO_2. On Monday 16/1, a significant NO_2 increase was observed in the classroom during school hours, with an average concentration of 12.7 ppb, practically the same as the outdoor average concentration of 12.5 ppb.

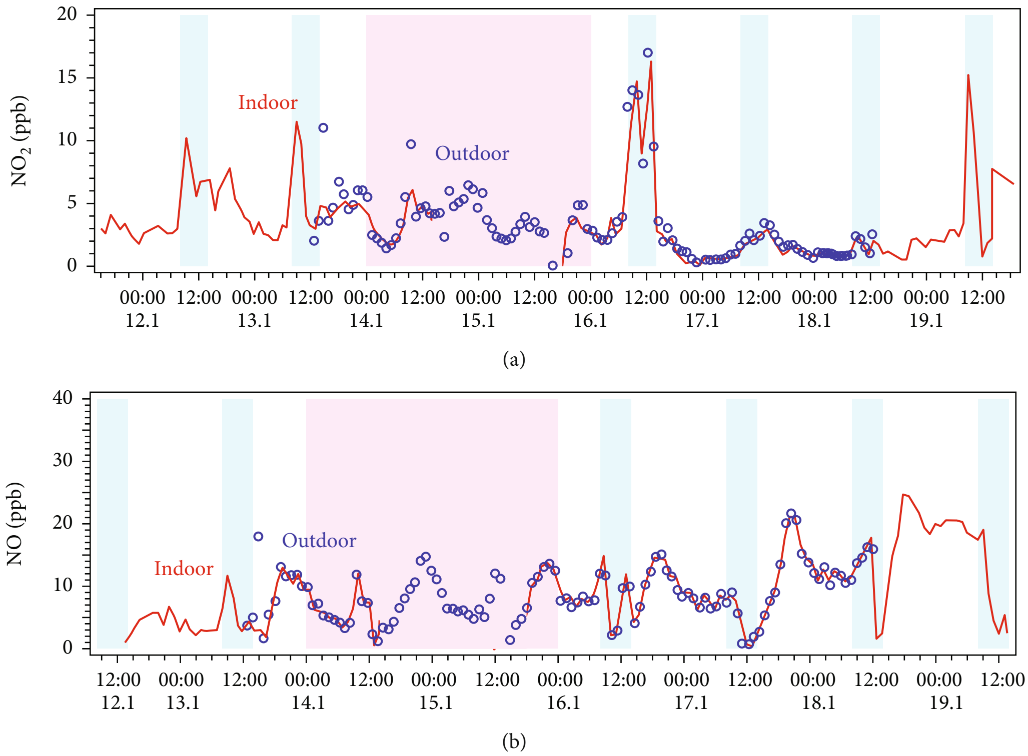


FIGURE 5: Indoor (red line) and outdoor (blue symbols) concentrations of (a) NO_2 and (b) NO for the duration of the campaign. The light blue shading represents the school hours and the pink shading represents the weekend.

During the cleaning period and nonschool hours, the average in-classroom NO_2 concentrations were 2.4 (2.9 ppb for outdoors) and 0.7 ppb (1.0 ppb for outdoors), respectively. This significant increase on Monday 16/1 is likely due to the increased traffic during that day. A similar pattern was observed on Thursday 19/1.

The nitric oxide (NO) levels peaked prior to the beginning of classes and had a second peak after they ended (Figure 5). These are probably attributed to the emissions of the automobiles of the parents dropping off and picking up their children. Traffic in the area, for example, people going to work, may also be contributing to these higher NO levels. Average in-classroom concentrations during school hours, cleaning periods, and nonschool hours were 6.5, 5.5, and 12 ppb, respectively. Similar to the other gas-phase pollutants, outdoor air was the main source of in-classroom NO.

BC levels were practically the same inside and outside of the classroom (Figure 6). During school hours, the average in-classroom levels were 1.1 $\mu g\,m^{-3}$. An increase in these levels was observed during the cleaning period (1.5 $\mu g\,m^{-3}$), followed by a 75% decrease during nonschool hours (0.4 $\mu g\,m^{-3}$). In-classroom BC levels are primarily associated with outdoor sources, such as fuel combustion [12], which was also the case in this school.

3.4. VOCs. The levels of seven VOCs (formaldehyde, acetaldehyde, benzene, toluene, benzaldehyde, C9 aromatics, and styrene) were analyzed due to their association with health effects [24, 25, 31, 43].

3.4.1. Aldehydes. The formaldehyde average concentrations in the classroom were 0.3, 0.7, and 0.9 ppb during school hours, cleaning periods, and nonschool hours, respectively. Elevated formaldehyde levels only inside the classroom were not observed, which suggests the absence of indoor formaldehyde sources, such as carpets [44, 45]. The outdoor concentrations were quite similar to the indoor levels (0.3, 0.5, and 0.8 ppb during school hours, cleaning periods, and nonschool hours, respectively) (Figure 7). The equal outdoor and in-classroom levels suggest that outdoor air is the main source of formaldehyde in the classroom during school hours. However, formaldehyde increased during the cleaning period, indicating that the cleaning products were a small formaldehyde source. The indoor formaldehyde levels measured in the examined classroom were significantly lower (up to a factor of 10) compared to the indoor WHO guideline and the literature-reported values [30–32]. The lower levels are likely due to the good ventilation and the relatively low emission rates.

Similar to formaldehyde, acetaldehyde and benzaldehyde had lower levels during school hours, followed by an increase during the cleaning period and the nonschool hours (Figure 7). The same indoor and outdoor concentrations during school hours support the hypothesis that the outdoor air was the main source of these aldehydes. The small increase during the cleaning period is attributed to the cleaning products, as these aldehydes are the main constituents of cleaning and sanitation products used [25, 31]. The concentrations were lower than previously reported values of 2.8–9.5 ppb [18, 25, 33, 45, 46], posing no threat to the children's health.

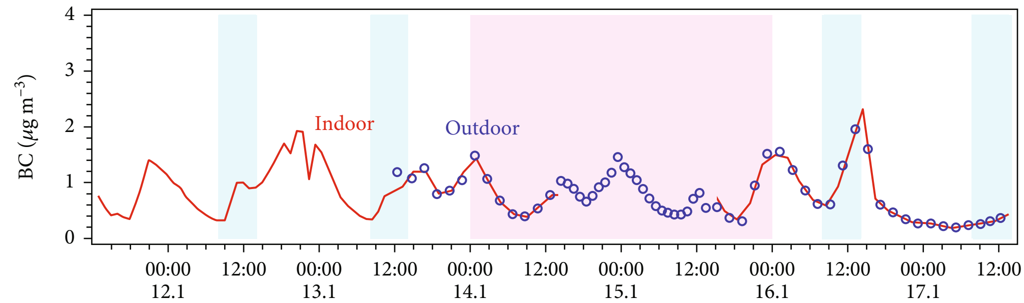


Figure 6: Indoor (red line) and outdoor (blue symbols) concentrations of black carbon for the duration of the campaign. The light blue shading represents the school hours and the pink shading represents the weekend.

