

Article

Pollution Levels in Indoor School Environment—Case Studies

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Abstract: Air quality in school environments is of particular interest due to the significant amount of time children spend in these settings. Children, being a particularly sensitive demographic, are exposed to various pollutants at school or kindergarten. In this regard, our studies have focused on monitoring the concentrations of three main categories of pollutants: VOCs (volatile organic compounds), VICs and PM (particulate matter). We conducted two experimental campaigns in seven classrooms within public educational institutions. The average concentration values of TVOC (total volatile organic compounds) ranged from 554 $\mu\text{g}/\text{m}^3$ to 2518 $\mu\text{g}/\text{m}^3$, of CO_2 from 1055 ppm to 2050 ppm, of NH_3 (Ammonia) from 843.2 $\mu\text{g}/\text{m}^3$ to 1403.4 $\mu\text{g}/\text{m}^3$, of PM2.5 from 25.1 $\mu\text{g}/\text{m}^3$ to 89.9 $\mu\text{g}/\text{m}^3$, and of PM10 from 63.7 $\mu\text{g}/\text{m}^3$ to 307.4 $\mu\text{g}/\text{m}^3$. In most instances, the registered values exceeded the limit values set by national or international regulations. Furthermore, this study highlights the significant impact of a heat recovery ventilation system in improving indoor air quality by substantially reducing the levels of CO_2 and PM. However, it also underscores the need for further measures to more efficiently reduce TVOC concentrations. The aim of our paper was to enhance the understanding of pollution levels in school environments, increase awareness of the importance of indoor air quality, and highlight the adverse effects of polluted air on the health of occupants.

Keywords: school environment; indoor air quality; pollution level; VOCs; VICs; PM



Citation: Vasile, V.; Catalina, T.; Dima, A.; Ion, M. Pollution Levels in Indoor School Environment—Case Studies. *Atmosphere* **2024**, *15*, 399. <https://doi.org/10.3390/atmos15040399>

Academic Editor: Kumar Vikrant

Received: 20 February 2024

Revised: 11 March 2024

Accepted: 20 March 2024

Published: 24 March 2024



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1. Introduction

Environmental pollution, especially indoor air pollution, has become a global problem and affects almost all areas of life [1]. Indoor air quality (IAQ) has an important impact both on human health [2] and for ensuring a healthy and sustainable habitat [3]. People spend approximately 80–90% of their day in indoor spaces [1,3–11], with different types of destinations (residences, offices, educational institutions, commercial spaces, public buildings, etc.), where they are exposed to high concentrations of various pollutants emitted from construction materials, furniture, consumer products, occupants, and from their activities, with recognized harmful effects on health [3,6,8–10].

The problems posed by long-term exposure to indoor air pollution have become more evident in recent years due to the growing concern for energy conservation, with recent buildings being much more airtight than older ones, which can lead to a significant accumulation of indoor pollutants [7,10,12]. The main categories of indoor air pollutants monitored in previous studies carried out in different types of public or private spaces [7,9,12–20] are volatile organic compounds (VOCs), particulate matter (PM), and volatile inorganic compounds (VICs). The main characteristics of VOCs are severe toxicity, high volatility, and poor degradability, which can cause serious problems to both the ecological environment and human health. Long-term exposure to indoor VOC concentrations can cause skin irritation, dizziness, and fatigue, as well as impairment of lung function [9] and symptoms related to sick-building syndrome [1,4,6,21,22], even if the values are low—in the order of ppb. BTX (benzene, toluene, and xylene) is an example of VOCs that require monitoring

because, even at very low concentrations, these compounds can cause adverse effects on human health. Benzene has been classified as a group 1 carcinogen by the International Cancer Research Agency [1]. Its exposure has been linked to the occurrence of several blood diseases, such as aplastic anemia and a variety of cancers, including acute myeloid leukemia. According to WHO, a benzene concentration of 1.7 mg/m^3 is probably to cause leukemia in 1 from 100,000 people, as cited in [14]. Toluene is a known teratogen and causes abnormalities of the fetus. Xylene acts as a skin sensitizer and can cause dryness, cracking, and exfoliation of the skin. At higher concentrations, toluene and xylene can cause weakening of the nervous system, kidneys, and liver. When released into the atmosphere, VOCs not only affect human health, but also cause various environmental complications, such as depletion of the ozone layer, deterioration of crops and vegetation, and the formation of secondary organic aerosols (SOAs), and ozone at the ground level [23–25]. Particulate matter (PM) consists of solid particles and liquid droplets, suspended in the air, of different sizes, shapes, chemical compositions, and origins, with negative effects on human health. It is estimated that, globally, fine particles (PM_{2.5}) are the cause of more than 2 million deaths annually, as cited in [26]. Among the volatile inorganic pollutants, carbon dioxide (CO₂) is the most common pollutant in the indoor environment of buildings and it is one of the many health relevant pollutants, which is measured in different types of buildings, often at concentrations exceeding the maximum permissible values [13,14,18,20,27]. The accumulation of CO₂ leads to respiratory acidosis, causing headache, confusion, anxiety, drowsiness, and stupor (CO₂ narcosis). Stable respiratory acidosis can be well tolerated, but can lead to memory loss, sleep disturbances, excessive daytime sleepiness, and personality changes [27]. Another type of VICs has attracted people's concern in recent years, namely ammonia (NH₃), with indoor high concentrations and negative effects on human health, like irritation effects on the skin, eyes, and nose; headache and nausea in mild cases; and pulmonary edema and respiratory distress syndrome in severe cases [28,29]. Additives from decorative materials and concrete admixtures used in building materials are notable sources of NH₃ (ammonia) concentrations indoors, along with indoor activities such as the use of cleaning products, cooking, and smoking. Additionally, humans themselves are a significant source of ammonia emissions, with an average rate of approximately 5.9 mg per person per hour [28]. Furthermore, factors such as indoor temperature, the clothing worn, and the age of occupants can also contribute to the levels of ammonia emissions in indoor air [28,29]. Because of their specific character compared with other buildings, educational buildings, i.e., school and kindergarten buildings require more attention regarding indoor environmental quality [14,18,19]. Moreover, educational buildings represent a special case, mainly because of their specific occupants, activities, and occupancy patterns, considering that children spend a significant part (around 25%) of their time at school [19,30]. Children are particularly sensitive category of the population, are still physically developing, and, due to their immature immune system and faster breathing rate, they are more susceptible to adverse health effects, as cited in [14].

In this respect, the objective of our exploratory case studies was to increase knowledge by collecting scientific information and carrying out campaigns to raise awareness of the importance of indoor air quality and the effects that contaminated air can have on the health of occupants. Our study aimed to identify and analyze pollution levels through monitoring, statistical interpretation, and comparison with permissible limits established by national and international regulations in some of schools and kindergartens in Bucharest, Romania.

The results obtained from these exploratory cases studies help identify the research and development needs for future approaches to the issue of indoor air quality.

