

## Article

# Air Quality Monitoring in Secondary School Classes in Warsaw—Measurements and Correlation

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## Abstract

This article discusses the results of measurements and surveys on indoor air quality in Warsaw secondary school classrooms. Measuring selected air parameters and basing them on subjective user assessments enables a comprehensive diagnosis that identifies key issues. Temperature, humidity, and carbon dioxide concentration were measured in all rooms on the second floor. Concurrently, a survey was conducted among high school students. The aim of the survey was to gather students' perceptions of the comfort of their stay in selected rooms and their opinions on air quality. The next step in the analysis was to correlate indoor air quality measurements with student perceptions. This allowed for the observation of numerous correlations and several paradoxes. An analysis of carbon dioxide concentration versus perceived comfort showed a distinct correlation. However, no correlation was observed between carbon dioxide concentration and perceived discomfort. Unfortunately, indoor air quality in all rooms where measurements were taken in the studied school was poor. The air parameters tested did not meet any standards. Students reported symptoms such as drowsiness, difficulty concentrating, and headaches, which are strongly associated with elevated carbon dioxide levels and impair learning efficiency.

**Keywords:** survey research; indoor air temperature; indoor air humidity; carbon dioxide concentration; thermal comfort



Academic Editor: Ian Colbeck

Received: 29 June 2026

Revised: 24 July 2026

Accepted: 27 July 2026

Published: 30 July 2026

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## 1. Introduction

Ensuring adequate indoor air quality (IAQ) in public facilities, especially schools, is a complex, interdisciplinary challenge that combines many elements. Key parameters such as temperature, humidity, and carbon dioxide (CO<sub>2</sub>) concentration determine human comfort and health [1,2].

The daily reality in many schools, especially older ones, often fails to meet modern legal requirements. This is particularly important in the context of the intensive modernization of existing buildings, which, by improving thermal insulation, can compromise effective air exchange. This leads to a paradoxical situation where actions aimed at improving building standards can result in a deterioration of indoor air quality [3].

An important aspect in the context of indoor air quality is the broadly understood technical condition of the building, including elements such as the airtightness and construction of windows and partitions. The type of ventilation used, its condition, and whether it exists at all in the building are important. The behavior of people in the room and how long they stay there are also important [4].

Among the parameters affecting indoor air quality, carbon dioxide concentration is becoming a key parameter in school environments. Its primary source in enclosed spaces is the occupants themselves, and the concentration increases directly with their number and the time spent in a poorly ventilated room [1,5]. The air exhaled by an adult is characterized by a CO<sub>2</sub> concentration of approximately 35,000–50,000 ppm. Currently, outdoor carbon dioxide concentration in the air is approximately 425 ppm according to NOAA [6] and is increasing. Indoors, the concentration is approximately 1000 ppm [7].

According to WHO [8], the recommended value of CO<sub>2</sub> concentration in the air should not exceed 1000 ppm and at 1500 ppm the air becomes stale and stuffy.

Other studies [9], conducted in various indoor environments, demonstrate the dynamics of CO<sub>2</sub> accumulation and its effects. In a classroom experiment involving 18 students and two instructors, concentrations reached 3299 ppm after 3 h and 15 min. After just the first hour of class, students experienced significant declines in concentration, increased drowsiness, and decreased productivity. The authors concluded that an increase in concentration above the norm negatively impacts people's quality of life; the effects of poor indoor air quality vary from person to person, with children and the elderly being the most vulnerable groups.

An equally important aspect influencing our well-being is thermal comfort, determined by air temperature and humidity [10]. Thermal comfort is a state in which a person experiences a balance between the release and absorption of heat throughout the body. This heat exchange is influenced by factors such as physical activity level, the insulating properties of clothing, and environmental parameters such as temperature, speed of movement, and relative humidity [11].

In the European Union, issues related to thermal comfort are regulated by the EN ISO 7730 standard [12]. In Poland, there is no single legal act specifying temperature values in rooms. One of the few is the Regulation of the Minister of Labor and Social Policy [13]. In the context of school temperatures, the minimum temperature should be 18 °C, as specified in the Minister of National Education's Notice [14].

