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Use of the IAQmeter in Indoor Air Quality Monitoring Studies

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ABSTRACT

According to reports from the scientific, public health and medical communities around the world, the quality of ambient and indoor air has a significant impact on the health of the population. Maintaining adequate indoor air quality in accordance with the standards set by the European Union and the WHO guarantees a reduction in the risk of many diseases and improved work capacity. It is extremely important to assess the air quality in schools. This is because during adolescence, the body undergoes significant development, making it particularly susceptible to harmful factors. The purpose of this study was to assess the indoor air quality based on physical, chemical and particulate pollutants present in the air in classrooms at an elementary school. The measurement was carried out using an IAQmeter, designed and manufactured by employees of the Faculty of Environmental Engineering at Lublin University of Technology, which allows continuous measurement and recording of temperature, humidity, CO_2, SO_2, NO_2, VOCs (volatile organic compounds), formaldehyde, PM 2.5, and PM 10. The study was conducted for grades I-III, where students go out only at break and continue in the same room throughout the day. In addition, the factors that can affect the concentration of pollutants, such as ventilation or prolonged opening of doors, were monitored. Sensors were placed in the classroom and in the corridor nearby classroom. The study showed that while spending time at school, students are exposed to a number of factors that can affect their well-being and health, which is best illustrated by the CO_2 concentrations. The results of the study show that for more than 90% of the time spent at school, children are in indoor environments where the carbon dioxide concentrations exceed 1000 ppm. It was also shown that the indoor environment in corridors is of lower quality than the environment in classrooms. The designed device enabled rapid measurement, recording a wide range of pollutants.

Keywords: formaldehyde, carbon dioxide, NO_x, VOC, SO_x, indoor air quality, IAQmeter.

INTRODUCTION

The topic of indoor air quality (IAQ), which was previously overlooked and often neglected, is now attracting particular attention. This is due to the increase in public awareness of the dangers associated with inadequate indoor air quality and the fact that modern man primarily spends time indoors. Currently, about 80–90% of the time is spent indoors, including apartments, workplaces, schools, and other public buildings. For children, the elderly and the sick, this time can be even longer, making highly sensitive people most vulnerable to indoor air pollution. Therefore, ensuring adequate indoor air quality should be a priority. Inadequate indoor air quality can affect concentration, motivation, work and learning performance, as well as people's health and well-being (Abhijith et al., 2022; Wong et al., 2013; Wong et al., 2008).

Studies have shown a link between indoor air quality and work and teaching performance, as well as sickness absenteeism among employees and students. When indoors, people breathe air that can contain a variety of chemical, physical, and biological contaminants (Salonen et al., 2018; Amato et al., 2014, Demirel et al., 2014). Indoor air quality depends on both external and internal pollutants. Building materials, cleaning products, pets, heating and air conditioning systems can all emit pollutants. In addition, modern buildings, which are increasingly airtight, can keep dirt inside (Blondeau et al., 2005).

Indoor air quality refers to the condition of indoor air that can affect the health and well-being of occupants. Definitions of IAQ vary in the literature. For some, it is the purity of the air that meets the expectations of users, for others the quality of the air supplied to the room and the amount of pollutants it contains. There is also a context that defines IAQ as the sum of air characteristics that affect human health and mental well-being.

The key elements affecting the quality of indoor air are thermal comfort, humidity, the presence of biological and chemical contaminants and suspended particles. Good air quality means air purity at a level satisfactory to users. Perceived air quality (PAQ) is a term related to subjective perception of air quality. PAQ takes into account detectable odors, chemicals and subjective assessments of air quality (Che et al., 2021; Kalimeri et al., 2019).

In general, as shown by the simulation studies conducted by Na et al. 2023, and Chen et al. 2022, effective ventilation flows allow for the renewal of air in classrooms and lowering the level of pathogens in the environment. In this context, many studies have shown that without effective ventilation, CO_2 concentrations can exceed 1500 ppm [Stabile et al., 2015, Schibuola et al., 2016], which can lead to breathing difficulties, headaches, fatigue as well as reduced ability to concentrate and learn in students [Bogdanovica et al., 2020].

Although CO_2 is not directly related to the SARS-CoV-2 infections, it is an effective indicator of the indoor air renewal rate [Azuma et al., 2018]. Determining maximum CO_2 concentrations depending on the number of people in the room can give an approximate picture of air quality and the risk for students [Poirier et al., 2021]. Other studies have shown a direct relationship between the concentration of fine particles matter (PM) in the air and the risk of viral infections indoors [Harvard et al., 2020]. Accordingly, Ramalho et al. noticed that air dust particles from the Saharan winds directly contribute to the spread of respiratory diseases [Ramalho et al., 2015]. Therefore, higher exposure to PM 2.5 and PM 10 increases the long-term risk of mortality. The European Environment Agency (EEA) and the WHO take this into account by setting daily and annual maximum exposure values for PM 2.5 and PM 10, as shown in Table 1.

Building materials such as plasterboard, paints, adhesives and floor coverings emit a variety of chemicals, including volatile organic compounds. These compounds can cause respiratory irritation, headaches, and other health ailments. Formaldehyde, often found in finishing materials, is recognized as a potential carcinogen [Che et al., 2021; Jafari et al., 2015]. New furniture, especially made of chipboard and MDF, can emit a large amount of formaldehyde and other VOCs. Studies have shown that levels of these pollutants can be significantly elevated for several months after the purchase of new furniture [Canha et al., 2016]. Cleaning products used in schools often contain volatile organic compounds that can affect indoor air quality. Examples of these pollutants are benzene, toluene, xylol, as well as aldehydes [Che et al., 2021; Fuller et al., 2022]. Using cleaning products without proper ventilation can lead to their accumulation in the air.