2. Methods

The case studies were carried out in two experimental campaigns, in four gymnasium schools (classrooms abbreviated AIC, SG5, SG6, SG7, and SG8), and two kindergartens (GR1 and GR2) located in Bucharest (Figure 1). In the first campaign (AIC, SG5–SG7, GR1, and GR2), the selection criterion was the exposure risk level of the target occupants, namely

children between the ages of 4 and 9 who participated in indoor activities for about 7 h per day. Monitoring the indoor air in the spaces that were the subject of the case studies was carried out under normal operating conditions, at the beginning of the day, for 2 h, with the concentration of total volatile organic compounds (TVOCs) and carbon dioxide (CO_2) concentration being recorded every minute. Ammonia (NH_3) with particulate matter with sizes of $2.5\ \mu\text{m}$ ($\text{PM}_{2.5}$) and $10\ \mu\text{m}$ (PM_{10}) was monitored at 5 min time increments. During the entire monitoring period (October 2022), the ventilation of the analyzed spaces was carried out exclusively through natural ventilation (doors and windows). Monitoring of the indoor air in the spaces of the case studies was carried out under their normal operating conditions, at the beginning of the day, for 2h, similar to [31], with the concentration of total volatile organic compounds (TVOCs) and the carbon dioxide (CO_2) concentrations being recorded every minute. Ammonia (NH_3) with particulate matter with sizes of $2.5\ \mu\text{m}$ ($\text{PM}_{2.5}$) and $10\ \mu\text{m}$ (PM_{10}) was monitored at 5 min increments.

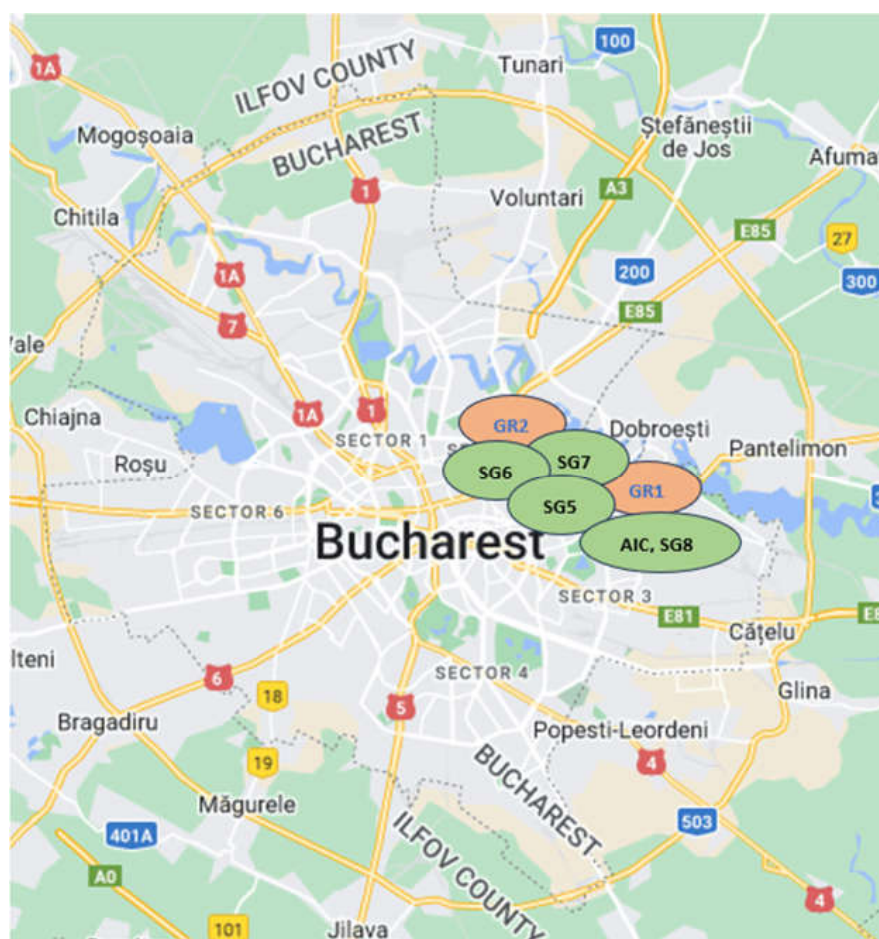


Figure 1. Location of school environments.

In the second campaign (SG8), the classroom studied was initially tested without any fresh air supply and then using a heat recovery unit. The monitored compounds, over an average period of eight months, were the total volatile organic compounds (TVOCs) and carbon dioxide (CO_2) with particulate matter with sizes of $2.5\ \mu\text{m}$ ($\text{PM}_{2.5}$) and $10\ \mu\text{m}$ (PM_{10}).

2.1. Monitored Space Description

The monitored spaces were part of similar buildings with the same architecture, built during the communist period, with the gymnasium schools having a total constructed area of more than 2000 square meters, constituting the basement, ground floor, and two floors (P + 2). The design housed classrooms, along with dedicated laboratories for chemistry,

biology, and informatics. It also included administrative offices, including the director's office, a library, medical and technical spaces, and additional annexes and storage areas. The construction plan of the kindergartens was similar to that of the gymnasium schools, with the only difference being that they had only one floor (P + 1). This layout represented the typical infrastructure found in Romanian schools and kindergartens during that period. The building's construction included thick brick walls, with outside walls measuring about 35 cm in thickness and inside structural walls of 25 cm in thickness. These dimensions reflected the construction techniques of the time, which prioritized durability and thermal mass. In the last decade, the buildings underwent a process of thermal rehabilitation in accordance with the national strategy for increasing the building energy performance.

The building's heating system utilized steel radiators, chosen for their durability and excellent thermal capacity, reflecting the era's preference for long-lasting materials. These radiators were connected to Bucharest's centralized heating system, which efficiently supplied thermal energy. The supply was dynamically adjusted based on external temperatures, ensuring an optimal balance of comfort and energy use. The system's design underscored the seamless integration of building services to maximize spatial utilization and enhance energy distribution efficiency. This integration was facilitated by routing the system through the technical basement and up through vertical columns, ensuring a discreet yet effective distribution network. The monitored classroom in the AIC gymnasium school building was located on the ground floor of the building. The school building was thermally rehabilitated. It had south-facing windows, brick masonry walls, was plastered and finished with aqueous dispersion paint, and the floor was finished with solid wood parquet. The windows were made of PVC profiles and thermal insulating glass, and the door was made of MDF (medium density fibers) with a glazed surface. The classroom had heating elements, namely three fan coil units, which were non-functional at the time of monitoring; six lighting fixtures; and the following furniture elements: a table and a chair for the teacher, 24 school desks, 24 chairs, and 18 school cupboards. The classroom was equipped with a printer, a smart blackboard, a glass blackboard, and a school projector. During the monitoring period, the windows were not opened but the door was opened several times.