The most effective method for improving air quality is to implement technological and structural solutions during the design and modernization stages of buildings. Temporary methods are effective, but the future and greatest potential lie in innovations built into the building structure itself [5,15].

A key element of a modern building is intelligent building management systems (BMS), which coordinate all installations and devices. The basis for BMS operation is a network of sensors that continuously monitor internal and external environmental parameters, such as temperature, humidity, CO<sub>2</sub> concentration, solar radiation, and more. To reduce temperature, when the sensors detect high solar radiation, the system first automatically closes the blinds or roller shutters. If the sensors detect a further temperature increase, the system activates the air conditioning. The overarching principle of the system is that it controls each device individually while creating and executing complex scenarios that turn on or off devices as needed to improve conditions or prevent deterioration inside the building [16,17].

The aim of this study was to assess microclimatic comfort in selected rooms of a secondary school in Warsaw. The study aimed to analyze air quality, identify exceedances of permissible indoor air parameter values, and understand the dynamics of phenomena

occurring in classrooms during their use. The research was conducted under actual operating conditions during the heating season, under atmospheric conditions unfavorable for natural ventilation. Relationships between measured indoor air parameters and individual student assessments were determined. Measuring selected indoor air parameters and basing them on individual student assessments enables comprehensive diagnosis and identification of key problems. The results of this study can contribute to promoting air quality and improving learning conditions not only in the studied school but also in all educational buildings.

The main goal of this study is to identify discrepancies between objectively measured microclimate parameters (particularly CO<sub>2</sub> concentration) and students' subjective perception and well-being in naturally operating classrooms. Particular emphasis is placed on analyzing the phenomenon of weakened occupant sensory response to the progressive deterioration of indoor air quality (IAQ).

## 2. Materials and Methods

The entire floor of the building was analyzed (Figure 1). The research was conducted at a secondary school in Warsaw (central Poland, Central Europe) located in a 100-year-old building. The research was conducted in November and December 2025. In Poland, this is the least favorable period for natural ventilation. During the experiment, the pressure was low, it was raining, and there was a strong, cold wind [18].



**Figure 1.** Analyzing a high school located in a historic building.

The primary research method was a case study. The research was experimental in nature, combining methods that utilize numerical data to analyze phenomena with qualitative methods, where quality over quantity is important, and based on the analysis of subjective experiences.

To capture the dynamics and repeatability of the phenomena, a research model was adopted that involved measuring the same air quality variables over an extended period

(8 weeks). The total measurement campaign lasted eight weeks, spanning November to December 2025. During this period, a total of 45 complete measurement series were completed. Each series covered the duration of a lesson (45 min) and the preceding and following breaks (10–20 min). The results presented below are representative profiles of repeated classroom load conditions. During all measurements, the windows in the rooms remained closed due to low outside temperatures and unfavorable weather conditions, and the mechanical ventilation system in room 120 operated continuously without user-adjustable output. The outdoor carbon dioxide concentration was assumed to be 400 ppm, a typical value used to assess indoor air quality. The threshold value, exceeding which is considered significant for comfort and cognitive function, was set at 1500 ppm, in accordance with the requirements of the PN-EN 16798-1:2019-06 standard [19]. This threshold is associated with shortness of breath, decreased concentration, and a noticeable deterioration in well-being among building occupants.

Each of the rooms studied had a different type of ventilation. Measurements were taken in the following rooms: 101, 103, 105, 107, 112, 113, 114, and 118 with natural ventilation; 120 with mechanical ventilation; a corridor with a volume of 300 m<sup>3</sup>; and the corridor wing where vocational classes take place with a volume of 270 m<sup>3</sup>. All of these rooms are places for students to relax and study. The selection of classrooms (101 to 118 and room 120) was deliberate. The criteria for selecting the spaces were their diverse architectural characteristics (volume ranging from 82.5 m<sup>3</sup> to 160 m<sup>3</sup>) and different ventilation systems (natural ventilation in most classrooms, decentralized mechanical ventilation in room 120), which enabled an assessment of the impact of these parameters on the microclimate dynamics. In short, all classrooms and corridors were examined.

The survey was administered to a group of students currently in the classroom during the measurement period. The selection criterion was their physical presence in the classroom. The surveys were conducted on different days and times to avoid responses from the same individuals in the same context.