In addition to chemical pollutants, particulate matter, i.e. solid or liquid particles suspended in the air that can be inhaled into the lungs, also poses a significant problem. PM2.5 refers to the particles with a diameter of less than 2.5 micrometers, and PM 10 refers to the particles with a diameter of less than 10 micrometers. Particulate matter can come from a variety of sources, including external pollutants, but also internal pollutants, such as dust from floors and furniture. The exposure to PM is associated with an increased risk of cardiovascular, respiratory and other health problems. Schools located near busy roads are also exposed to high levels of nitrogen oxides (NO_x), particulate matter and other chemical pollutants from motor vehicle exhaust. Such pollutants can penetrate into buildings, increasing indoor air pollutants [Fisk, 2017]. Similarly, industrial plants that can emit a variety of pollutants, including heavy metals,

Table 1. Limit values for $PM_{2.5}$ and PM_{10} [WHO, 2023, EEA, 2023]

Averaging Period	WHO		EEA	
	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}
Annual [μg/m^3]	10	20	25	40
24h [μg/m^3]	15	40	–	50

VOCs, and particulate matter. The schools located near such plants may experience elevated levels of these compounds in the air [Che et al., 2021]. In the regions with high levels of atmospheric pollution, smog can significantly affect the quality of air inside school buildings. Smog is a mixture of particulate matter, nitrogen oxides, ozone and other chemical pollutants [Gilliland et al., 2001].

Requirements for indoor air quality in educational institutions in Poland are not clearly defined in regulations and legal acts. Due to the lack of clear national regulations related to the levels of pollutants in indoor school air, recommendations recommended by, i.a. WHO are often used. The parameters that should not be exceeded for individual substances are [Fuller et al., 2022]:

- PM_{10}: the average annual concentration should not exceed 40 µg/m³,
- $PM_{2.5}$: the average annual concentration should not exceed 25 µg/m³,
- Formaldehyde: the permissible concentration should not exceed 0.1 mg/m³,
- CO_2: concentration should not exceed 1000 ppm (WHO).

Research method

The measurements were carried out using IAQmeters, which enable continuous measurement and recording of various air quality parameters. The devices were installed in classrooms and corridors in one of the primary schools. The air quality tests lasted 15 days in 1-minute intervals. During the study, the number of people in the room was systematically controlled, the activities that could affect air quality were recorded, such as: using electrical appliances, opening windows, and cleaning the room. The rooms are typical educational rooms of millennial schools, equipped with gravitational ventilation. The collected results and data allowed for the preparation of a detailed analysis of indoor air quality. The IAQmeter (Fig. 1) is a tool designed and constructed by the authors of the publication [Guz et al. 2023] from Lublin University of Technology and is used for measuring indoor air quality. The meter consists of sensors listed in Table 2. The external air parameters during the considered time period were obtained from the National Air Quality Monitoring Network of the Chief

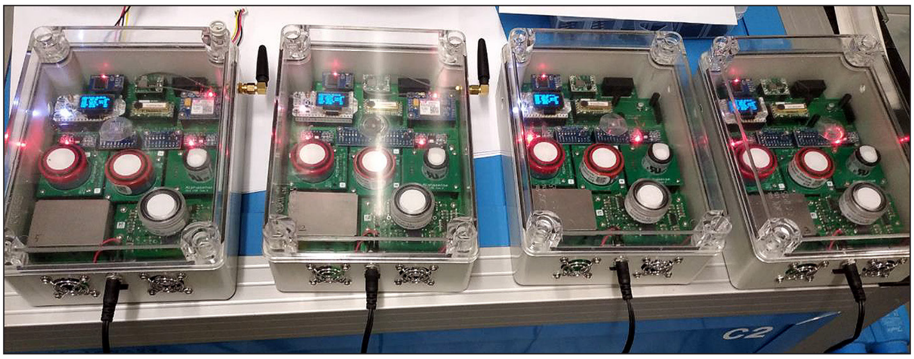

Figure 1. IAQmeters during tests after intercalibration

Table 2. Basic statistics of the measured air quality parameters depending on measurement location and part of the week

ID	Parameter	Range	Accuracy	Sensor
1	Temperature [°C]	-40 ÷ 85 °C	1 °C	Bosch BME280
2	Relative humidity	0 ÷ 100%	3%	
3	Barometric pressure	300 ÷ 1100 Pa	1.7 Pa	
4	Particulate matter $PM_{2.5}$	0 ÷ 1000 µg/m³	1 µg/m³	Plantower PMS5003
5	Particulate matter PM_{10}	0 ÷ 1000 µg/m³	1 µg/m³	
6	CO_2 concentration	300 ÷ 5000 ppm	50 ppm	Figaro CDM7160
7	VOC concentration	0 ÷ 50 ppm	1%	Alphasense PID-AH2 detector
8	Nitrate dioxide concentration	0 ÷ 20 ppm	5%	Alphasense NO_2-B43F
9	Sulfur dioxide concentration	0 ÷ 100 ppm	5%	Alphasense SO_2-B4
10	Formaldehyde concentration	0 ÷ 10 ppm	0.1 ppm	Mambrapor CH_2O-C-10

Inspectorate of Environmental Protection [GIOŚ, 2024]. Measurements of NO_2, SO_2, $PM_{2.5}$, and PM_{10} concentrations in the external air were performed automatically every hour at the Lublin-Obywatelska station.