The monitored classroom in the SG5 gymnasium school building was located on the ground floor of the building. The school building was thermally rehabilitated. It had south-facing windows, brick masonry walls, was plastered and finished with an aqueous dispersion paint, and the floor was finished with epoxy-resin based products. The windows were made of PVC profiles and thermal insulating glass, and the door was made of MDF (medium density fibers) with a glazed surface. The classroom was equipped with heating elements, specifically three fan coil units, which were non-functional at the time of monitoring. Additionally, it contained six lighting fixtures and various pieces of furniture: a table and a chair for the teacher, 24 school desks with accompanying chairs, and 18 school cupboards. The classroom also featured a printer, a smart blackboard, a glass blackboard, and a school projector. During the monitoring period, the windows remained closed, while the door was opened several times. The monitored classroom in the SG6 gymnasium school building was located on the ground floor of the building. The school building was thermally rehabilitated. It had west-facing windows, brick masonry walls, was plastered and finished with aqueous dispersion paint, and the floor was finished with epoxy-resin-based products. The windows were made of aluminum profiles and thermal insulating glass, and the door was made of MDF (medium density fibers). The classroom had heating elements, namely three steel radiators, which were non-functional at the time of monitoring; fifteen LED-based square-shaped lighting fixtures; and the following furniture elements: a table and a chair for the teacher, thirty school desks, thirty chairs, and three school cupboards. The classroom was equipped with a printer, a smart blackboard, and a glass blackboard. During the monitoring, the classroom door was opened several times, and during a break, a window was partially opened.

The monitored classroom in the SG7 gymnasium school building was located on the 1st floor of the building. The school building had undergone thermal rehabilitation. It featured windows facing south, walls constructed from brick masonry that were plastered and coated with aqueous dispersion paint, and floors finished with epoxy-resin-based products. The windows were equipped with PVC profiles and thermal insulating glass, while the door was crafted from MDF (medium density fiberboard) and included a glazed surface.

In one of the classrooms, the heating system consisted of three steel radiators, which were not functional at the time of monitoring. The room was illuminated by six square-shaped, LED-based lighting fixtures. The furniture included a table and a chair for the teacher, twenty-three student desks and chairs, and nine school cupboards. For the teaching aids, the classroom was outfitted with a smart blackboard and a glass blackboard. During the monitoring period, two windows were partially opened (one at the front and one at the rear), and another window was fully opened for 30 min. The monitored classroom in the GR1 kindergarten building was located on the ground floor of the building. The building was not thermally rehabilitated. It had south-east-facing windows, brick masonry walls, plastered and finished with aqueous dispersion paint, and the floor finished with solid wood parquet. The windows are made of PVC profiles and thermal insulating glass, and the door is made of MDF (medium density fibers). The classroom had heating elements, namely three steel radiators, non-functional at the time of monitoring; ten lighting fixtures; and the following furniture elements: a table and a chair for the teacher, seven round small tables, thirty-five seats for children, eight sleeping furniture modules that had eighteen small wardrobes on top, and nine kindergarten cupboards. The classroom was equipped with a printer, a PC desk, a monitor, a projector, a smart blackboard, and a TV. During monitoring, ventilation was provided only by opening the door.

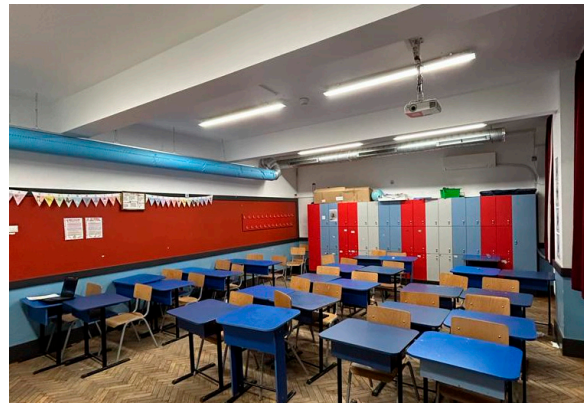
The monitored classroom in the GR2 kindergarten building was located on the 1st floor of the building. The building was not thermally rehabilitated. It had south-facing windows, brick masonry walls, was plastered and finished with aqueous dispersion paint, and the floor was finished with laminate parquet. The windows were made of PVC profiles and thermal insulating glass, and the door was made of MDF (medium density fibers). The classroom was equipped with heating elements, which included three steel radiators; however, these were non-functional at the time of monitoring. The lighting was provided by nine LED-based, square-shaped fixtures. Regarding the furniture, the classroom contained a table and a chair for the teacher, six small round tables, and thirty seats for children, to create a conducive learning environment for young learners. Additionally, the room featured six sleeping furniture modules; on top of these modules were eighteen small wardrobes with six kindergarten cupboards for storage. For technology and educational support, the classroom was outfitted with a printer, a PC desk, a laptop, and a TV, ensuring a blend of traditional and modern teaching methods. During the monitoring period, both a window and the door were kept partially open to facilitate ventilation.

Another extensive campaign was carried out in the classroom that was abbreviated in the paper as SG8 (Figure 1), which was located in the same building with classroom AIC, with the same general characteristics presented in Section 2.1. The classroom was illuminated with compact fluorescent bulbs, which were energy efficient. The lack of mechanical ventilation and air-cooling systems was recognized as a notable disadvantage, which was likely to result in increased levels of interior air pollution and discomfort in hotter seasons, as seen during the monitoring period. The thermal restoration initiatives carried out in 2010–2011 were a crucial measure aimed at enhancing the energy efficiency and indoor environmental conditions of the building. The procedures encompassed the application of fire-resistant expanded polystyrene for external wall insulation, the substitution or repair of heating distribution pipes with more resilient and efficient polypropylene pipes, and the installation of exhaust fans in sanitary facilities to increase the air quality.

The studied classroom was initially tested (Figure 2a) without any fresh air supply and then with a heat recovery unit (Figure 2b).



(a)



(b)

Figure 2. (a) Natural ventilated classroom and (b) mechanically ventilated classroom.

This system was meant to provide fresh air and to remove stale air and it was comprised as a network of ducts for the supply and removal of air in the classroom. The ventilation system was operated in a free-cooling mode when the outdoor temperatures were lower than the temperature inside. The device could accommodate a variety of air flow rates, ranging from 150 to 2000 cubic meters per hour. For this particular use case, a model with an air flow rate of 800 cubic meters per hour was selected as these values were sufficient for the 25 pupils and 1 teacher. The system had a quick installation process and required less air dampers. It used G3 + F7 filters and instantly switched to free cooling mode when there was excessive heat. It was designed to function within a temperature range of -15 to $+50$ °C. The fresh air intake was facilitated by textile piping, while air extraction was carried out using steel ducts.

2.2. Equipment

The equipment used in the first experimental campaign, Gray Wolf Direct Sense IQ-610, also used in other international studies [32–34], for monitoring TVOCs and CO₂; Gray Wolf Direct Sense TG-501, for monitoring of NH₃; and Gray Wolf Handheld 3016 for PM (Figure 3), were placed 1 m away from the wall and at a sampling height of 140 cm from the floor level for the spaces in gymnasium schools and 100 cm for the spaces in the kindergartens, with the benchmark being the height level of the vulnerable occupants. The equipment mentioned was calibrated before the measurements, at the manufacturer office in Ireland (the main office of manufacturer is in USA), with calibration certificate no. 50463 for IQ-610 and calibration certificate no. 50463 for TG-501. Handheld 3016 did not require a special calibration, the purging operation that was carried out at predetermined time intervals was sufficient and was achieved before the measurements.