Measurements were taken continuously: during lessons for 45 min and during breaks throughout the entire duration. Measurements were taken with a Testo 440pD meter. The meter has a CO<sub>2</sub> measurement range of 0 to 5000 ± (100 ppm + 5% of measured value), a temperature measurement range of 0 to 50 °C with an accuracy of 0.5 °C, and a humidity measurement range of 5% to 95% with an accuracy of 1%. This meter was selected because it provides the required accuracy and allows for convenient export to other devices.

The survey was developed based on the literature review [20]. It contains five closed-ended questions with multiple-choice answers, enabling accurate, decisive responses. The aim of the survey was to gather students' opinions on indoor comfort and air quality. The questionnaire was anonymous. A total of 320 students participated in the study. Questions included in the survey:

1. How do you rate the freshness of the air at this moment?
2. How do you assess the temperature in the room at the moment?
3. How do you rate the humidity in the room at this moment?
4. Have you experienced any of the following symptoms in the last few minutes?
5. How would you rate the overall comfort of learning in the classroom?

The surveys were completed immediately before the room measurement began. This allowed for a correlation between the participants' momentary impressions and the objective measurement results. Before the surveys were distributed, a brief explanation of the evaluation principles was provided.

Correlation analysis between measurement data and survey results involved comparing the former's mean values with the frequency of specific sensations among students. Based on this comparison, an assessment was made of whether changes in the levels of the

measured parameters coincided with changes in sensations, allowing the identification of the existence and direction of potential relationships.

The survey tool was developed based on a literature [20]. Although the questionnaire did not undergo formal psychometric validation, its structure was verified in a pilot study for comprehensibility of wording. Spearman's rank correlation was used to assess the significance of relationships between the measured physical parameters and students' responses, given the qualitative and ordinal nature of the survey data. The analysis was limited by the inability to strictly control for confounding variables, such as momentary fluctuations in students' metabolic activity. The choice of test was dictated by the qualitative and ordinal nature of the data obtained from the survey questionnaires. The level of statistical significance was set at  $p < 0.05$ .

Due to the lack of direct access to ventilation air flow measurements, the air exchange rate (ACH,  $\text{h}^{-1}$ ) and the unit clean air flow per student were estimated indirectly using the  $\text{CO}_2$  mass balance method in the steady state (in the final minutes of the lesson), assuming constant carbon dioxide emissions from students at the level of 19 l/h per person (sedentary activity, low) [21].

Total indoor carbon dioxide emissions ( $E$  [ $\text{m}^3/\text{h}$ ]) calculated using Formula (1):

$$E = \frac{N}{G}, \quad (1)$$

where  $N$ —number of people staying in the room [–],  $G$ —specific  $\text{CO}_2$  emission stream per person  $\text{m}^3/\text{h}$  per person (assumed  $G = 0.019 \text{ m}^3/\text{h}$  [21]).

Ventilation air flow ( $Q$  [ $\text{m}^3/\text{h}$ ]) calculated using Equation (2):

$$Q = \frac{E}{C_{in} - C_{out}} = \frac{NG}{C_{in} - C_{out}}, \quad (2)$$

where  $C_{in}$ —measured internal  $\text{CO}_2$  concentration  $\text{m}^3/\text{m}^3$ ,  $C_{out}$ — $\text{CO}_2$  concentration in outdoor air  $\text{m}^3/\text{m}^3$ .

Air exchange rate (ACH [ $\text{h}^{-1}$ ]) calculated using Formula (3):

$$ACH = \frac{Q}{V}, \quad (3)$$

where  $V$ —room volume [ $\text{m}^3$ ].