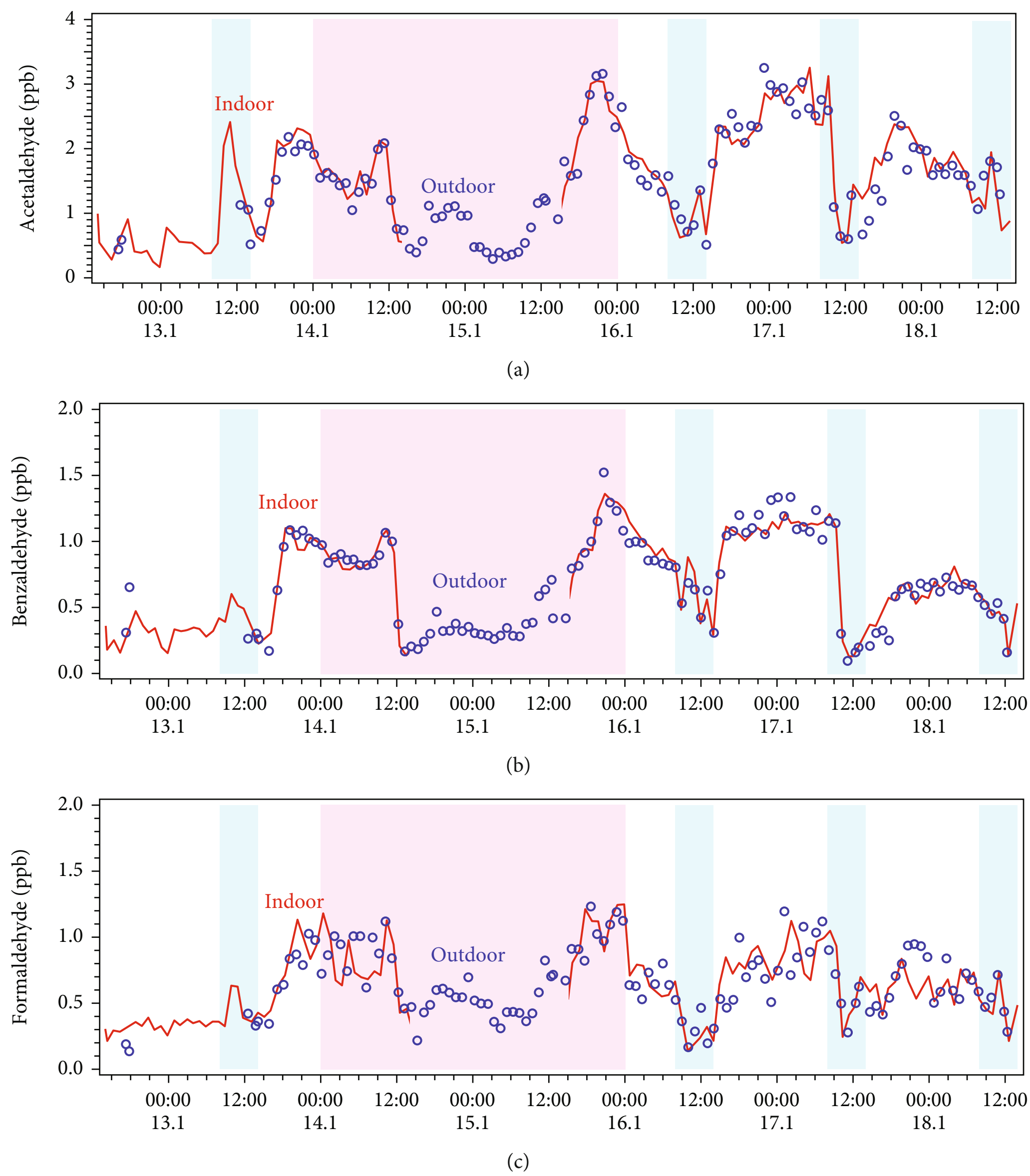


Figure 7: Indoor (red line) and outdoor (blue symbols) concentrations of aldehydes: (a) acetaldehyde, (b) benzaldehyde, and (c) formaldehyde for the duration of the campaign. The light blue shading represents the school hours and the pink shading represents the weekend.