Direct Sense IQ-610



Particulate Handheld 3016



Direct Sense TG-501

Figure 3. Monitoring equipment.

The information about the monitored parameters, measuring principle, domain, and accuracy are presented in Table 1.

Table 1. Technical characteristics of the monitoring equipment.

Parameter	Measuring Principle	Domain/Accuracy
TVOCs	Photoionization detector (PID)	20 ÷ 20,000 ppb/1 ppb
Carbon Dioxide (CO ₂)	Non-Dispersive Infrared (NDIR)	0 ÷ 10,000 ppm/±50 ppm
Ammonia (NH ₃)	Electrochemical	0 ÷ 100 ppm/<1 ppm
Particulate matter (PM2.5, PM10)	Optical	0.3 ÷ 10.0 µm/100% for particle > 0.45 µm

Concerning the measurement equipment from the second experimental campaign, this was a sophisticated sensor that was specifically intended to monitor a wide range of factors crucial for evaluating the quality of the indoor environment. The sensor was called IAQ Daikin and it was capable of measuring environmental parameters such as ambient light, temperature, humidity, fine dust (PM10/PM2.5), CO₂, and total volatile organic compounds (TVOCs). This resulted in a versatile instrument for assessing indoor environmental quality (IEQ).

The ambient light sensor had a broad range of 0 to 120,000 lux, with a precision of ±10% and a high resolution of 0.1 lux. This allowed for precise measurements of light levels in various interior environments. The temperature measurements were consistently recorded between −40 °C and 85 °C. The accuracy was particularly noteworthy, with a deviation of ±1 °C within the range of 0 to 65 °C. Additionally, the measurements had a resolution of 0.1 °C, allowing for precise temperature profiling. Humidity was quantified using a scale that spanned from 0 to 100% relative humidity (RH), with an accuracy of ±3% RH and a resolution of 0.1% RH. This enabled meticulous regulation of the humidity levels.

The concentration of fine dust was carefully monitored for particles with a diameter of 10 µm (PM10) and 2.5 µm (PM2.5), within a measuring range of 0 to 1000 µg/m³. The sensor had a level of accuracy of ±15 µg/m³ for measurements up to 100 µg/m³ and ±15% for measurements beyond that, up to 1000 µg/m³. It had a resolution of 1 µg/m³, which was crucial for evaluating the air quality. The measurement of CO₂ levels ranged from 0 to 5000 ppm. The precision of the measurement was ±30 ppm up to 1000 ppm and ±3% beyond that range. Additionally, the resolution of the measurement was 1 ppm, which was crucial for assessing the efficiency of ventilation. TVOCs measurements ranged from 0 to 1187 parts per billion (ppb), boasting an accuracy of ±10% and a resolution of 1 ppb. This level of precision was crucial for identifying and quantifying indoor air contaminants effectively.

3. Results and Discussion

The obtained results in the first experimental campaign (AIC, SG5–SG7) are summarized in Table 2. The variation in average concentrations of TVOCs, CO₂, NH₃, PM2.5, and PM10 in the analyzed spaces of the school environment are presented in Figures 4–7.

Table 2. Summary of the obtained results.

Type of Space	Volume of Space, m ³	Number of Students	Air Volume per Student, m ³	TVOC, (min/max) µg/m ³	CO ₂ , (min/max) ppm	PM2.5, (min/max) µg/m ³	PM10, (min/max) µg/m ³	NH ₃ , (min/max) µg/m ³
AIC	155.3	20	7.8	727/1921	1485/2462	57.3/109.5	190.8/412.0	739.6/985.4
SG5	151.9	24	6.3	1054/4917	1442/2269	58.3/78.0	144.4/228.4	768.4/1403.4
SG6	224.4	23	9.8	584/1154	899/1487	61.8/102.0	116.5/209.8	740.1/1126.2
SG7	148.3	16	9.3	469/695	1023/1489	33.2/36.0	86.7/141.9	543.5/843.2

Table 2. Cont.

Type of Space	Volume of Space, m ³	Number of Students	Air Volume per Student, m ³	TVOC, (min/max) µg/m ³	CO ₂ , (min/max) ppm	PM2.5, (min/max) µg/m ³	PM10, (min/max) µg/m ³	NH ₃ , (min/max) µg/m ³
GR1	235.6	19	12.4	957/1991	957/1165	23.4/27.1	50.8/84.4	780.7/1231.7
GR2	171.3	20	8.6	706/840	1495/2783	75.9/114.9	143.3/226.2	670.5/1020.3
Admissible limit				500/1000	1000	25	50	300 ¹ /100 ¹
References				[35,36]	[31,36]	[36,37]	[36,37]	[38]

¹ The value of 300 µg/m³ is for exposure of 30 min and value of 100 µg/m³ is for exposure period of 24 h.

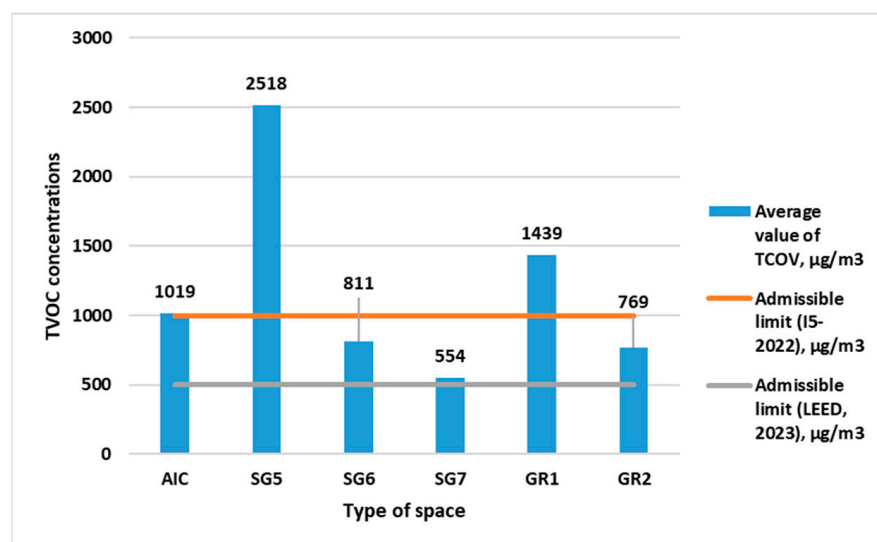
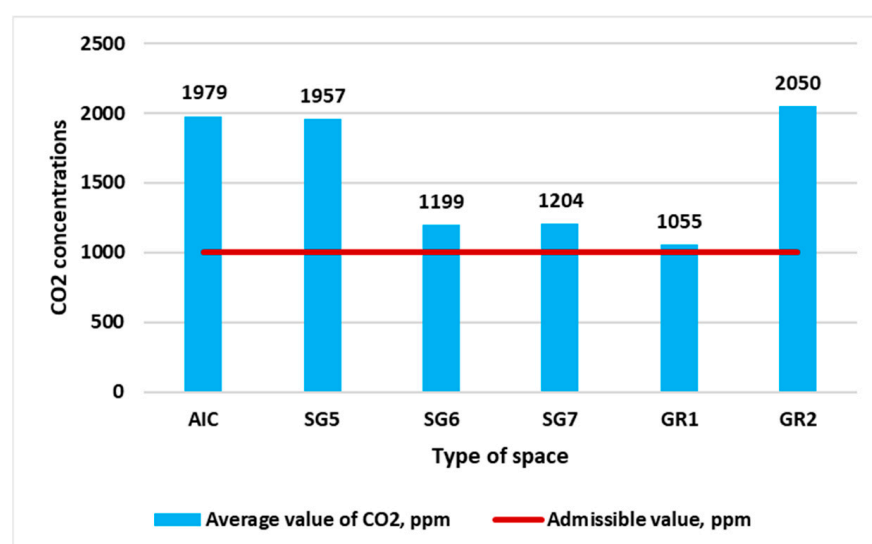