Specific air flow per person ( $Q_{pers}$  [ $\text{l/s}$ ]) calculated using Equation (4):

$$Q_{pers} = \frac{Q}{3.6N}, \quad (4)$$

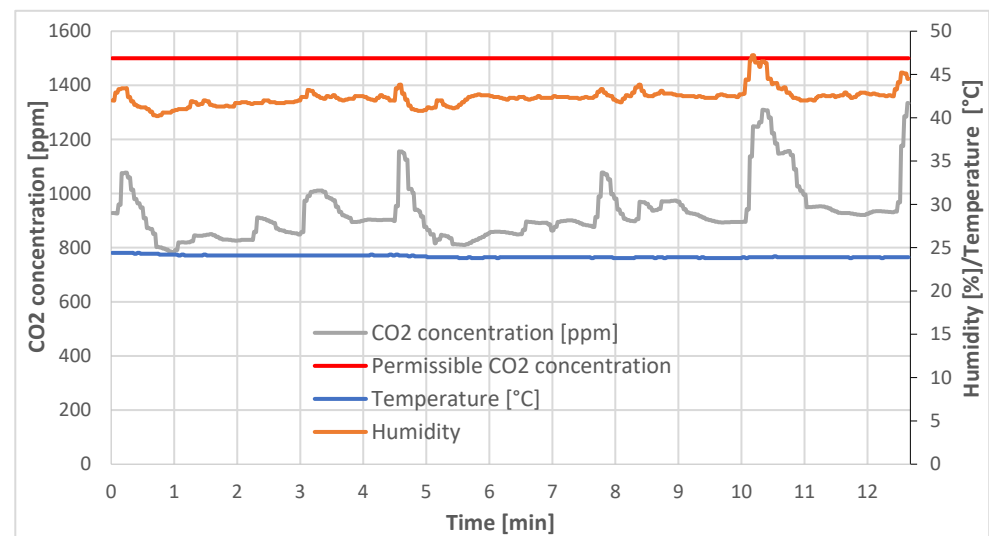
### 3. Results

Air quality tests conducted in technical school classrooms revealed that in half of them, the permissible carbon dioxide concentration was exceeded within the first few minutes of class. Over time, the concentration systematically increased, in some cases reaching values significantly exceeding the thresholds recommended by hygiene standards, which coincided with the reported discomfort and well-being of those present. Furthermore, in the remaining six classrooms, the permissible  $\text{CO}_2$  concentration level was exceeded approximately halfway through the measurement period. In only a few rooms did the  $\text{CO}_2$  concentration not exceed the permissible level. The analysis showed that in only one classroom (room 103, representing approximately 8% of the classrooms studied),  $\text{CO}_2$  concentrations remained below the permissible normative level of 1500 ppm for most of the monitoring period. In communication zones (corridors), the safe concentration range

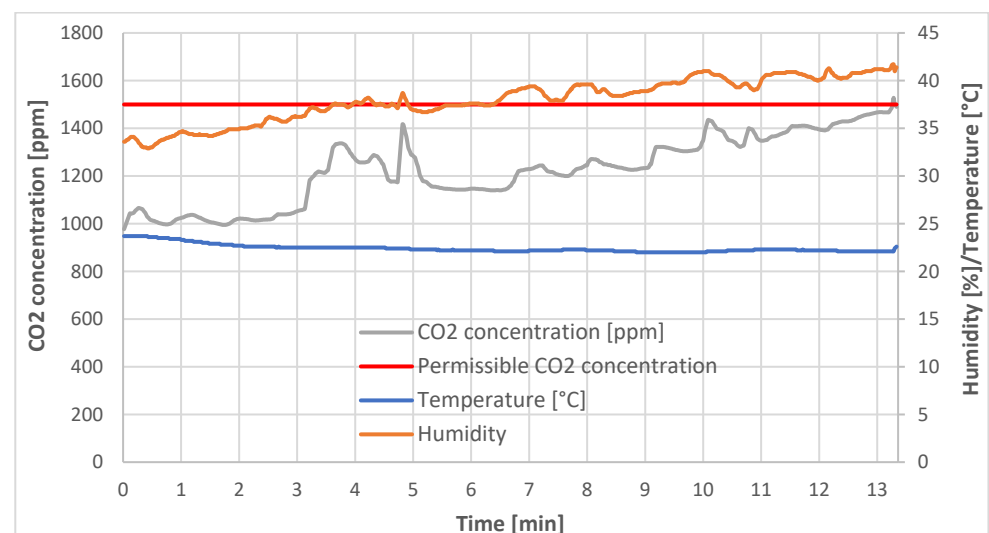
was maintained for approximately 85% of the measurement period. In the remaining 89% of classrooms, exceedances of the limit value were recorded for an average of 75% of the lesson duration.