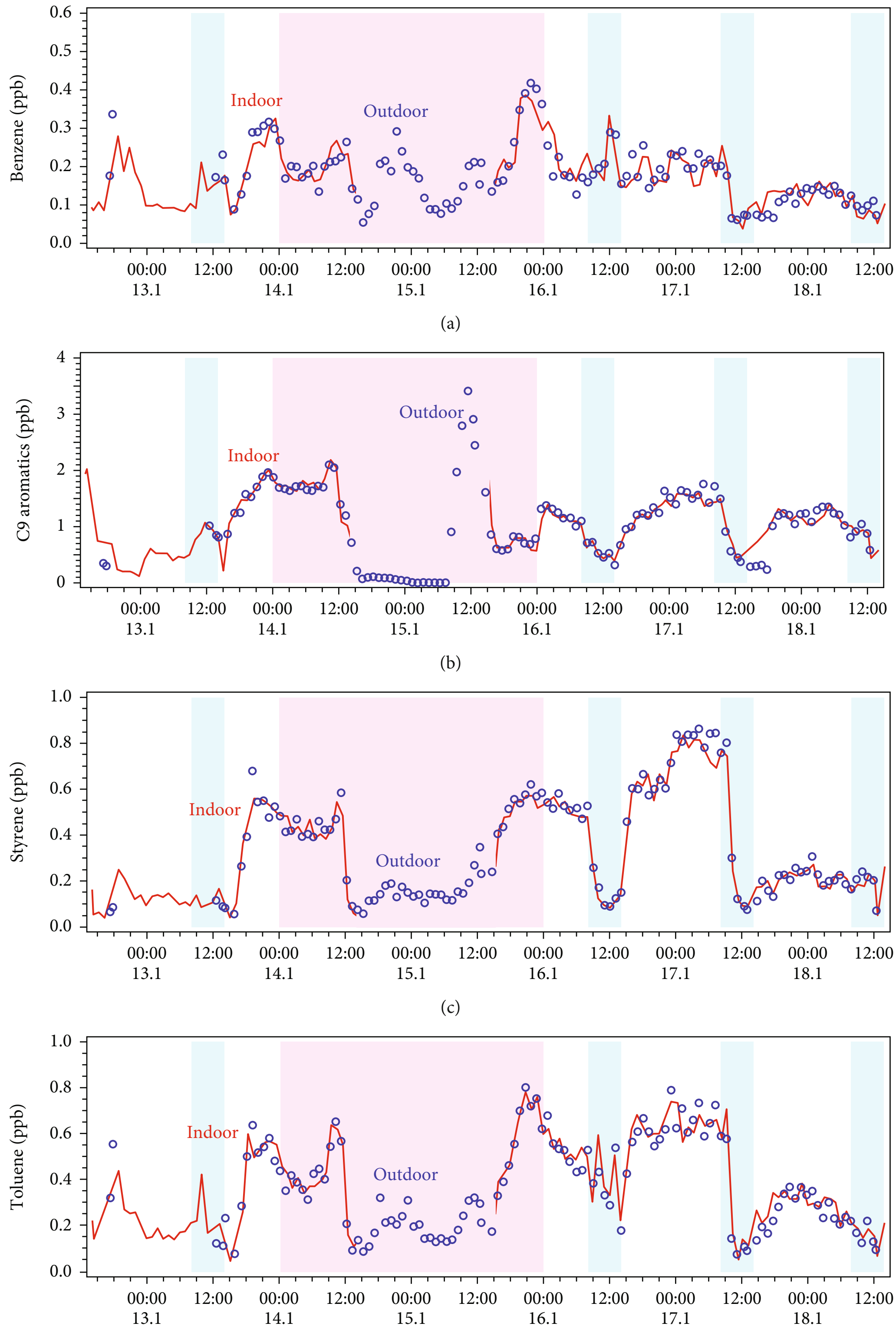


FIGURE 8: Indoor (red line) and outdoor (blue symbols) concentrations of aromatics: (a) benzene, (b) C9 aromatics, (c) styrene, and (d) toluene for the duration of the campaign. The light blue shading represents the school hours and the pink shading represents the weekend.

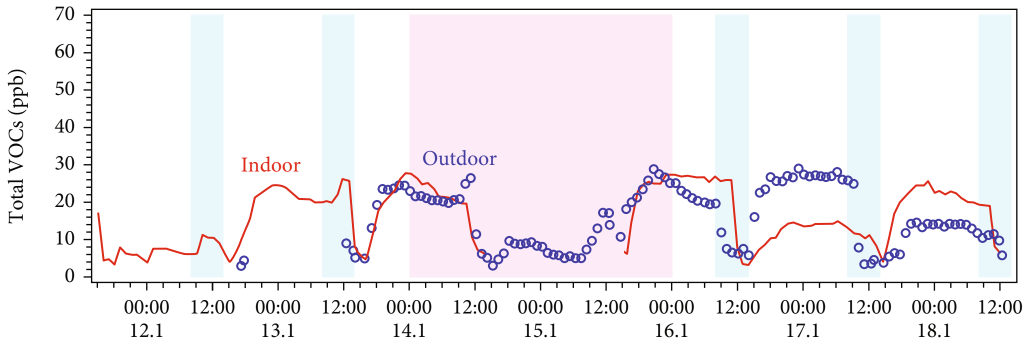


Figure 9: Indoor (red line) and outdoor (blue symbols) concentrations of the sum of VOCs reported by the PTR-MS for the duration of the campaign. The light blue shading represents the school hours and the pink shading represents the weekend.

Table 1: Correlation of the examined VOCs within the classroom. The data timescale was 1 h.

	R^2					
	Formaldehyde	**Acetaldehyde**	**Benzene**	**Toluene**	**Benzaldehyde**	**C9 aromatics**
Acetaldehyde	0.79					
Benzene	0.40	0.39				
Toluene	0.76	0.77	0.50			
Benzaldehyde	0.81	0.82	0.42	0.92		
C9 aromatics	0.54	0.54	0.19	0.56	0.66	
Styrene	0.74	0.71	0.35	0.87	0.88	0.68

Table 2: Correlation of the examined VOCs with gas-phase and particulate pollutants in the classroom. The data timescale was 1 h.

	R^2							
	BC	**CO_2**	**CO**	**NO_2**	**NO**	**O_3**	**SO_2**	**$PM_{2.5}$**
Formaldehyde	0.07	0.00	0.58	0.01	0.46	0.08	0.12	0.04
Acetaldehyde	0.06	0.00	0.63	0.02	0.53	0.04	0.21	0.03
Benzene	0.03	0.01	0.27	0.03	0.20	0.19	0.15	0.06
Toluene	0.05	0.00	0.65	0.01	0.48	0.15	0.16	0.01
Benzaldehyde	0.08	0.00	0.76	0.00	0.56	0.14	0.15	0.02
C9 aromatics	0.06	0.00	0.56	0.00	0.29	0.11	0.10	0.03
Styrene	0.08	0.00	0.66	0.00	0.44	0.11	0.13	0.04

The measured aldehyde levels in this study were low compared to those reported in classrooms of countries with different climates due to ventilation and the absence of in-classroom sources, such as carpets. In France, reported aldehyde levels in classrooms ranged from a few to tens of parts per billion [25, 47], even though there was natural ventilation. In Portugal, the aldehyde levels observed [33] were of the order of a few parts per billion and up to 2 ppb higher than the values measured in our study. The warmer climate of countries like Greece facilitates efficient natural ventilation and prevents the accumulation of pollutants like aldehydes in classrooms.

3.4.2. Aromatics. Benzene is considered a carcinogenic VOC, and there is no safe level of exposure according to WHO [30]. The levels of in-classroom benzene varied between 0.1 and 0.4 ppb, with some of the higher values recorded outside school hours (Figure 8). The measured average in-classroom concentration was 0.2 ppb and practically equal to the average outdoor value, indicating that outdoor air was the main source of indoor benzene.

In-classroom levels of toluene, styrene, and C9 aromatics also followed the outdoor concentrations (Figure 8). Their levels decreased during school hours, while an increase was observed during the cleaning period and nonschool hours. Toluene concentrations were 0.4, 0.6, and 0.6 ppb inside and outside of the classroom during school hours, cleaning periods, and nonschool hours. The corresponding styrene concentrations were 0.2, 0.5, and 0.7 ppb for the school hours, cleaning periods, and nonschool hours, respectively. The C9 aromatics levels were 0.6, 0.8, and 1.5 ppb, respectively. During school hours, the main source of these aromatics was the outdoor air.

