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Activity

On-Site Monitoring Indoor Air Quality in Schools: A Real-World Investigation to Engage High School Science Students

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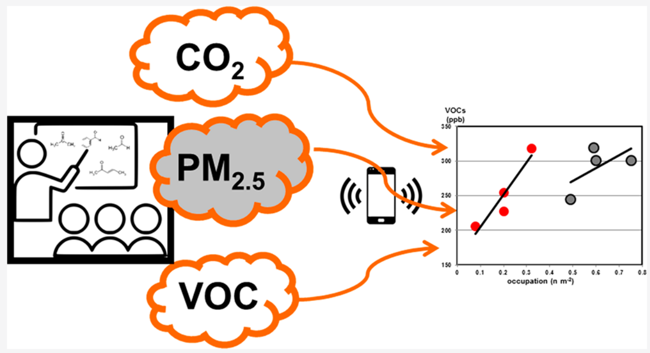
ABSTRACT: This article describes the on-site monitoring of indoor air quality (IAQ) in school classrooms and laboratories. The students were personally involved in the monitoring experience, by using low-cost IAQ sensors, and then in evaluation and interpretation of the measured values. The joint school−university project, which provides lessons, equipment, and support to high school classes, is a model of how to engage students in real-world science research and learning. The obtained results pointed out two alerts: unacceptable high levels of fine particle matter ($PM_{2.5}$)—mainly entered into indoor environments from highly polluted outdoor air—and uncomfortably high CO_2 levels—due to classroom crowding and inadequate ventilation.



KEYWORDS: *High School/Introductory Chemistry, Environmental Chemistry, Hands-On Learning/Manipulatives, Atmospheric Chemistry, Analytical Chemistry*

■ INTRODUCTION

Nowadays, there is increasing concern about the impact of indoor air quality (IAQ) on human health. This may generate long-term adverse effects, as most of the air exposure occurs indoors, where people spend a large fraction of their lives.[1,2] This is particularly critical in school buildings, considering that young people spend more than 60% of their time in schools and they are very sensitive to indoor pollutants, also including a significant decrease in the efficiency of student learning processes and cognitive performances.[3−7] Accordingly, it may be useful to develop new subjects related to these topics in the curricula of different school degrees in sciences and technology, in order to raise student awareness about the quality of the environment where they learn and live.[3,6,8−11]

With this is mind, the activity presented here is focused on indoor air quality monitoring in schools, in order to provide students with direct knowledge of the quality of the air they breathe. The students were actively involved in the teaching−learning activity, since they personally used low-cost sensors, based on the modern sensor technology, that are able to collect high-density temporal and spatial data in a broader range of households.[11−15] In addition, the students were given instructions to elaborate the IAQ data measured in their own classroom/laboratory, in order to analyze their dependence on different environment conditions.[7,10,13,14]

The project was developed as part of the "Piano Lauree Scientifiche" project (Italian Educational and Research Minister, MIUR) linking university and high schools. Such a school−university collaboration may generate benefit in the teaching−learning processes and enhance student interest in the proposed subjects.[8−11] Finally, this study is a further contribution to the characterization of the indoor air quality in Italian schools.[1,3,13,16−18]

The activity was designed to work with the basic contents of chemistry, physics, math, and computing sciences learned in the first classes of Italian high schools. The project integrated lecture-based teaching on IAQ concepts with experimental hands-on activity, as a Project-Based Learning approach particularly applicable to environmental chemistry.[8−11]

The educational objectives of this activity were as follows:

- exposing student to basic information on indoor air quality, with specific concern for the parameters responsible of indoor air pollution;
- approaching on-site modern sensor technology as the basis for developing high-density networks of low-cost instruments that may provide reliable information to citizens on air quality;
- enhancing awareness on the impact of personal behavior on air pollution and promote more responsible actions.