### 3.1. Analysis of Internal Conditions in Classrooms—Measurements

The analysis of internal conditions began with the circulation areas: the corridor (Figure 2) and the corridor of the so-called “vocational wing” (Figure 3). The measurements revealed high instability of parameters in most cases, except for temperature, which always remained at a similar level (Figures 2 and 3). The main cause of these changes was the dynamic movement of students during breaks, causing local air turbulence.



**Figure 2.** Air parameters in the corridor.



**Figure 3.** Air parameters in the corridor—professional wing.

Comparing the average values for both parts of the corridor, a clear influence of the building’s architecture and traffic volume was observed. The highest average CO<sub>2</sub> concentration was observed in the vocational wing, which is perpendicular to the rest of the building and separated by a wall, limiting natural air exchange with the rest of the building. The vocational wing is where most activities take place, and it is of great importance, as evidenced by the measurement results. Temperature differences between locations were minimal, up to 1.5 °C. Humidity was comparable in all corridors.

Air quality in the high school corridors, characterized by large cubic capacity and relatively low density (ranging from several to several dozen), was good. Instantaneous values fluctuated within a safe range of 800 to 1200 ppm, showing no sustained upward trend. An equally consistent pattern was observed for thermal and humidity parameters. Air temperature remained constant at approximately 24 °C, and humidity ranged between 40 and 45% (Figures 2 and 3). Such winter temperatures in the building, which was not heated during the measurements, indicate good thermal insulation of the older structure.

The main heat sources were occupants and electrical appliances. It is also worth noting that although the temperature values are within the acceptable range for occupational health and safety regulations [22], they sometimes exceed the PN-EN 16798-1:2019-06 standard [19] for the heating season, which recommends a temperature of 20–24 °C. Humidity levels of 40–45% may be caused by outside air flowing in through the entrance door. The short time students spent in these spaces and the fact that they were allowed to go outside during breaks mean that even prolonged exposure to these conditions could have minimal impact on occupants' well-being and health.

The most important stage of the research was the analysis of air parameters in classrooms. Unlike in circulation areas, data analysis revealed significant dynamic changes, strong variation in results, and extended periods during which CO<sub>2</sub> concentrations exceeded threshold values (Table 1), which were closely correlated with the cubic capacity and number of people in the room. The measurements showed that the trend in CO<sub>2</sub> concentration changes was always linear, although not always increasing (Figures 4–7). The conducted studies revealed a typical increase in air pollution resulting from the tightness of the rooms and the presence of people. No differences were observed between rooms with and without mechanical ventilation. The measurements revealed that the ventilation airflow was too low and inadequately adjusted to the number of people in the rooms. However, it should be emphasized that the measurements were conducted in the fall, when airing the room during classes would have led to rapid cooling, and consequently, to a significant reduction in thermal comfort and an increased risk of illness among both students and teachers.

**Table 1.** Summary of air parameters in teaching rooms.

| Room Number                  | Cubature<br>[m³] | No. of People | Temperature [°C] |      |         | Humidity [%] |      |         | CO₂ Concentration [ppm] |      |         | Estimated Air Flow |
|------------------------------|------------------|---------------|------------------|------|---------|--------------|------|---------|-------------------------|------|---------|--------------------|
|                              |                  |               | Max              | Min  | Average | Max          | Min  | Average | Max                     | Min  | Average | [l/s Person]       |
| 12 November 2025 (Wednesday) |                  |               |                  |      |         |              |      |         |                         |      |         |                    |
| 120                          | 82.5             | 11            | 24.8             | 23.2 | 24.2    | 53.9         | 45.9 | 48.5    | 2220                    | 1153 | 1654    | 2.9                |
| 101                          | 150              | 22            | 26               | 23.7 | 25      | 55.7         | 44.5 | 47.5    | 2331                    | 860  | 1585    | 2.73               |
| 113                          | 160              | 13            | 23.7             | 23   | 23.4    | 59.7         | 51.7 | 54.7    | 2822                    | 2241 | 2515    | 2.18               |
| 118                          | 160              | 17            | 25.5             | 24.3 | 25      | 58.6         | 50.7 | 52.2    | 3087                    | 2586 | 2825    | 1.96               |
| 120                          | 82.5             | 30            | 25.9             | 19.1 | 24.5    | 56.9         | 47   | 51.9    | 4025                    | 1540 | 2759    | 1.46               |
| Corridor1                    | 300              | 30            | 24.4             | 23.8 | 24      | 47.2         | 40.2 | 42.3    | 1334                    | 783  | 927     | 5.65               |
| Corridor2                    | 300              | 30            | 25.7             | 24   | 24.7    | 44.6         | 40   | 42      | 1525                    | 993  | 1163    | 4.69               |
| Corridor<br>prof. wing       | 270              | 30            | 23.5             | 23.2 | 23.4    | 46.1         | 44.6 | 45.3    | 1409                    | 1193 | 1254    | 5.23               |