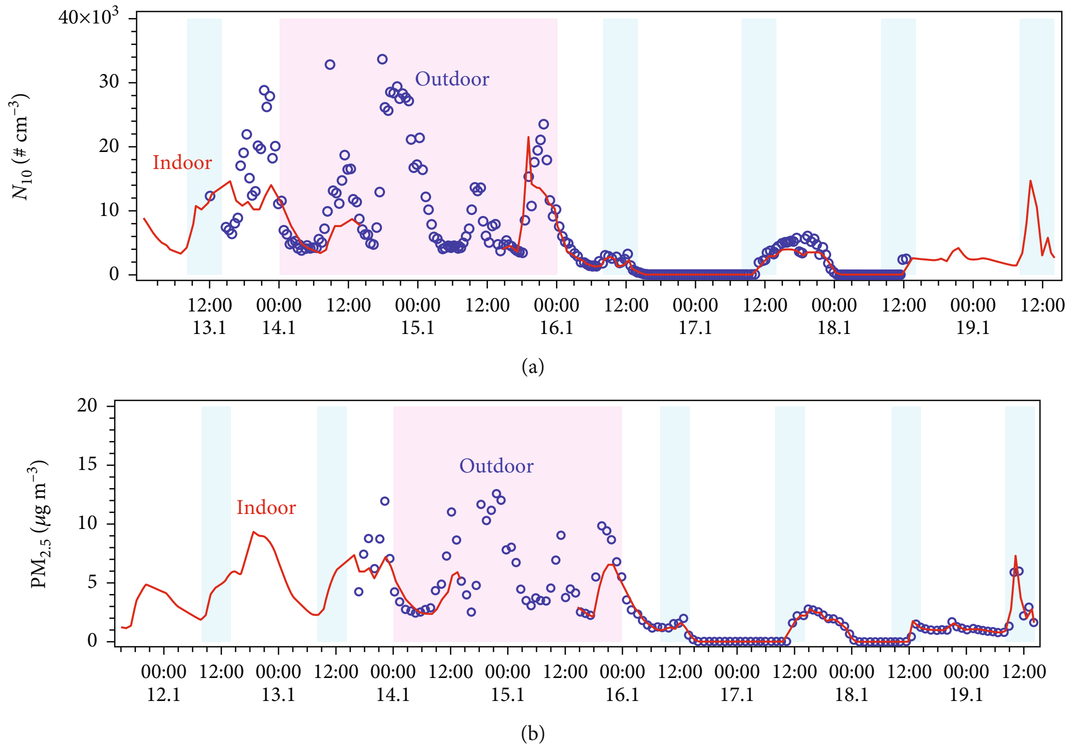


FIGURE 10: Indoor (red line) and outdoor (blue symbols) concentrations of (a) N_{10} and (b) $PM_{2.5}$ for the duration of the campaign. The light blue shading represents the school hours and the pink shading represents the weekend.

3.4.3. Levels of Total VOCs. The total VOC levels, reported by the PTR-MS, on a typical school day were of the order of 10 ppb (Figure 9). The measured individual fragments were, similar to the seven VOCs, also at low levels. In all cases, an increase during the cleaning period was observed (Figure 9). The lowest concentrations of the total VOCs were observed during school hours (average of 9.0 and 9.3 ppb in the classroom and outside, respectively), while the highest levels were observed during nonschool hours (average of 26.4 and 26.7 ppb in the classroom and outside, respectively) (Figure S1).

The correlation among the levels of the various measured VOCs inside the classroom was also examined. High correlations ($R^2 > 70\%$) are observed between the aldehydes, toluene, and styrene ($R^2 > 85\%$) (Table 1). These species are the main constituents of cleaning products [24, 25, 31]; thus, their correlation and the same increase observed during the cleaning period are consistent with a common source. Benzene showed a lower correlation with the other toxic VOCs ($R^2 \leq 50\%$), indicating a different source. In addition, significant correlations ($R^2 > 60\%$) were observed between selected VOCs and CO, as well as NO (Table 2). CO has been previously used for the estimation of formaldehyde originating from vehicular emissions, and NO is associated with combustion sources, that is, vehicle exhaust [48]. The results of this and previous studies are summarized in Table S2.

3.5. Particulate Levels. The $PM_{2.5}$ indoor levels ranged between 1.4 and 3.8 $\mu g\,m^{-3}$ during school hours (Figure 10). The outdoor levels varied between 0.7 and 6.2 $\mu g\,m^{-3}$, with the average level during school hours being 3.6 $\mu g\,m^{-3}$, a factor of 1.5 higher than the indoor levels. The indoor levels followed the same trend and were similar or lower than the outdoor levels. Thus, it appears there was no significant indoor source of particulates, and the outdoor air was the main indoor source.

Figure 10 shows the number concentration of particles with a diameter larger than 10 nm (N_{10}) [49]. The in-classroom N_{10} levels follow the outside number concentration, with higher values observed during school hours and cleaning periods. The elevated activity from the increased traffic during the school days resulted in elevated N_{10} levels. The in-classroom levels were on average a factor of 1.3 lower than the outdoor concentrations, indicating the absence of significant indoor particulate sources.

Figure 11 presents the measured particle number distribution indoors and outdoors. After the cleaning period, higher levels of particles with a diameter of 60–80 nm were observed, while a wider size range was observed during school hours. Smaller particles can easily penetrate into the lower lung, causing damage to cellular membranes and an imbalance in the free radical levels [11, 12]. Such effects can lead to oxidative stress when particulate levels are elevated. The observed particles could reach the inner parts of the children's respiratory system; however, their levels during the campaign remained quite low, posing no threat to the students' health. The results of these previous studies are summarized in Table S1.