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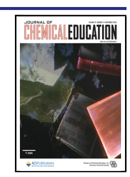

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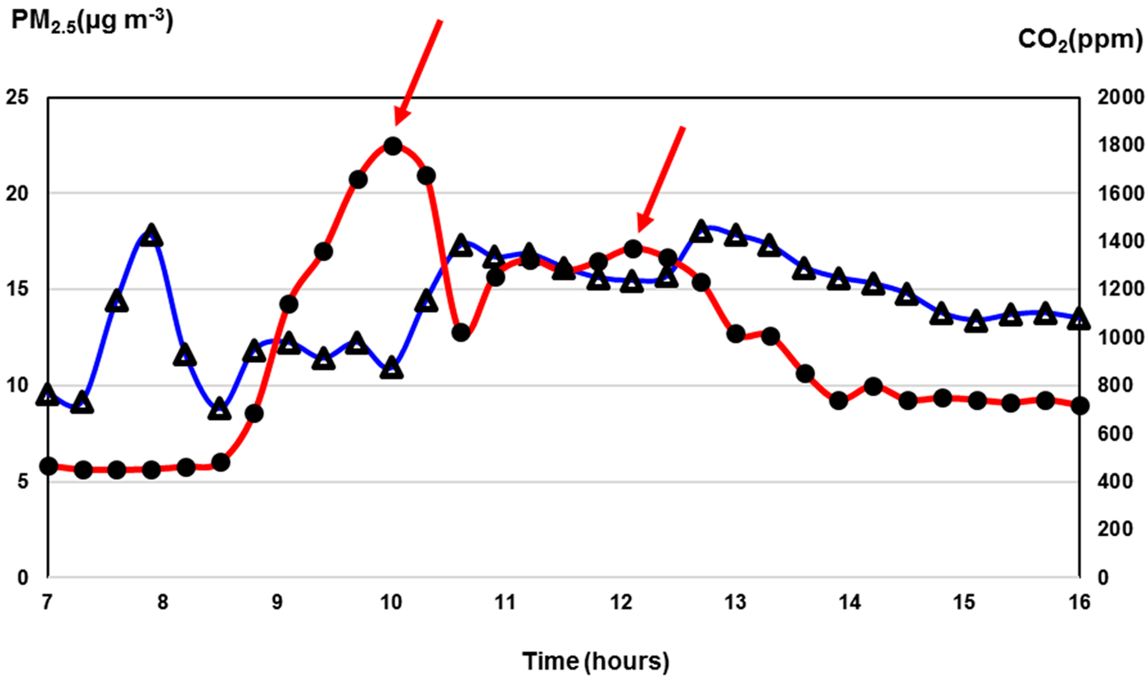

Figure 1. Temporal evolution of the monitored indoor $PM_{2.5}$ and CO_2 concentrations through the occupation hours monitored in classroom Cl3 during Feb. 14, 2019. Black points, indoor CO_2 level; empty triangles, indoor level. Red arrows indicate windows opening.

■ MATERIALS AND METHODS

The activity was performed during February−March 2019 in two secondary schools in the Emilia-Romagna region (Northern Italy) and involved nearly 200 students (details are reported in the Supporting Information).

The project was performed in different steps: presentation at the high school classes, monitoring of the IAQ parameters, data collection and analysis, and final presentation of the results to the students.

Phase 1: Presentation at the High School

The activity started with a presentation given by a university researcher at each participating class, introducing students to concepts of indoor air quality, covering the main indoor air pollutants, their sources, and also information about the threshold levels for alert conditions.[1,3,7,12] In addition, the monitoring sensors were described, highlighting their capability of continuous on-site monitoring of the IAQ parameters.[12−14,19]

Phase 2: Monitoring of IAQ Parameters

In each school environment the IAQ parameters were on-site measured using monitoring sensors operating 24 h continuously. The investigated parameters were temperature, relative humidity (RH%), concentration of fine particle matter ($PM_{2.5}$) and concentration of volatile organic compounds (VOCs), ubiquitous compounds with significant impact on the environment and human health, and CO_2, a surrogate for the quality of ventilation in the indoor environment.[1,4,7,13,18,19]

Measurements were performed with Foobot sensors purchased from Foobot (AirBoxLab, Luxembourg). The sensor measures 0.3−2.5 μm particles using light scattering technology and total VOCs, through a metal oxide semiconductor, from which a CO_2 equivalent concentration is estimated by an algorithm conversion.[12,19] In each school, the monitors operated in four rooms of at the same time. The devices communicated the real-time measurements via Wi-Fi to the manufacturer Web site (https://partner.foobot.io/), from which data can be downloaded using a smartphone application.