Figure 4. Average concentration of total volatile organic compounds (TVOCs) in the analyzed spaces.

Figure 5. Average concentration of carbon dioxide (CO₂) in the analyzed spaces.

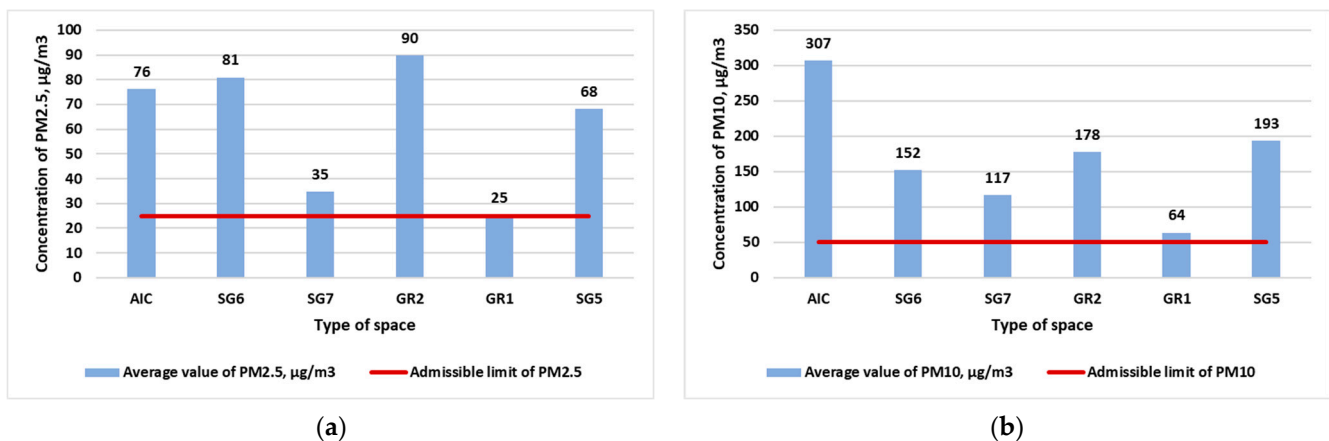


Figure 6. (a) Average concentration of particulate matter (PM) PM_{2.5} in the analyzed spaces and (b) average concentration of particulate matter (PM) PM₁₀ in the analyzed spaces.

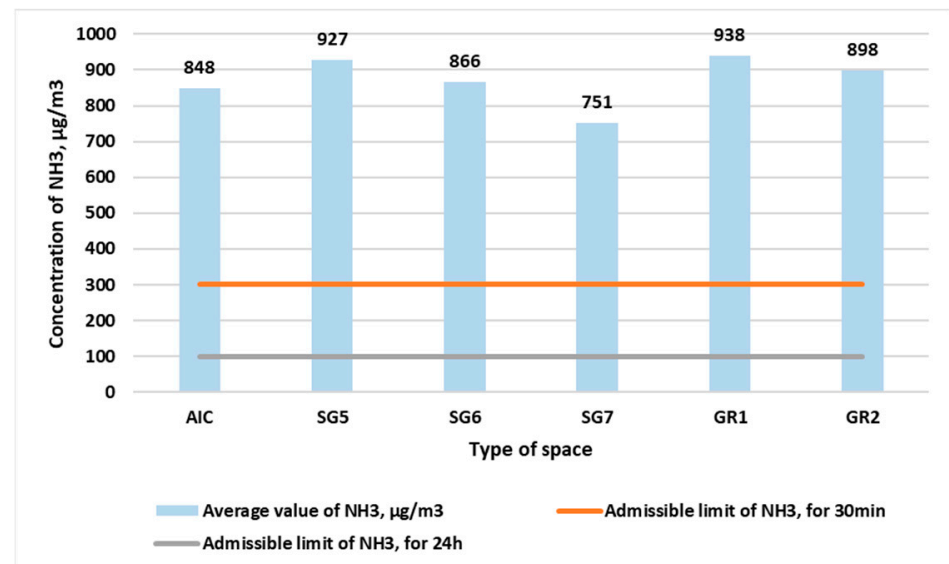


Figure 7. Average concentration of NH_3 in the analyzed spaces.

The analysis of the average TVOC concentration values presented in Figure 4 reveals that in all six cases, the admissible limit of $500 \mu\text{g}/\text{m}^3$, and in three cases out of six, the admissible limit of $1000 \mu\text{g}/\text{m}^3$, were exceeded according to [35,36]. Regarding the average CO_2 concentrations, it was found that in all of the analyzed spaces, the admissible limit of 1000 ppm, provided by [31,36], was exceeded (Figure 5). However, only three spaces exceeded the limit of 1500 ppm, provided by [39].

For the CO_2 results, it can be seen they were slightly lower than those from, for example [36], where the minimum average value was 1376 ppm and the maximum was 3012 ppm.

The average PM_{2.5} (Figure 6a) and PM₁₀ (Figure 6b) concentrations values were exceeded in all six of the monitored spaces, according to the admissible limits in [36,37].

Also, the NH_3 average concentrations values exceeded the admissible limits according to [38] in all six of the monitored spaces (Figure 7).

The analysis of correlations between the air volume per student and TVOCs, CO_2 , NH_3 , PM_{2.5}, and PM₁₀, and between the volume of analyzed space and the concentrations of monitored pollutants, is showed in Figures 8–11.