Table 1. Cont.

| Room Number                 | Cubature<br>[m³] | No. of People | Temperature [°C] |      |         | Humidity [%] |      |         | CO₂ Concentration [ppm] |      |         | Estimated Air Flow<br>[l/s Person] |
|-----------------------------|------------------|---------------|------------------|------|---------|--------------|------|---------|-------------------------|------|---------|------------------------------------|
|                             |                  |               | Max              | Min  | Average | Max          | Min  | Average | Max                     | Min  | Average |                                    |
| 17 November 2025 (Monday)   |                  |               |                  |      |         |              |      |         |                         |      |         |                                    |
| 103                         | 150              | 12            | 25               | 24   | 24.4    | 53.1         | 39.6 | 45.8    | 1633                    | 940  | 1260    | 4.28                               |
| 105                         | 150              | 13            | 25.6             | 24.3 | 25.1    | 48.5         | 44.6 | 45.6    | 2365                    | 1912 | 2100    | 2.69                               |
| Corridor1                   | 300              | 30            | 24.9             | 24.2 | 24.5    | 41.5         | 36.6 | 37.6    | 1135                    | 740  | 860     | 7.18                               |
| Corridor2                   | 300              | 30            | 25.3             | 24.5 | 24.8    | 40           | 36.4 | 38.1    | 1290                    | 999  | 1122    | 5.93                               |
| 25 November 2025 (Tuesday)  |                  |               |                  |      |         |              |      |         |                         |      |         |                                    |
| 107                         | 150              | 8             | 23.9             | 22.9 | 23.6    | 42.2         | 35   | 36.4    | 1410                    | 1071 | 1274    | 5.23                               |
| 112                         | 150              | 21            | 24               | 21.6 | 23.1    | 51.4         | 43.5 | 47.7    | 3346                    | 1830 | 2619    | 1.79                               |
| 114                         | 160              | 15            | 22.1             | 21.1 | 21.6    | 50.5         | 41.5 | 46.9    | 2757                    | 1395 | 2140    | 2.24                               |
| Corridor1                   | 300              | 30            | 22.8             | 21.9 | 22.3    | 41.6         | 33.6 | 37.5    | 1894                    | 867  | 1247    | 3.53                               |
| Corridor<br>prof. wing      | 270              | 30            | 23.7             | 22   | 22.4    | 41.7         | 32.9 | 38      | 1528                    | 977  | 1225    | 4.86                               |
| 3 December 2025 (Wednesday) |                  |               |                  |      |         |              |      |         |                         |      |         |                                    |
| 118                         | 160              | 18            | 24.4             | 23.5 | 24      | 51.1         | 46.9 | 48.6    | 3439                    | 2530 | 3047    | 1.74                               |
| Corridor1                   | 300              | 30            | 23.9             | 23.2 | 23.6    | 41.3         | 36   | 39      | 1375                    | 994  | 1196    | 5.41                               |
| Corridor<br>prof. wing      | 270              | 30            | 24.5             | 23.4 | 23.8    | 42.7         | 36.1 | 39.8    | 1679                    | 1120 | 1446    | 4.13                               |