The school was built in 1915 and is located in the center of a city with more than 300 000 inhabitants. The school has recently undergone thermal modernization. Insulation works and replacement of window joinery was carried out 5 years ago Usable area amounts to 4536 m^2, cubic capacity is 17 561 m^3, and it is a 3-story building (2 above ground and 1 underground):

- Facility ventilation: Most of the school premises are equipped with a ventilation system comprising gravitational exhaust air supply with air supply taking place on the principle of infiltration through windows and doors. The performance of the systems is poor and depends to a large extent on the weather conditions outside (temperature, pressure), and the altitude of ventilation ducts. The gravity ducts in brick chimneys are unobstructed, which is confirmed by the chimney sweep report (information from the current report periodic review of the school).
- Central heating system: calculated heat demand 243 884 W, 13.89 W/m^3, 53.77 W/m^2, water installation 85/60 ^oC, with bottom distribution, operating in a closed system, supplied from the municipal network, with panel radiators and a dual-purpose node exchanger.
- External walls: perforated bricks, insulated with mineral wool, lamellar wool with a thickness of d = 14 cm and a thermal conductivity coefficient of λ = 0.042 W/(mK), which guaranteed a heat transfer coefficient of U = 0.241 W/(m^2K), i.e. in accordance with then applicable Regulation of the Minister of Infrastructure on the technical conditions to be met by buildings and their location. For the external wall made of slag concrete U = 0.238 W/(m^2K).
- Flat roof: insulated with PIR panels λ = 0.025 W/(mK), d = 12 cm, U = 0.167 W/(m^2K).
- Windows: PVC equipped with hygro-controlled ventilators U = 1.3 W/(m^2K).

The publication analyzes the air parameters that most often appear in the literature in the context of Polish schools.

Results and discussion

In Poland, the majority of educational facilities are buildings from the 1960s and 1970s, subjected to various types of renovations in recent years. They often took the measures to reduce energy consumption, mainly through modernization of the central heating system and heat substations, insulation of building partitions and replacement of window frames. Most of them are two-story buildings with gravity ventilation and a traditional heating system based on panel radiators. The height of gravity ventilation ducts, especially for a higher floor, is very low, which means that in the periods of no wind, the value of active pressure causing air flow is low and prevents air from flowing into the room. The widespread replacement with high-tightness windows results in minimal air flows and close to zero, which is one of the main reasons for excessive concentrations of various pollutants in rooms. Regulations, standards or guidelines in force or recommended in various countries indicate carbon dioxide as an indicator of indoor air quality. It is generally recognized that controlling and diluting CO_2 will allow maintaining an appropriate microclimate free from excessive amounts of gaseous or particulate pollutants.

This is particularly evident in the case of CO_2. On the basis of the literature review and the research carried out, it was found that in Polish schools where gravitational ventilation is used, the CO_2 level exceeds the recommended 1000 ppm (relative to the level in the outside air) just a few minutes after the start of classes. The problem is exacerbated by modernization activities, limiting the supply of fresh air to classrooms.

The basic statistics are presented in Table 3. The table includes physical factors, such as temperature (T) [°C], relative humidity (RH) [%], concentrations of suspended particulate matter $PM_{2.5}$ and PM_{10} [μg/m³], as well as chemical factors, such as carbon dioxide (CO_2) [ppm], volatile organic compounds (VOC) [ppm], nitrogen dioxide (NO_2) [μg/m³], sulfur dioxide (SO_2) [μg/m³], and formaldehyde (CH_2O) [ppb]. The calculated parameters include minimum, maximum, mean, median, and standard deviation.

The average concentrations of carbon dioxide in the classroom are significantly higher than in the corridor (Fig. 2). This is due to the longer duration of students' presence in the classroom. A standard school day consisted of eight 45-minute classes, with breaks lasting 5, 10 and 15 minutes. The window area relative to the room volume in the corridor is larger than in the classroom. The maximum concentration in the classroom reached

Table 3. Basic statistics of air quality parameters depending on measurement location

Point	Parameter	T [°C]	RH [%]	$PM_{2.5}$ [μg/m³]	PM_{10} [μg/m³]	CO_2 [ppm]	VOC [ppm]	NO_2 [μg/m³]	SO_2 [μg/m³]	CH_2O [ppb]
Corridor	Min	19.2	34.4	3	3	579.5	0.0137	0	0	0
	Max	24.5	54.1	165	167	2898.3	0.494	13.2	7.9	516.0
	Mean	21.3	40.4	25.5	35.5	1267.8	0.239	4.1	4.7	37.1
	Median	21.2	4.2	24	33	1170.3	0.239	3.4	5.1	26
	Std. dev.	1.0	3.3	11.0	15.4	561.9	0.032	2.0	1.0	49.1
Classroom	Min	18.4	36.4	1	1	519.7	0.120	0	0	0
	Max	23.1	53.7	42	53	3777.5	0.6064	17.0	7.4	173
	Mean	20.4	43.6	17.0	18.9	1217.0	0.260	9.2	4.8	19.2
	Median	20.3	43.5	16	18	1102	0.254	9.3	4.9	8
	Std. dev.	0.7	3.2	6.9	7.8	627.4	0.041	1.8	0.4	26.2
Exterior	Min	–	–	3.1	3.2	–	–	1.4	2.3	–
	Max	–	–	67.7	72.4	–	–	45.7	10.3	–
	Mean	–	–	24.5	26.7	–	–	16.5	4.96	–
	Median	–	–	25	27.2	–	–	14.8	4.7	–
	Std. dev.	–	–	10.8	12	–	–	9.2	1.52	–