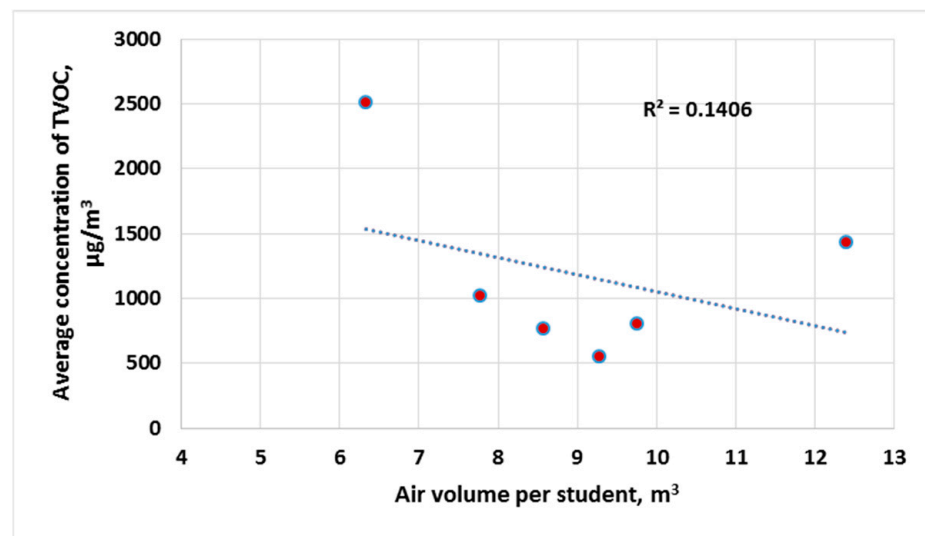
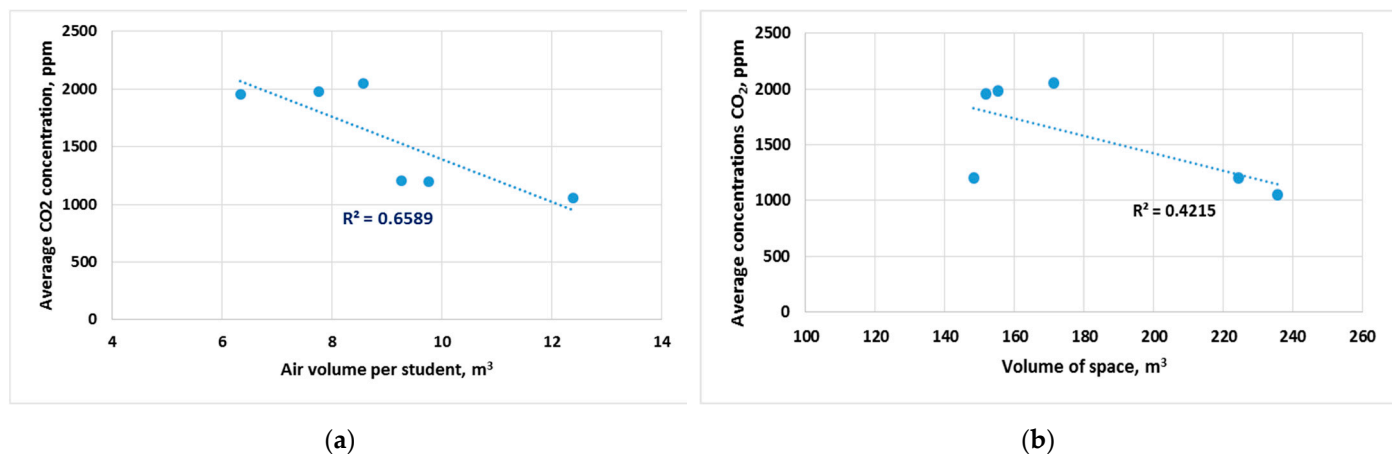


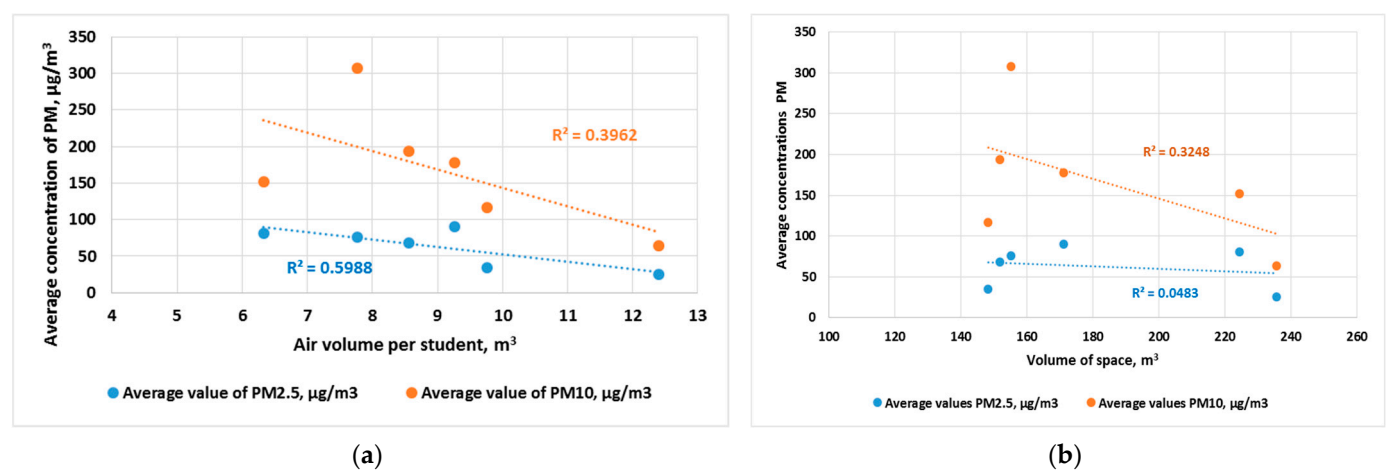
Figure 8. Inverse correlation between TVOC concentration and air volume per student.



(a)

(b)

Figure 9. (a) Inverse correlation between CO₂ concentration and air volume per student and (b) inverse correlation between CO₂ concentration and volume of space.



(a)

(b)

Figure 10. (a) Inverse correlation between PM concentration and air volume per student and (b) inverse correlation between PM concentration and volume of space.

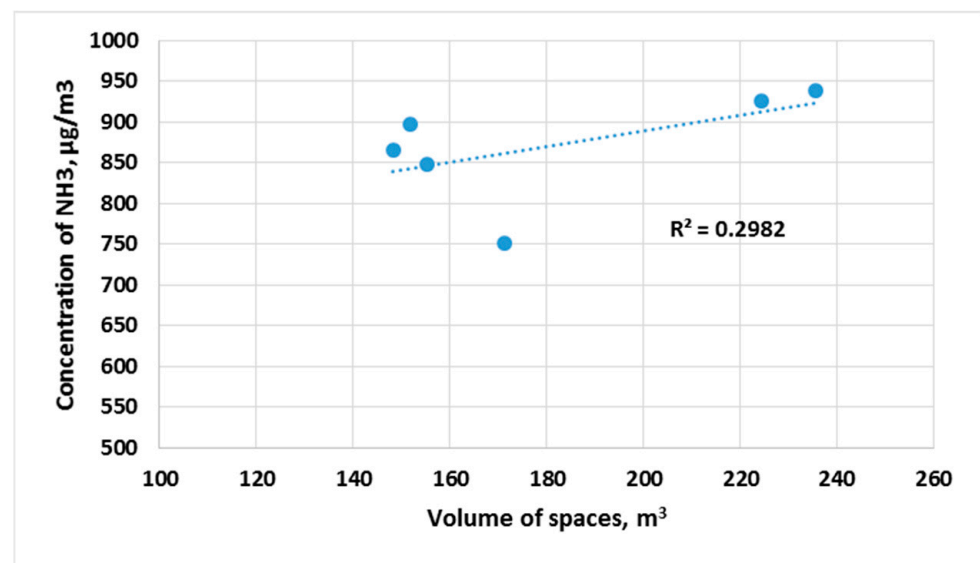


Figure 11. Direct correlation between NH_3 concentration and volume of space.