Phase 3: Data Collection and Analysis

The sensors were placed at the side of each room in a location that minimized disruption to classroom activities. For each day, two students were asked to register any classroom event, such as lesson/laboratory activity, lesson changing, and windows and doors opening/closing. Each school teacher was provided with continuous access to the remote server where IAQ raw data were saved (at 5 min intervals). At the end of each monitoring campaign, hourly data of each IAQ parameter were discharged and shared with the students for visualization and investigation.

Phase 4: Final Presentation of Results

At the end of the two sampling campaigns, the university researchers presented the whole data set to each participating class. Thus, all of the data were available to the students for comprehensive analysis and interpretation of the results. A classroom activity was performed consisting of an open discussion where the students were actively involved to comment on the measured IAQ values, with specific focus on the impact of the different environmental conditions.

■ RESULTS AND DISCUSSION

Classroom Activity on IAQ Parameters of Individual Classroom/Laboratory

After 2 weeks of saving data, the students gathered the IAQ values in the classroom/laboratory where they spent school time. They worked in groups of 4−6 participants with the support of school teachers to report and analyze the data. The students were given instructions to elaborate single parameters, temporal profiles, different time averages, summary tables, and correlations between parameters. Excel files were used to report the temporal evolution of the IAQ levels through the occupation hours. As an example, Figure 1 reports the variation of $PM_{2.5}$ mass and CO_2 concentrations in the most crowded classroom

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Cl3 (occupancy, 0.75 m^{-2}; Table S1 in the Supporting Information). It was related to any event that occurred during the lesson/laboratory and registered by the students in order to highlight its effects on room air quality. From the plot, it is clear that the indoor CO_2 (black points in the figure) and $PM_{2.5}$ values (empty triangles) largely changed throughout the occupation hours, mainly depending on windows opening (arrows in the figure). In fact, we can see that CO_2 started to increase with the lesson beginning after 8 AM to reach a maximum value at 10 AM, when the windows were opened to introduce fresh air. Then, CO_2 was nearly constant (≈13,000 ppm) until a further air exchange performed at 12 PM, before the last lesson. In contrast, the window opening generated a significant increase in the indoor $PM_{2.5}$ concentration up to 17 $\mu g\ m^{-3}$. In fact, the $PM_{2.5}$ concentration was the highest close to 8 AM, when windows were opened before lesson beginning, and at 10.30 AM and 12.30 PM, when the windows were opened again for air changing (Figure 1).

In addition, for each monitored IAQ parameter, the students computed the median daily values using only the data collected during occupation time, to be representative of their exposure time. They also related indoor (I) to outdoor (O) $PM_{2.5}$ levels by computing the indoor to outdoor I/O ratio in order to quantify the contribution of particles incoming from outside.[13,14,16,18]

Classroom Activity on the Whole Data Set of IAQ Parameters

In each participating class, a meeting was organized, where the university supervisor invited the students to present and comment on the results of the IAQ parameters measured in their classroom/laboratory. Such student presentations demonstrated that the performed activity enhanced students' knowledge on the modern sensor technology and its ability to provide reliable information on the real-world characteristics.

Then, the university researcher gave a summary of the whole set of IAQ values measured in the monitoring periods, also reporting two additional parameters, such as outdoor $PM_{2.5}$ concentrations and room occupancy, quantified as the number of students on a room surface (reported in Table S1 in the Supporting Information). On the basis of such information, the students were invited to discuss the data collected in their classroom/laboratory and compare them with the other data, with specific focus on indoor $PM_{2.5}$ and CO_2 concentrations, that were found the most critical parameters in all of the investigated environments. Examples of the problems posed to the students are the following:

- evaluate the indoor air quality in own classroom/laboratory in relation with threshold levels imposed by Italian legislation;[1]
- compare the IAQ levels in own classroom/laboratory with those of other classrooms/laboratories in the same and other schools;
- analyze the evolution of indoor $PM_{2.5}$ levels in relation with the outdoor $PM_{2.5}$ during the study days;
- evaluate the relationship of CO_2 concentration with the student occupancy in the different rooms;
- elaborate a hypothesis on the possible influence of outdoor $PM_{2.5}$ pollution, based on the indoor to outdoor ratio of $PM_{2.5}$ levels in the monitored classes.