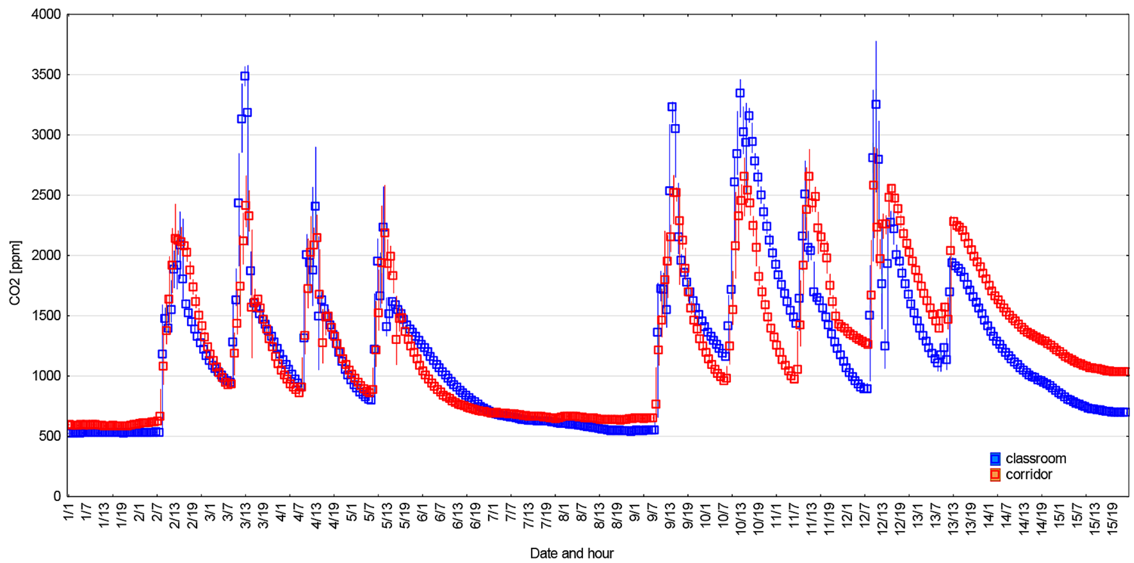

Figure 2. CO_2 concentration in the classroom and in the school corridor

up almost to 3800 ppm, which is well above the recommended levels. During each school day, a concentration of around 2500 ppm was almost always reached. The average CO_2 concentration in the classroom was 1217 ppm, ranging from 519 to 3777 ppm, while in the corridor, the average value was 1267 ppm, with a minimum-maximum range of 579 to 2898 ppm.

Natural ventilation in the classroom is not effective and does not ensure good air quality. Figure 3 presents measurements from two typical school days after the weekend. From the very beginning of the school day, there is a rapid increase in carbon dioxide concentration, first in the corridor before 8:00 AM, where students gather, and then in the classroom from 8:00 AM onwards. A reduction in CO_2 concentration occurs only when the classroom is not in use. Momentary window opening during regular classes is insufficient. After the end of the school day, the CO_2 concentration gradually decreases but does not reach the levels observed at the beginning of the school week. As a result, subsequent days are characterized by elevated carbon dioxide levels, around 1000 ppm. This could be significant from the perspective of achieving educational outcomes

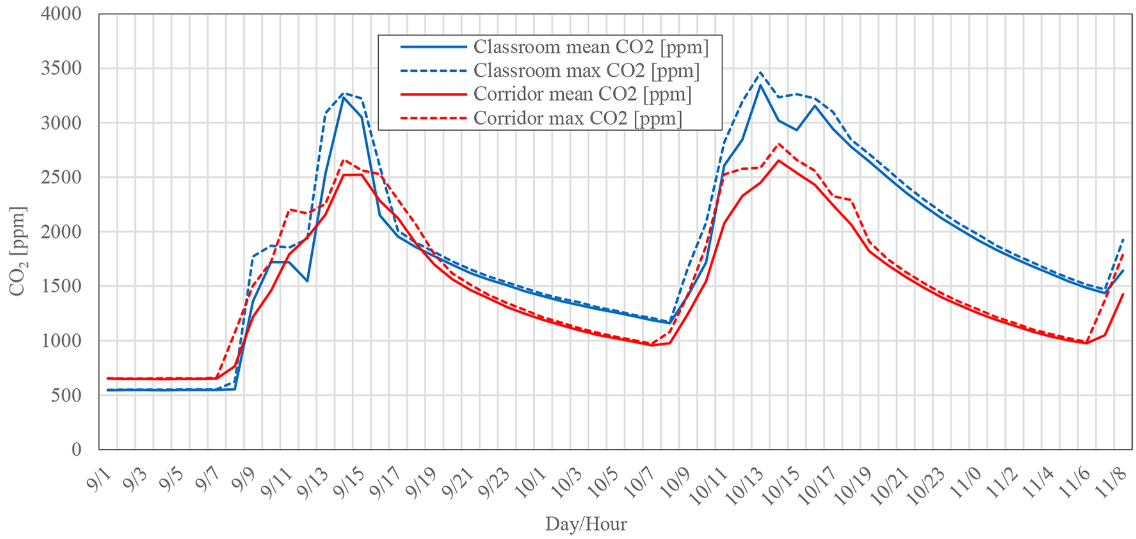

Figure 3. Change of CO_2 concentration in the classroom and in the school corridor during two of the school day after weekend

in individual classes. If the schedule is poorly planned, it may lead to unequal opportunities for achieving good academic results. The number of exceedances of the 1000, 1500, and 2000 ppm levels are 66.1, 52.6, and 25.2 hours, respectively, representing 83%, 66%, and 32% of the total lesson time. The external concentration was measured only momentarily and averaged 410 ppm.