3.6. Ventilation Rate Estimation. The natural ventilation of the classroom throughout the school hours allows for the

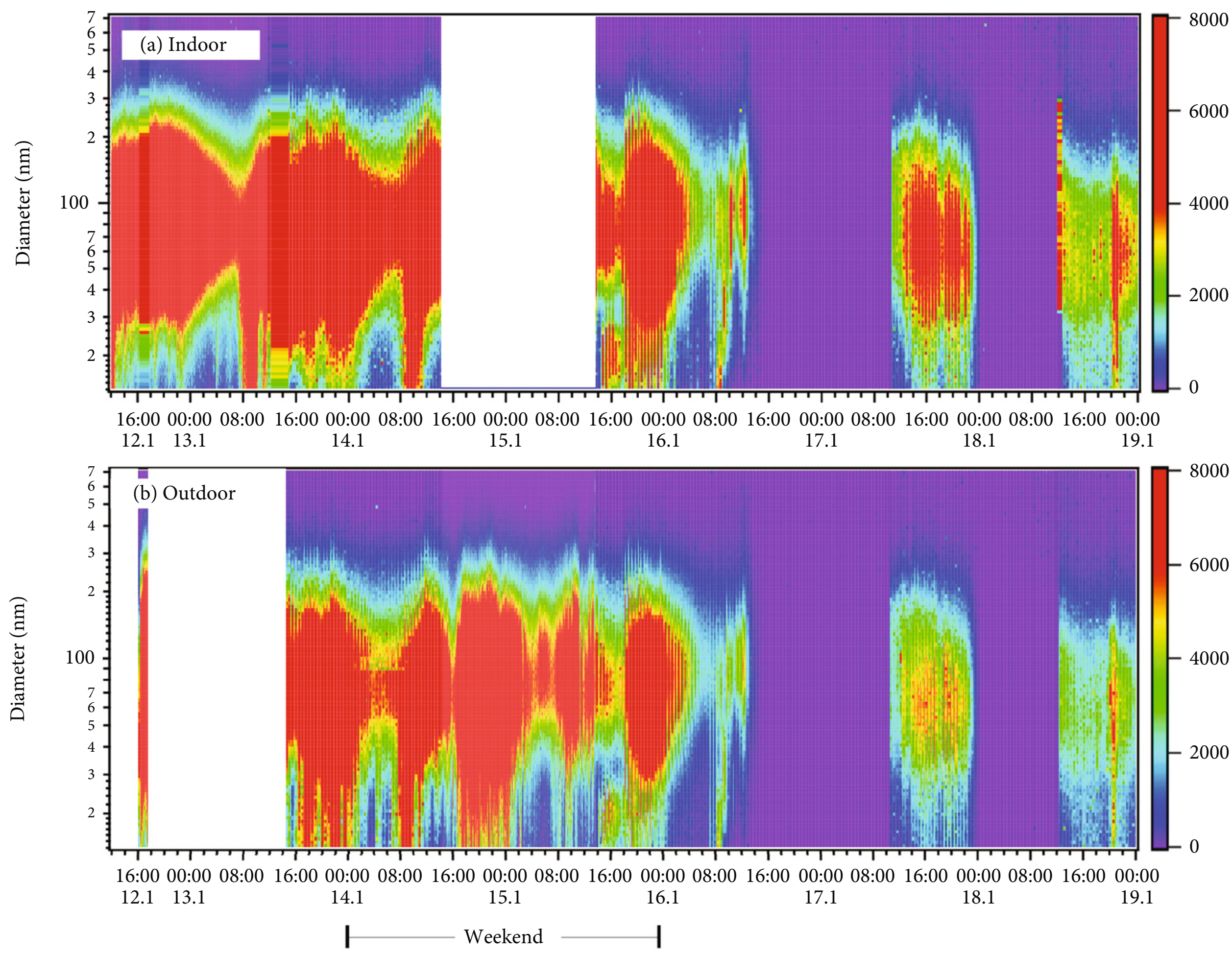


Figure 11: Average particle number distribution (dN/dlogDp) for (a) indoor and (b) outdoor air for the duration of the campaign.

exchange of indoor and outdoor air. To quantify its magnitude, we constructed a simple box model for CO_2. No chemical interactions were considered in the model. We assumed an average CO_2 emission rate of $8.8 \times 10^{-6}\, g\, s^{-1}\, person^{-1}$ [50]. The number of people within the classroom for each class was $n = 21$ (20 students and one teacher), and the volume of the classroom was $V = 224\, m^3$. The model was used to estimate the ventilation rate based on the measured indoor and outdoor levels.

The indoor CO_2 concentration, CO_{2in}, is described by

$$V \frac{dCO_{2in}}{dt} = \text{VR (ventilation rate)}\left(CO_{2out}(t) - CO_{2in}(t)\right) + nGp_{CO_2}(t) \tag{1}$$

where V is the volume of the classroom (cubic meters), t is the time from the beginning of the simulation (seconds), VR is the ventilation rate ($m^3\, s^{-1}$), CO_{2out} is the outdoor CO_2 concentration ($g\, m^{-3}$), CO_{2in} is the indoor CO_2 concentration ($g\, m^{-3}$), n is the number of persons in the classroom, and Gp_{CO_2} is the CO_2 emission rate ($g\, s^{-1}$ $person^{-1}$).

The average air change rate (ACR = VR/V) was estimated with 10 min resolution by assuming that the VR remains constant during each 10 min step. The solution algorithm calculates the VR at which the calculated and the measured indoor CO_2 concentrations have a minimum difference.

The average ACR for the duration of the study was estimated to be 2.8 h^{-1} (Figure 12). The lowest average ACR was calculated for the weekend at 1.4 h^{-1} and the highest during classes at 3.5 h^{-1}. The relatively high average ACR during the weekend is mainly due to a window of the classroom that was left partially open. During breaks and the cleaning period, the average ACR was 3.1 and 3.0 h^{-1}, respectively, and the overall average ACR during school hours was 3.3 h^{-1}. During the weekdays, the average ACR was 2.4 h^{-1} because a window remained partially open and the door of the classroom was often not fully closed, allowing for the outside air to enter the classroom.

The calculated ACR was above the minimum recommended standards by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [51]. More specifically, ASHRAE recommends an average ventilation rate of 15 $ft^3\, min^{-1}$ per person, which in the case of the examined classroom translates to an ACR of 2.4 h^{-1}. Therefore, the average ventilation rate of 3.5 h^{-1} was 45%