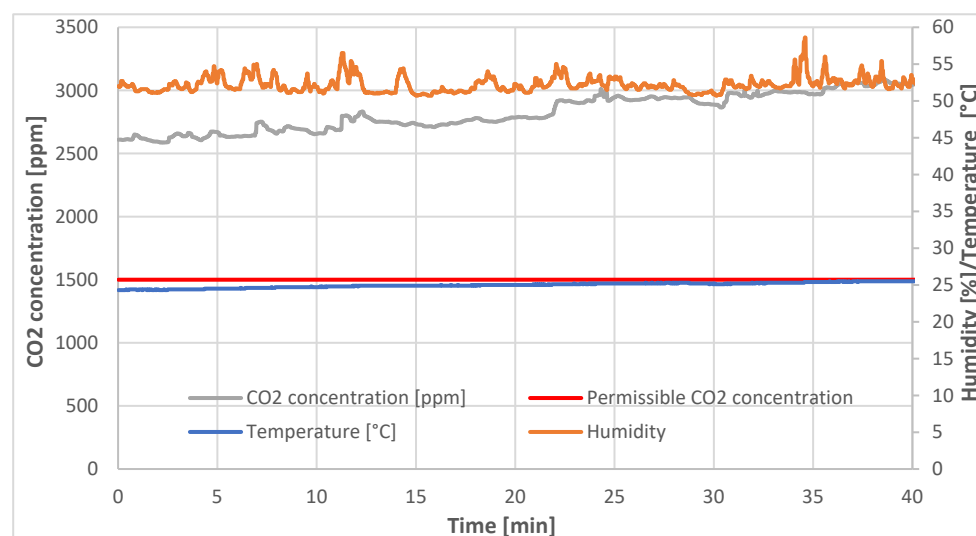


Figure 4. Air parameters from room 118 on 12 November 2025.

Differences in relative humidity values were observed. On the first day of measurement, these values significantly exceeded 50% (Figures 4–7, Table 1), reaching a maximum of nearly 60% (max. 59.7%). On the remaining days, humidity was lower in the first minutes of measurement, most often oscillating around 40–45% (Table 1).

This variability is closely related to external conditions; during this period, outdoor air humidity exceeded 90%. The higher initial humidity could have resulted from water vapor accumulation after days off, when students were absent from school and rooms were aired out by cleaning staff for extended periods.

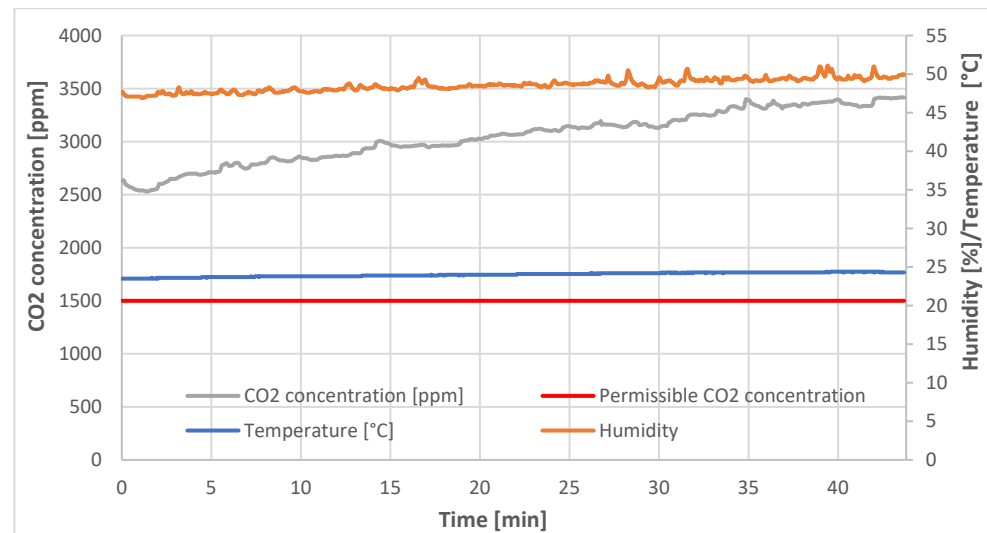


Figure 5. Air parameters from room 118 on 3 December 2025.