In Figure 4, the variations of carbon dioxide concentration in the classroom and corridor during individual lessons was presented. The whiskers on the graphs represent the minimum-maximum range, while the box indicates the mean value ±0.95 confidence interval. The time domain categories are labeled as follows: W – free time (3 PM-8 AM), P – break, L1-L8 – individual lessons. The highest concentrations were observed during the third lesson hour in the classroom. After this lesson, a short break (10 minutes) occurs, while after the sixth lesson hour, a longer break (20 minutes) takes place, which contributes to the reduction in CO_2 concentration. The classroom is often empty during the last lesson hour, which is also reflected in the decrease in CO_2 levels. Conversely, for the corridor, the assumption that peak concentrations would occur during school breaks was confirmed.

The average concentrations of suspended particulate matter PM2.5/PM10 in the classroom

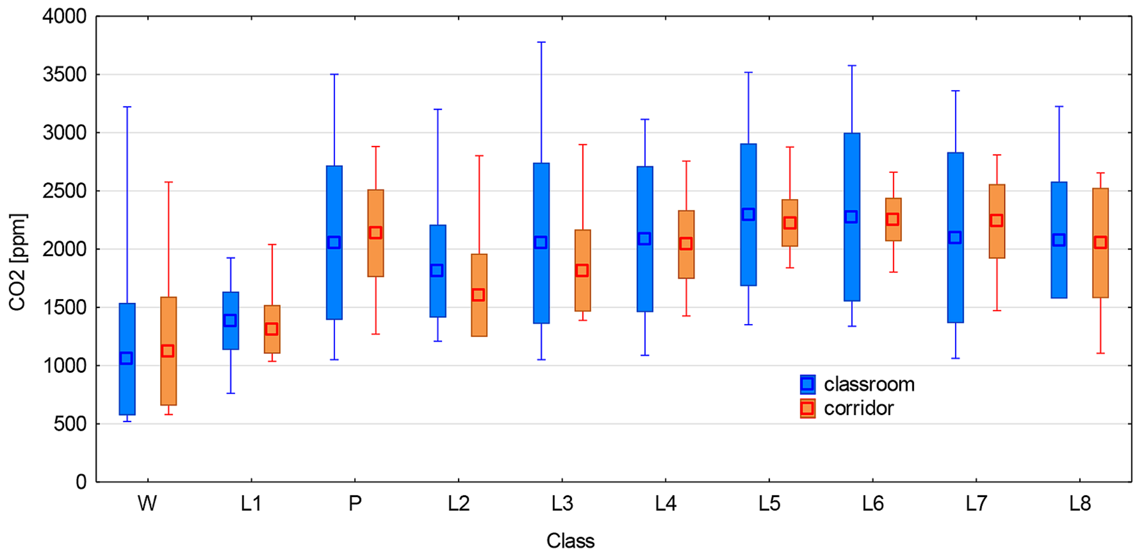

Figure 4. The variations of carbon dioxide concentration in the classroom and corridor during individual lessons.

were 17/18.9 μg/m³, while in the corridor, they were 25.5/35.5 μg/m³. The instantaneous peak concentrations of PM2.5/PM10 in the corridor were 165/167 μg/m³, significantly higher than in the classroom, where they were 42/53 μg/m³.

The school was monitored during the heating season. The school is located in an area surrounded by buildings and tenements that are often heated with solid fuels (coal, wood) or gas, and there is also a busy city street nearby that is frequently congested. As a result, suspended particulate matter infiltrates the interior spaces; however, its concentration is significantly lower than outside (Fig. 5). The measurements also indicate higher concentrations of particulate matter in the corridor. This is attributed to the larger surface area of untight windows relative to the room's volume. Additionally, there is significant foot traffic in the corridor (class changes, activities), which causes dust to be stirred up from flat surfaces.

The relationship between the concentration of $PM_{2.5}$ and PM_{10} in the corridor and classroom to the outdoor parameters during two weeks of continuous measurements is presented in Figure 6. The measurement data from the IAQmeter devices were averaged to 1-hour intervals to allow