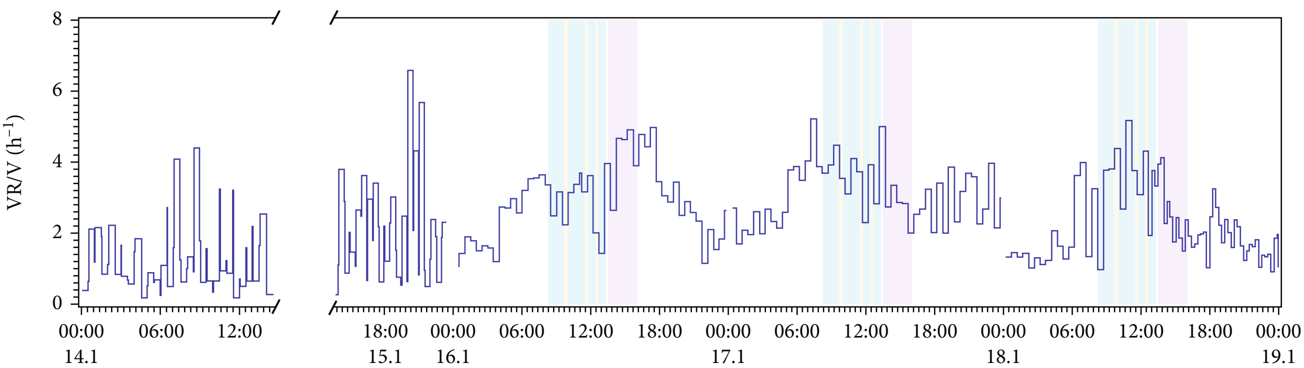
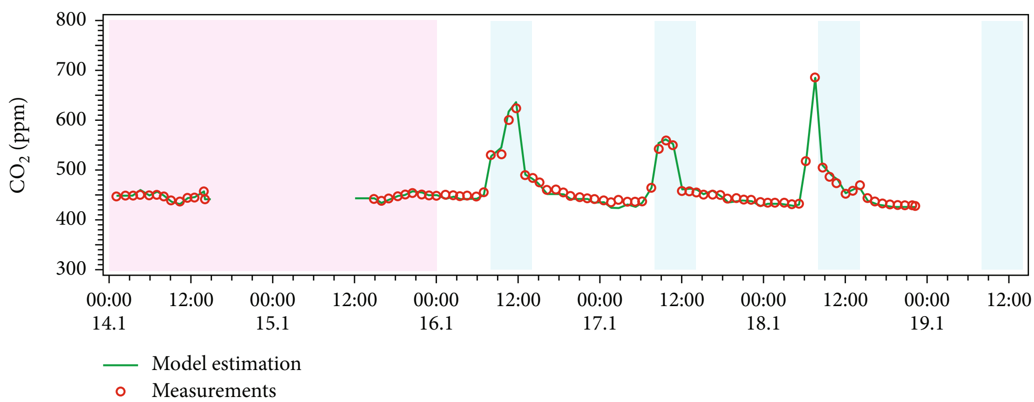
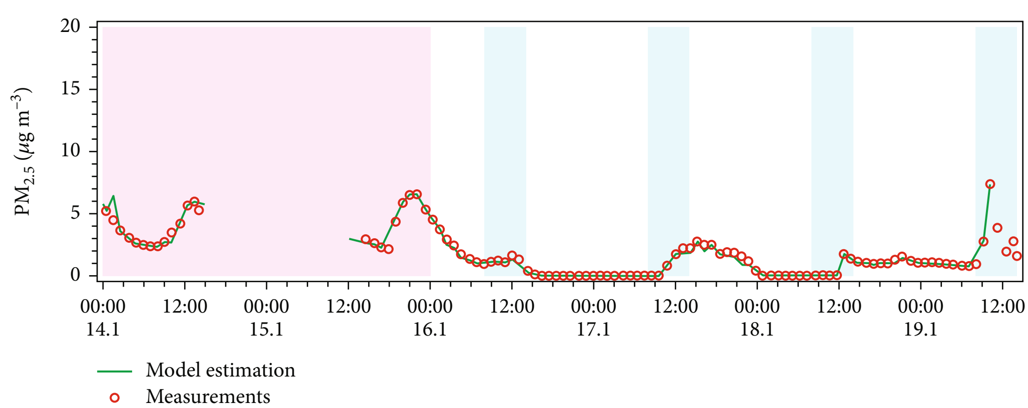


FIGURE 12: Estimated air exchange rate during the campaign. The light blue shading represents the school hours and the pink shading represents the weekend.



(a)



(b)

FIGURE 13: Comparison of indoor (a) CO_2 and (b) $PM_{2.5}$ model predictions and measurements. The light blue shading represents the school hours and the pink shading represents the weekend.

higher than the value recommended by ASHRAE. The relatively short duration of the present study prevents us from performing a detailed analysis of the variability of the ventilation rate under different weather conditions. However, given that the measurements took place during a relatively cold period of the year, the ventilation rates are expected to be at the same level or even higher during the fall, spring, and summer. The ventilation rates at colder periods in Greek schools will be the topic of future work.

The predicted CO_2 levels inside the classroom using the estimated ACRs are compared with the measurements in Figure 13. The agreement is excellent with a difference on average of less than 1%. As an independent test, we simulated the indoor $PM_{2.5}$ levels using Equation (1) but assuming zero emission rate inside. The model in this case assumes that the only source of indoor $PM_{2.5}$ is the outside air. Excellent agreement was obtained for this pollutant too (Figure 13), with errors of a few percent suggesting that the air exchange rates estimated are quite robust. This test of the model for $PM_{2.5}$ does not use any adjustable parameters, so it can be viewed as an evaluation test of the simple model used in this study. A comparison of predicted and observed values is also shown in Figure S2.

The sensitivity of the estimated ACR to the values of the selected parameters was examined in a series of sensitivity tests. An increase in the assumed CO_2 emission rate per person by 20% led to an increase in the estimated ACR of approximately 5% on average. The sensitivity increases to 20% in certain periods and is exactly the same for the number of persons in the room. In a similar sensitivity test, we changed by 20% the indoor and outdoor CO_2 concentrations. This resulted in an average variation of the estimated ACR of 10%–20% depending on the period examined. These tests also support the robustness of our ACR estimates.

4. Conclusions

Investigation of the air quality of a classroom in a suburban area in Greece during winter showed the presence of low pollutant levels. The overall concentrations of the gaseous and particulate species remained close to the lower limits reported in the literature. Regular ventilation via natural air (open windows) allowed for the maintenance of low pollutant levels. The estimated ACRs during the school days, based on the CO_2 indoor and outdoor levels, ranged from 0.5 to 5.4 h^{-1} with an average of 3.5 h^{-1} during the school hours.

The main source of pollutants inside the examined classroom was the outdoor air, while the cleaning products used at the end of the school impacted the VOC levels during nonschool hours and the CO_2 levels in the presence of the students. VOC sources in classrooms also include arts and crafts supplies, whiteboard markers, the students themselves, as well as their clothing. These sources could affect the VOC levels within the classroom under conditions of poor ventilation or excess use, but this was not the case in the examined case. Ventilation prior to the beginning of the school reduced the VOC levels in the classroom.

Overall, the investigated school classroom had good air quality, and we did not identify a major in-classroom pollutant source during school hours. Ventilation ensured low pollutant levels, emphasizing the importance of opening the windows regularly during school operations. These conclusions of course apply to the specific classroom and similar ones under conditions (ventilation, sources indoors and outdoors, etc.) similar to those of the present study.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Conceptualization: E.D. and S.N.P.; methodology: E.D., C.K., and S.N.P.; data collection: E.D., S.A., and A.S.; data analysis: E.D.; writing—original draft preparation: E.D.; writing—review and editing: I.A., C.K., and S.N.P.; supervision: S.N.P.

Funding

This research was funded by the EU Horizon Europe, project SynAirG (grant number 101057271).