It can be observed that there was an inverse correlation between air volume per student for TVOCs, CO_2 , and PM, and no correlation for NH_3 . From the point of view of volume of space, there was inverse correlation for CO_2 and PM, a direct correlation for NH_3 , and no correlation for the TVOCs concentrations.

Regarding the study from school SG8, there were two sets of data as the studied classroom had undergone the installation of a ventilation system.

The implementation of the heat recovery ventilation system greatly enhanced the quality of the indoor air by substantially decreasing the carbon dioxide (CO_2) concentrations within the monitored setting (Figure 12).

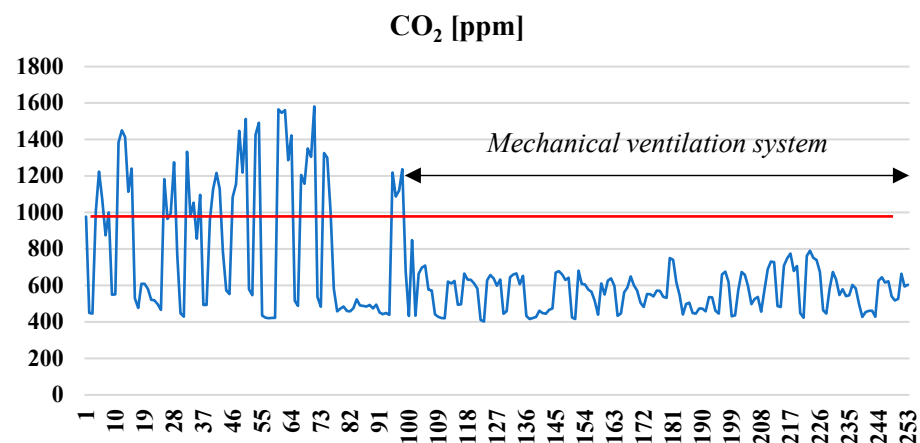


Figure 12. CO_2 variations before and after the installation of the mechanical ventilation unit.

Before the installation of the system, the levels of CO_2 reached a peak of 1581 ppm, with an average concentration of 848 ppm. Significantly, the concentration of 1000 parts per million (ppm) was surpassed on 40.9% of the days that measurements were taken. This suggests that there were frequent instances of air quality falling below ideal levels, which could potentially impact the comfort and cognitive function of the occupants. After the installation of the ventilation system, a significant enhancement in CO_2 levels was noted. The highest documented CO_2 concentration decreased to 790 ppm, which was far lower than the previously recorded maximum levels. In addition, the mean CO_2 concentration decreased to 564 ppm, indicating a substantial enhancement in the preservation of stable air quality. Crucially, there were no occurrences where the CO_2 levels exceeded a threshold

of 1000 ppm, thereby eliminating the previously recorded periods of low air quality. The data highlight a significant improvement in the quality of indoor air, with a decrease of 33.5% in CO₂ levels after the installation.

The use of the heat recovery ventilation system was also proven to be effective in decreasing the levels of particulate matter (PM), particularly PM₁₀ and PM_{2.5}, in indoor space (Figure 13). Prior to the installation of the ventilation system, the mean PM₁₀ concentration in the indoor air was measured at 10.6 µg/m³. After the system was put into operation, the average concentration was reduced to 7.3 µg/m³. After the ventilation system began operation, the average PM₁₀ concentration decreased significantly to 7.273 µg/m³. This indicates a significant decrease of 31.1% in PM₁₀ levels, demonstrating a notable gain in the indoor air's particulate matter filtration and purification mechanisms. The average PM_{2.5} concentration decreased from the initial level of 9.6 µg/m³, demonstrating the system's effectiveness at reducing both bigger and more harmful tiny particulates.

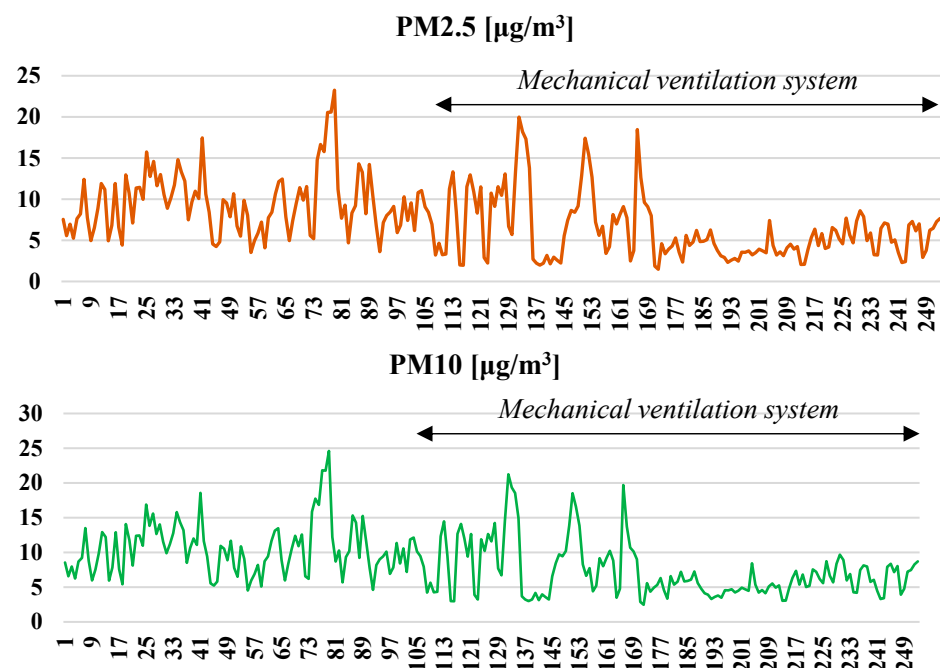


Figure 13. Particulate matter variations before and after the installation of the mechanical ventilation unit.

Following the installation, the mean concentration decreased to 6.2 µg/m³, indicating a reduction efficiency of 34.6%. This decrease not only indicated an improvement in air quality, but also a reduction in the potential health hazards linked to exposure to fine particulate matter. It is important to mention that, in both instances, the levels of PM did not overpass the admissible thresholds of 25 µg/m³ for PM_{2.5} and 50 µg/m³ for PM₁₀.