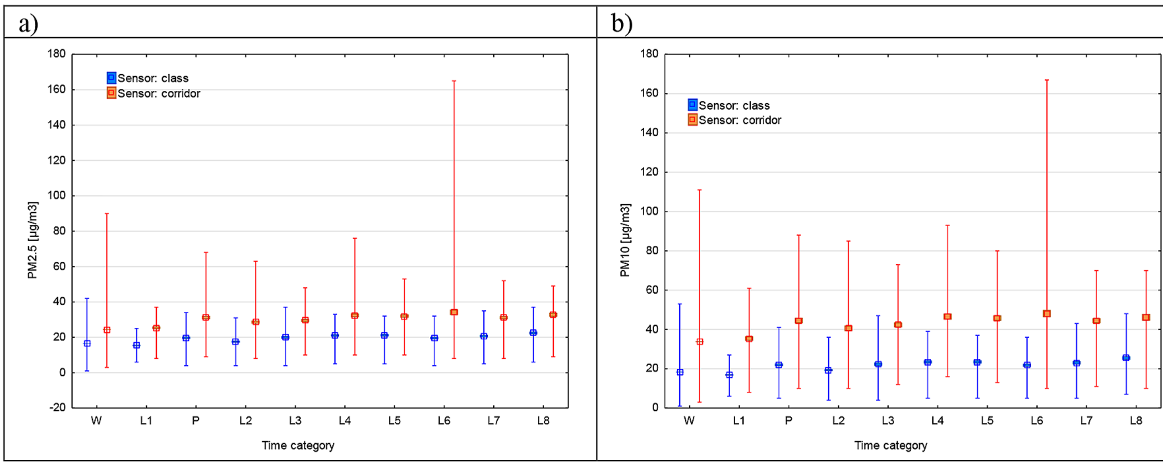

Figure 5. Concentration of particulate matter in the classroom and in the corridor: a) $PM_{2.5}$, b) PM_{10}

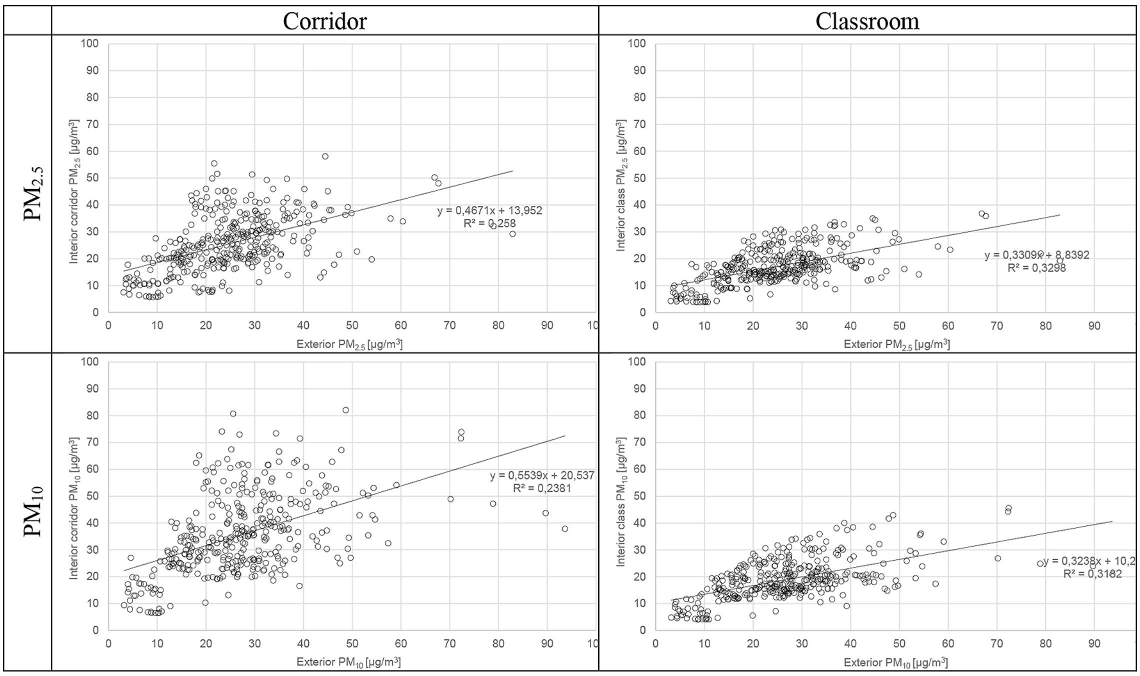

Figure 6. The relationship between the concentration of $PM_{2.5}$ and PM_{10} in the corridor and classroom to the outdoor parameters (GIOŚ) during two weeks of continuous measurements

for comparison with GIOŚ measurements, which are conducted at 1-hour intervals. The graphs reveal a correlation between the concentration of suspended particulate matter inside the monitored rooms and outside. However, this relationship is statistically insignificant, as the coefficient of determination R^2 for PM2.5 in the classroom and corridor is 0.329 and 0.258, respectively, while for PM10, it is 0.316 and 0.238, respectively.

In the case of volatile organic compounds (VOCs), no significant difference was observed between the measurement points (Fig. 7). The average concentration in the corridor was 0.239 ppm, while in the classroom, it was 0.260 ppm, remaining comparable throughout the entire period.

However, the situation is different for formaldehyde (Fig. 8). In the corridor, its average concentration was 37.1 ppm, while in the classroom, it was 19.2 ppm. This difference can be attributed to the higher emission from finishing materials due to sunlight exposure from the windows. The entire horizontal surface is intensely illuminated, as the width of the corridor is 3 meters from the windows. The corridor also experiences higher average temperatures and increased wear of the flooring materials due to higher foot traffic.