Acknowledgments

We thank the Kastritsi primary school principal, teachers, and personnel for their cooperation.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)* Table S1: $PM_{2.5}$ levels in classrooms and schools from previous studies. Table S2: VOC levels in classrooms and schools from previous studies. Figure S1: Average VOC concentration for each examined period. Figure S2: Predicted versus observed (a) CO_2 and (b) $PM_{2.5}$ values. Figure S3: A simple schematic of the surroundings of the examined classroom. Figure S4: Study map depicting the location of Greece.

References

[1] S. Sadrizadeh, R. Yao, F. Yuan et al., "Indoor air quality and health in schools: a critical review for developing the roadmap for the future school environment," *Journal of Building Engineering*, vol. 57, Article ID 104908, 2022.

[2] I. Alameddine, K. Gebrael, F. Hanna, and M. El-fadel, "Quantifying indoor $PM_{2.5}$ levels and its sources in schools : what role does location, chalk use, and socioeconomic equity play?," *Atmospheric Pollution Research*, vol. 13, no. 4, Article ID 101375, 2022.

[3] R. W. Hornung, B. P. Lanphear, and K. N. Dietrich, "Age of greatest susceptibility to childhood lead exposure: a new statistical approach," *Environmental Health Perspectives*, vol. 117, no. 8, pp. 1309–1312, 2009.

[4] J. F. Mejía, S. Low Choy, K. Mengersen, and L. Morawska, "Methodology for assessing exposure and impacts of air pollutants in school children : data collection, analysis and health effects - a literature review," *Atmospheric Environment*, vol. 45, no. 4, pp. 813–823, 2011.

[5] S. E. Grineski, T. W. Collins, and D. E. Adkins, "Hazardous air pollutants are associated with worse performance in reading, math, and science among US primary schoolchildren," *Environmental Research*, vol. 181, Article ID 108925, 2020.

[6] H. Burtscher and K. Schüepp, "The occurrence of ultrafine particles in the specific environment of children," *Paediatric Respiratory Reviews*, vol. 13, no. 2, pp. 89–94, 2012.

[7] J. Madureira, I. Paciencia, C. Pereira, J. P. Teixeira, and E. O. Fernandes, "Indoor air quality in Portuguese schools : levels and sources of pollutants," *Indoor Air*, vol. 26, no. 4, pp. 526–537, 2016.

[8] P. T. B. S. Branco, M. C. M. Alvim-Ferraz, F. G. Martis, and S. I. V. Sousa, "Quantifying indoor air quality determinants in urban and rural nursery and primary schools," *Environmental Research*, vol. 176, Article ID 108534, 2019.

[9] J. Bennett, P. Davy, B. Trompetter et al., "Sources of indoor air pollution at a New Zealand urban primary school: a case study," *Atmospheric Pollution Research*, vol. 10, no. 2, pp. 435–444, 2019.

[10] A. U. Raysoni, R. X. Armijos, M. M. Weigel et al., "Assessment of indoor and outdoor PM species at schools and residences in a high-altitude Ecuadorian urban center," *Environmental Pollution*, vol. 214, pp. 668–679, 2016.

[11] H. Fromme, J. Diemer, S. Dietrich et al., "Chemical and morphological properties of particulate matter (PM_{10}, $PM_{2.5}$) in school classrooms and outdoor air," *Atmospheric Environment*, vol. 42, no. 27, pp. 6597–6605, 2008.

[12] V. N. Matthaios, C. Kang, J. M. Wolfson et al., "Factors influencing classroom exposures to fine particles, black carbon, and nitrogen dioxide in inner-city schools and their implications for indoor air quality," *Environmental Health Perspectives*, vol. 130, no. 4, Article ID 047005, 2022.

[13] D. Brdari, E. Kovac-Andric, Š. Matej et al., "Indoor air pollution with benzene, formaldehyde, and nitrogen dioxide in schools in Osijek, Croatia," *Air Quality, Atmosphere & Health*, vol. 12, no. 8, pp. 963–968, 2019.

[14] A. Bradman, F. Gaspar, R. Castorina et al., "Formaldehyde and acetaldehyde exposure and risk characterization in California early childhood education environments," *Indoor Air*, vol. 27, no. 1, pp. 104–113, 2017.

[15] L. Fang, N. Liu, W. Liu et al., "Indoor formaldehyde levels in residences, schools, and offices in China in the past 30 years: a systematic review," *Indoor Air*, vol. 32, no. 10, pp. 1–17, 2022.

[16] M. Li, C. J. Weschler, G. Beko, P. Wargocki, G. Lucic, and J. Williams, "Human ammonia emission rates under various indoor environmental conditions," *Environmental Science & Technology*, vol. 54, no. 9, pp. 5419–5428, 2020.

[17] Y. Liu, P. K. Misztal, C. Arata, C. J. Weschler, W. W. Nazaroff, and A. H. Goldstein, "Observing ozone chemistry in an occupied residence," *Proceedings. National Academy of Sciences. United States of America*, vol. 118, no. 6, pp. 1–8, 2021.

[18] K. H. Lu, D. C. Vu, Q. T. Nguyen, and X. T. Vo, "Volatile organic compounds in primary schools in Ho Chi Minh City, Vietnam: characterization and health risk assessment," *Atmosphere*, vol. 12, no. 11, p. 1421, 2021.

[19] S. D. Lowther, S. Dimitroulopoulou, K. Foxall et al., "Low level carbon dioxide indoors—a pollution indicator or a pollutant? A health-based perspective," *Environments*, vol. 8, no. 11, p. 125, 2021.

[20] N. Muscatiello, A. McCarthy, C. Kielb, W. H. Hsu, S. A. Hwang, and S. Lin, "Classroom conditions and CO_2 concentrations and teacher health symptom reporting in 10 New York state schools," *Indoor Air*, vol. 25, no. 2, pp. 157–167, 2015.

[21] A. C. Olufemi, A. Mji, and M. S. Mukhola, "Health risks of exposure to air pollutants among students in schools in the vicinities of coal mines," *Energy Exploration & Exploitation*, vol. 37, no. 6, pp. 1638–1656, 2019.

[22] H. Salonen, T. Salthammer, and L. Morawska, "Human exposure to ozone in school and office indoor environments," *Environment International*, vol. 119, pp. 503–514, 2018.

[23] H. Salonen, T. Salthammer, and L. Morawska, "Human exposure to NO_2 in school and office indoor environments," *Environment International*, vol. 130, Article ID 104887, 2019.

[24] P. Lucialli, S. Marinello, E. Pollini et al., "Indoor and outdoor concentrations of benzene, toluene, ethylbenzene and xylene in some Italian schools evaluation of areas with different air pollution," *Atmospheric Pollution Research*, vol. 11, no. 11, pp. 1998–2010, 2020.