The students actively participated in the discussion and elaborated interesting conclusions, so proving that they achieved a deep understanding of the IAQ characteristics and the parameters responsible for indoor air pollution. Given the educational context of this work, the obtained experimental results are only briefly discussed here, and more detailed information are reported in the Supporting Information.

Overall, the mean indoor $PM_{2.5}$ concentrations measured in each room were close to the WHO threshold value (25.0 $\mu g\ m^{-3}$)[1], as they ranged from 20.7 ± 9.8 $\mu g\ m^{-3}$ (Lab3) to 25.0 ± 17.0 $\mu g\ m^{-3}$ (Lab2 and Cl2) (Table S2 and Figure S1). A clear dependence was found between indoor and outdoor $PM_{2.5}$ concentrations, with significant correlation ($p < 0.05$) for most of the investigated rooms (Table S3). This suggests that indoor $PM_{2.5}$ values are mainly dominated by the contribution of outdoor $PM_{2.5}$, which may enter indoor environments by natural ventilation when windows are opened, by penetration through cracks in building envelopes, and through the operation of mechanical ventilation systems.[2,7,13,14,16,17] The computed I/O values were close to 0.8, ranging from 0.67 ± 0.17 (Lab3) to 0.86 ± 0.43 (Cl2) (Table S2). These values always below 1 indicate that the penetration through building physical barriers can remove particles, so that the particle concentration experienced by persons inside the schools is lower than outdoors. This result is very relevant from the toxicological point of view, mainly when outdoor $PM_{2.5}$ concentration is too high.[14,16−18]

Another critical IAQ parameter discussed in detail was the indoor CO_2 concentration, as it is of relevant health concern in schools.[3,4,7,13,17,20] Overall, the mean CO_2 levels measured in the study pointed out critical situations, since half of the surveyed rooms showed CO_2 levels exceeding the limit of 1,000 ppm imposed by legislation[1] (Table S2). A deep insight into the evolution of CO_2 concentration in each investigated room (example in Figure 1) clearly showed that the indoor CO_2 accumulated during the teaching time until reaching high levels, and then it decreased by opening the windows to introduce fresh air.

The measured data showed that the CO_2 concentration is significantly correlated with the student occupancy (Pearson r, 0.72; $p > 0.01$), with a general increase in more densely crowded rooms (Tables S1 and S2). This is consistent with literature that reports that the CO_2 concentration in closed spaces mainly depends on emission from the human body of occupants through breathing and correlates with human metabolic activity.[2,4,7,13] Another reason for CO_2 accumulation may be an inadequate air exchange, as the investigated school buildings were lacking mechanical ventilation systems.[13,17,20] In general, high indoor CO_2 values have been commonly encountered in previous studies in Italian schools, as a consequence of inadequate ventilation.[3,13,16−18] Under such limitations, the window opening is the only way to intake fresh air and cycle pollutants out.

Final Results

On the basis of this information, the university researcher promoted a student concluding discussion to design an operative protocol for reducing the indoor levels of pollutants. The strategies suggested by the students included a proper window opening−closing behavior as well as more breaks and recesses between classes. This conclusion was proof that the students achieved a good awareness of the indoor pollution as well as they have been stimulated toward healthier and environmentally friendly behavior.

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CONCLUSIONS AND IMPLICATIONS FOR PRACTICE

The main outcomes of this school activity were very appreciated and interesting for the students, namely, the availability of IAQ monitoring sensors for on-site continuous measurements, the possibility to obtain information on IAQ in the room where they live, the identification of the most effective conditions that may mitigate indoor air pollution, the participation of university researchers, and the fact that such measurements had never been made in their schools. The obtained results pointed out two health alerts in the investigated schools: unacceptably high levels of $PM_{2.5}$ particles, mainly related to polluted outdoor air, and uncomfortably high CO_2 levels, due to the classroom crowding and inadequate ventilation.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.0c00065.

Detailed description of the activity including investigated laboratories and classrooms and sensors used for IAQ monitoring; additional information on the results obtained (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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