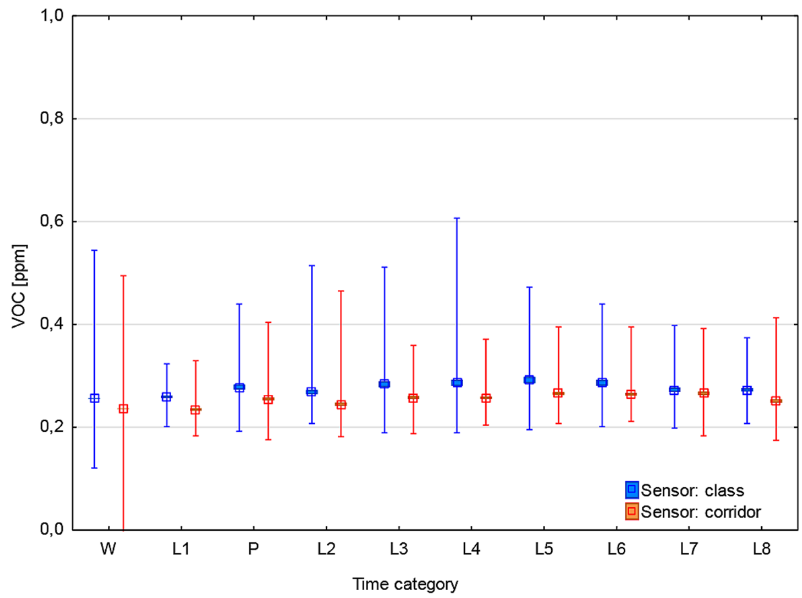

Figure 7. VOC concentration in the classroom and in the school corridor

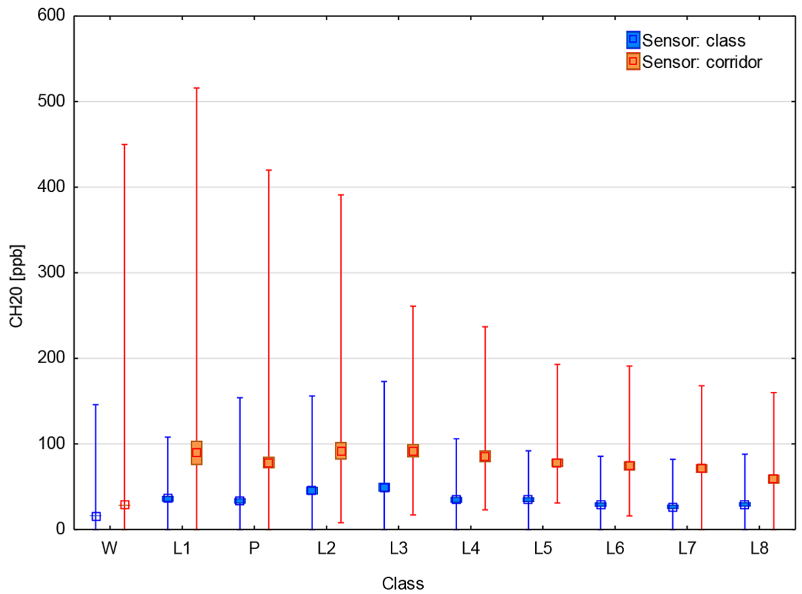

Figure 8. CH_2O concentration in the classroom and in the school corridor

During the study period, the external concentration of NO_2 averaged 16.5 µg/m³ and ranged between 1.4 and 45.7 µg/m³. Indoors, it was significantly lower. In the corridor, it averaged 4.1 µg/m³ with peaks reaching up to 13.2 µg/m³, while in the classroom, it averaged 9.2 µg/m³ with peaks reaching up to 17.0 µg/m³. A similar trend was observed for SO_2, with higher concentrations in the classroom than in the corridor. In the corridor, SO_2 averaged 4.7 µg/m³ with peaks up to 7.9 µg/m³, whereas in the classroom, it averaged 4.8 µg/m³ with peaks up to 7.4 µg/m³. During this time, the external concentration of SO_2 averaged 4.96 µg/m³ and ranged between 2.3 and 10.3 µg/m³. The higher concentration of these pollutants in the classroom is related to more frequent ventilation of the room during breaks.The relationship between the concentration of NO_2 and SO_2 in the corridor and classroom to exterior concentration is presented in Figure 9. The graphs reveal a correlation between the concentration of these contaminants in the monitored rooms and outside. This relationship can be considered statistically significant, as the coefficient of determination R^2 for NO_2 in the classroom and

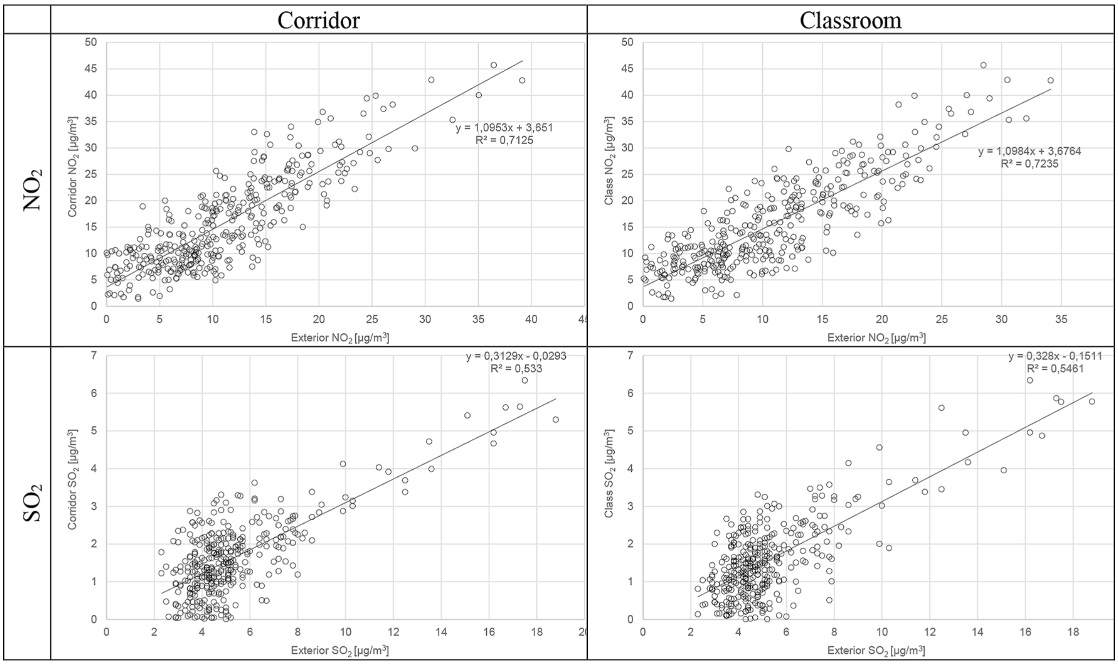

Figure 9. The relationship between the concentration of NO_2 and SO_2 in the corridor and classroom to exterior concentration