[25] C. Trocquet, I. Lara-ibeas, A. Schulz et al., "Continuous aldehydes monitoring in primary schools in France: evaluation of emission sources and ventilation practices over 5 weeks," *Atmospheric Pollution Research*, vol. 12, no. 1, pp. 340–351, 2021.

[26] R. H. Shamsollahi, M. Yunesian, S. Kharrazi et al., "Characterization of persistent materials of deposited $PM_{2.5}$ in the human lung," *Chemosphere*, vol. 301, Article ID 134774, 2022.

[27] E. Dovrou, S. Lelieveld, T. Berkemeier, A. Mishra, and U. Pöschl, "Influence of ambient and endogenous H2O2 on reactive oxygen species concentrations and OH radical production in the respiratory tract," *Environmental Science: Atmospheres*, vol. 3, no. 7, pp. 1066–1074, 2023.

[28] J. Rosbach, E. Krop, M. Vonk et al., "Classroom ventilation and indoor air quality - results from the FRESH intervention study," *Indoor Air*, vol. 26, no. 4, pp. 538–545, 2016.

[29] W. J. Trompetter, M. Boulic, T. Ancelet, P. K. Davy, Y. Wang, and R. Phipps, "The effect of ventilation on air particulate matter in school classrooms," *Journal of Building Engineering*, vol. 18, pp. 164–171, 2018.

[30] WHO, *WHO guidelines for indoor air quality: selected pollutants*, World Health Organization, 2010, Regional Office for Europe, Reference number: 9789289002134.

[31] I. C. Ribeiro, P. J. Kowalski, D. B. Callahan et al., "Foraldehyde levels in traditional and portable classrooms: a pilot investigation," *Journal of Environmental Health*, vol. 78, pp. 8–44, 2017.

[32] D. Hu, Y. Tobon, A. Agostini et al., "Diurnal variation and potential sources of indoor formaldehyde at elementary school, high school and university in the Centre Val de Loire region of France," *Science of the Total Environment*, vol. 811, Article ID 152271, 2022.

[33] T. Salthammer, "Acetaldehyde in the indoor environment," *Environmental Science: Atmospheres*, vol. 3, no. 3, pp. 474–493, 2023.

[34] L. Zhong, F. Su, and S. Batterman, "Volatile organic compounds (VOCs) in conventional and high performance school buildings in the U.S," *International Journal of Environmental Research and Public Health*, vol. 14, no. 1, p. 100, 2017.

[35] J. T. M. Rosbach, M. Vonk, F. Duijm, J. T. GinkelVan, U. Gehring, and B. Brunekreef, "A ventilation intervention study in classrooms to improve indoor air quality: the FRESH study," *Environmental Health*, vol. 12, no. 1, p. 110, 2013.

[36] N. G. Vasquezm, G. Beko, P. Wargocki et al., "Ventilation strategies and children's perception of the indoor environment in Swedish primary school classrooms," *Building and Environment*, vol. 240, Article ID 110450, 2023.

[37] C. Kaltsonoudis, S. D. Jorga, E. Louvaris, K. Florou, and S. N. Pandis, "A portable dual-smog-chamber system for atmospheric aerosol field studies," *Atmospheric Measurement Techniques*, vol. 12, no. 5, pp. 2733–2743, 2019.

[38] C. Kaltsonoudis, E. Kostenidou, K. Florou, M. Psichoudaki, and S. N. Pandis, "Temporal variability and sources of VOCs in urban areas of the eastern Mediterranean," *Atmospheric Chemistry and Physics*, vol. 16, no. 23, pp. 14825–14842, 2016.

[39] L. E. Mitchell, J. C. Lin, D. R. Bowling et al., "Long-term urban carbon dioxide observations reveal spatial and temporal dynamics related to urban characteristics and growth," *Proceedings of the National Academy of Sciences*, vol. 115, no. 12, pp. 2912–2917, 2018.

[40] O. Hänninen, N. Canha, A. V. Kulinkina et al., "Analysis of CO_2 monitoring data demonstrates poor ventilation rates in Albanian schools during the cold season," *Air Quality, Atmosphere and Health*, vol. 10, no. 6, pp. 773–782, 2017.

[41] J. Shen and Z. Gao, "Ozone removal on building material surface: a literature review," *Building and Environment*, vol. 134, pp. 205–217, 2018.

[42] G. Pei, Y. Xuan, G. Morrison, and D. Rim, "Understanding ozone transport and deposition within indoor surface boundary layers," *Environmental Science & Technology*, vol. 56, no. 12, pp. 7820–7829, 2022.

[43] S. Jin, L. Zhong, X. Zhang, X. Li, B. Li, and X. Fang, "Indoor volatile organic compounds: concentration characteristics and health risk analysis on a university campus," *International Journal of Environmental Research and Public Health*, vol. 20, no. 10, p. 5829, 2023.

[44] A. Katsoyiannis, P. Leva, and D. Kotzias, "VOC and carbonyl emissions from carpets: a comparative study using four types of environmental chambers," *Journal of Hazardous Materials*, vol. 152, no. 2, pp. 669–676, 2008.

[45] T. Salthammer, "Data on formaldehyde sources, formaldehyde concentrations and air exchange rates in European housings," *Data in Brief*, vol. 22, pp. 400–435, 2019.

[46] F. Caron, R. Guichard, L. Robert, M. Verriele, and F. Thevenet, "Behaviour of individual VOCs in indoor environments : how ventilation affects emission from materials," *Atmospheric Environment*, vol. 243, Article ID 117713, 2020.

[47] N. Canha, C. Mandin, O. Ramalho et al., "Assessment of ventilation and indoor air pollutants in nursery and elementary schools in France," *Indoor Air*, vol. 26, no. 3, pp. 350–365, 2016.

[48] B. Rappengluck, P. K. Dasgupta, M. Leuchner, Q. Li, and W. Luke, "Formaldehyde and its relation to CO, PAN, and SO_2 in the Houston-Galveston airshed," *Atmospheric Chemistry and Physics*, vol. 10, no. 5, pp. 2413–2424, 2010.

[49] K. R. Bilsback, J. Baumgartner, M. Cheeseman et al., "Estimated aerosol health and radiative effects of the residential coal ban in the Beijing-Tianjin-Hebei region of China," *Aerosol and Air Quality Research*, vol. 20, no. 11, pp. 2332–2346, 2020.

[50] A. Persily and L. JongeDe, "Carbon dioxide generation rates for building occupants," *Indoor Air*, vol. 27, no. 5, pp. 868–879, 2017.

[51] ASHRAE, *Indoor Air Quality Guide (ISBN 978-1-933742-59-5)*, ASHRAE, 2010.