A decrease in the total volatile organic compounds (TVOCs) from an average of 102.8 parts per billion (ppb) prior to the installation of the heat recovery ventilation system to 99.2 ppb (Figure 14), thereafter indicated a slight reduction. A slight decrease in TVOCs levels, although suggesting an enhancement in the quality of indoor air, necessitated a detailed explanation due to the intricate nature of TVOCs sources and the dynamics of interior environments. Indoor materials could adsorb volatile organic compounds (TVOCs) from the air and subsequently released them back into the environment through desorption. In this scenario, even with enhanced ventilation, the levels of TVOCs only experienced a slight decline. This is because there was a constant emission of these compounds from various surfaces and materials present in the area, which maintained a dynamic equilibrium.

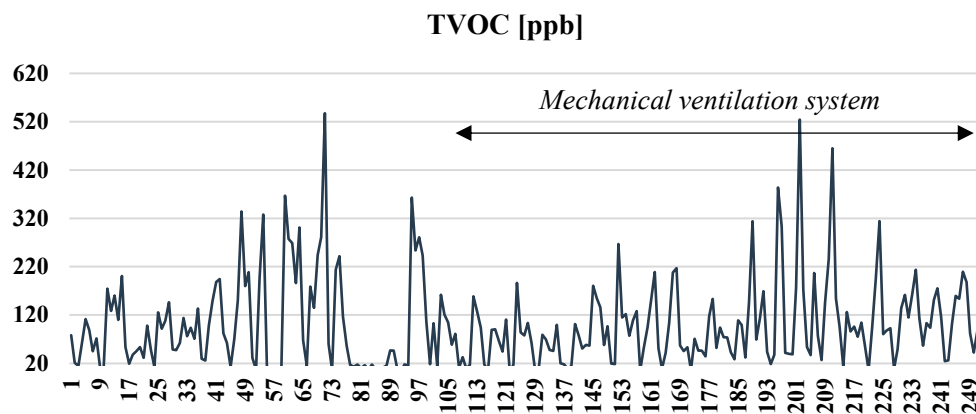


Figure 14. TVOC variations before and after the installation of the mechanical ventilation unit.

Furthermore, the potency and fluctuation of these sources could have a substantial impact on the concentration of TVOCs. The effectiveness of ventilation at reducing TVOCs levels may be limited if the sources remain constant or if new sources are introduced. Variations in TVOCs levels caused by alterations in indoor activity, humidity, temperature, and other environmental conditions could obscure the genuine effect of ventilation enhancements.

4. Conclusions

This research paper presents the results of two monitored campaigns of indoor air quality in some educational buildings, namely four gymnasium schools and two kindergartens, located in Bucharest, Romania, where children between the ages of 4 and 9, a sensitive category of the population, participated in indoor activities, for about 7 h per day. In the first campaign, the concentrations of three main categories of pollutants were monitored, namely VOC, CO₂, NH₃, and PM (PM_{2.5} and PM₁₀). The values of the average TVOCs concentrations varied between 554 µg/m³ and 2518 µg/m³, CO₂ concentrations between 1055 ppm and 2050 ppm, NH₃ concentrations between 843.2 µg/m³ and 1403.4 µg/m³, PM_{2.5} concentrations between 25.1 µg/m³ and 89.9 µg/m³, and PM₁₀ concentrations between 63.7 µg/m³ and 307.4 µg/m³. In most cases, the monitored pollutant concentration values exceeded the limit values provided by the national or international regulations, or in other previous studies. Therefore, an important measure to prevent negative health consequences for children in schools and kindergarten buildings is improving air quality using all possible methods. Understanding and controlling indoor pollutants can help reduce the risk of health problems, as the health effects of indoor air pollutants can be felt shortly after exposure or possibly years later.

Our study provides distinctive perspectives on indoor air quality in Romanian educational institutions based on their climate pollution and architectural characteristics. Our research offers detailed measurements of TVOCs, CO₂, NH₃, PM_{2.5}, and PM₁₀ concentrations in Romanian gymnasium schools and kindergartens, complementing previous studies on indoor air quality in European schools. Furthermore, our research acts as a crucial foundation for comparative analyses of indoor air quality in schools throughout the EU. This study contributes to the existing literature by establishing a standard for assessing the effectiveness of ventilation systems in comparable climate zones and architectural settings across the EU. Our work innovatively explores the usage of mechanical ventilation systems with textile air inlets in schools. Our research diverges from conventional studies on mechanical ventilation systems by providing a distinct approach that could enhance air distribution and improve air quality. The effectiveness of textile air inlets in decreasing CO₂ and particulate matter levels, as shown in our findings, indicates a notable progress in the application of ventilation technology. This distinctive feature of our research has not been thoroughly addressed in the existing literature, making a new and valuable contribution to the subject.

For the last study case with the comparison before and after the installation of heat recovery ventilation in classroom, the results demonstrate a notable enhancement in air quality after the installation, as evidenced by a considerable decrease in CO₂ levels. On average, the concentrations decreased by 33.5%, and there were no longer any cases where the levels were above the threshold of 1000 ppm. Similarly, there was a significant decrease in the concentrations of particulate matter. The levels of PM₁₀ and PM_{2.5} decreased by 31.1% and 34.6%, respectively.

By conducting field measurements and data analysis on four mechanical systems in an actual school environment, the study of Catalina et al. [40–42] assessed the impacts on air quality, thermal comfort, and noise levels, and found similar reductions in CO₂ levels to those presented in this paper.

This improvement in air quality related to particle matter consistently remained within safe exposure limits. Nevertheless, the decrease in TVOCs concentrations was limited, emphasizing the intricacy of addressing volatile organic compounds just by ventilation and emphasizing the necessity for comprehensive strategies that incorporate source management, improved filtering, and potentially air purification technologies. Overall, the implementation of the heat recovery ventilation system has been a crucial measure in improving indoor air quality.

Author Contributions: Conceptualization, V.V., T.C., A.D. and M.I.; methodology, V.V., T.C., A.D. and M.I.; validation, V.V., T.C. and A.D.; formal analysis, V.V., T.C., A.D. and M.I.; investigation, V.V., T.C. and A.D.; resources, V.V., T.C., A.D. and M.I.; data curation, V.V., T.C., A.D. and M.I.; writing—original draft preparation, V.V.; writing—review and editing, T.C., A.D. and M.I.; visualization, V.V., T.C. and A.D.; supervision, V.V. and T.C.; project administration, V.V.; funding acquisition, V.V., A.D. and M.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Romanian Government Ministry of Research Innovation and Digitization, project no. PN 19 33 04 02 “Sustainable solutions to ensure the health and safety of population in concept of open innovation and environmental protection” and the project the project no. PN 23 35 02 01: “Synergies of innovation and digitalization in the design of eco-materials and multifunctional products for sustainable constructions, with an impact on the environment and the circular economy”. This paper was also funded by the National Research Grants of the UTCB (ARUT 2023), project number UTCB-31.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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