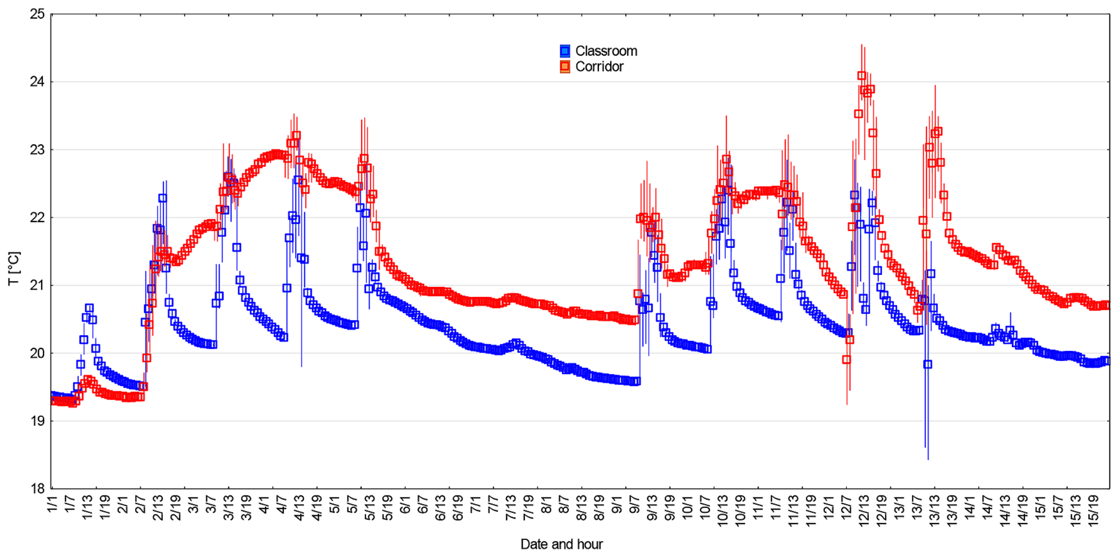

Figure 10. Temperature changes in the classroom and in the school corridor

corridor is 0.723 and 0.712, respectively, while for SO_2, it is 0.546 and 0.533, respectively. Despite frequent ventilation, average temperatures above 20 degrees (usually above 21, 22 °C) were recorded in each of the examined rooms (Fig. 10). The air temperature in the corridor was even higher than in the classroom. With the windows closed, there were instances where the temperature exceeded 24.5 °C due to the presence of a large number of people and sunlight exposure. In the classroom, temperature regulation via the central heating system was more effective. The radiator thermostatic valves were set to 20 °C, and the room temperature would approach this value after classes. If the windows were left slightly open, the temperature could drop to around 18.5 °C. Unfortunately, during classes, natural ventilation and airing did not yield satisfactory results. This issue is related to the extensive glazing and the lack of efficient central heating regulation. After the school day, the temperature in the classroom would decrease, while in the corridor, it remained elevated for most of the time. This is suboptimal from a usage standpoint, as students are typically active and moving around during breaks in the corridor (Fig. 10).

Research has shown that during breaks, in the corridor, students often stay under worse conditions than those recorded in the classroom. It should be emphasized that during the measurements, the teachers ventilated the room not only during breaks, but also left the windows temporarily ajar during the lesson. This situation concerned over 95% of the results combined. Information about the length of ventilation would also help to interpret the differences in the CO_2 concentrations obtained.

Looking at the detailed results of air quality in classrooms and analyzing various environmental factors, it can be concluded that a only mechanical ventilation system covering classrooms and corridors would ensure adequate air quality in the school and reduce the level of pollution. An air quality analysis should be carried out using a ventilation system.

CONCLUSIONS

Summing up the research carried out, it can be condluded that more effective ventilation in the room can bring a significant reduction in CO_2 concentration, which in turn will affect the concentration level of other pollutants. Also, differences in the concentration levels of the monitored pollutants depending on the time of day suggest that the use of rooms has a significant impact on air quality. Moreover, maintaining stable temperature and relative humidity in the room is important in order to create optimal, comfortable conditions in the room. The most important conclusion is that the environment outside the classroom – the corridor – also determines the conditions in the educational rooms. This impact is probably greater than that of indoor air. This is due to the frequency of opening doors and windows and the condition of the outside air (outside) and in the corridor.

The IAQmeter has proven itself in monitoring the indoor environment. The readout can be used for automatic control of the air handling unit. It is necessary to create an algorithm that allows adjusting the size of the air stream to the read levels of pollutants. The IAQmeter could be successfully used in the classrooms particularly exposed to pollution from road traffic, as it has the ability to monitor NO_x and SO_x.

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