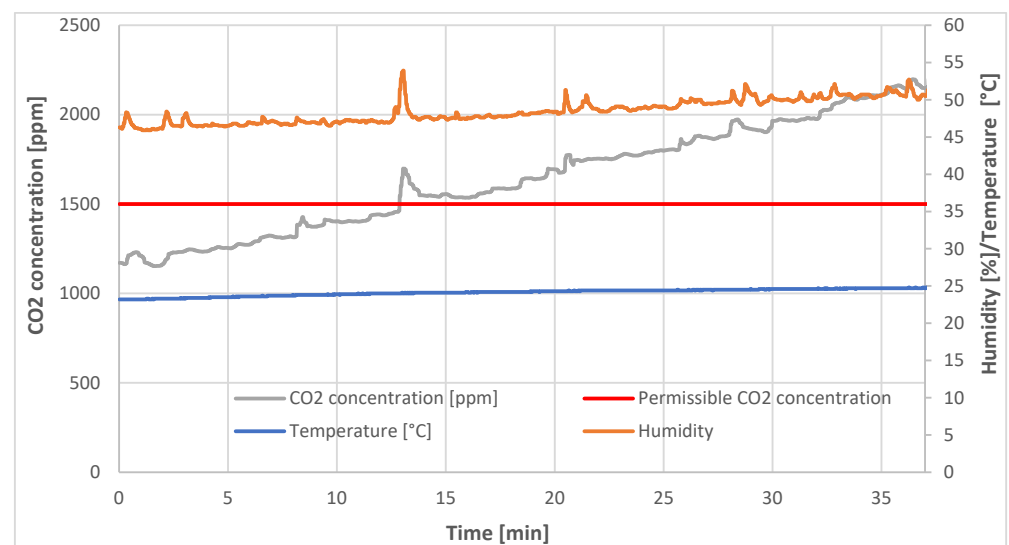


Figure 6. Air parameters from room 120 on the morning of 12 November 2025.

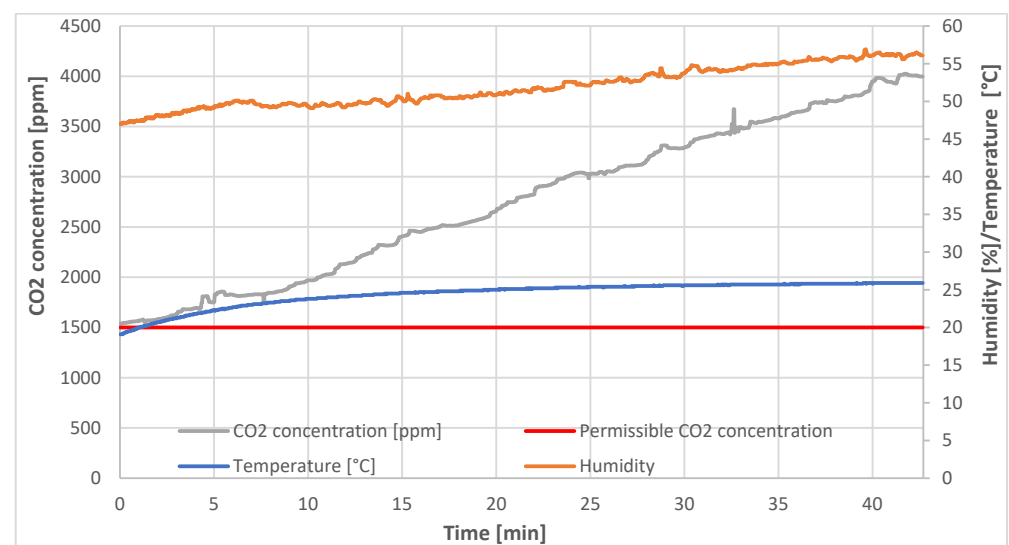


Figure 7. Air parameters from room 120 on 12 November 2025 in the afternoon.

Temperature analysis revealed exceedances in a significant number of cases; only a few rooms reached 20 °C within the first minutes of measurement (usually 24 °C). In extreme cases, temperatures reached 26 °C (Table 1). Persisting such high temperatures is a direct result of neglected room ventilation during breaks or a lack of mechanical ventilation. This lack of air exchange leads to continuous heating of the room by people and equipment, which is further exacerbated by the building envelope's good insulation. The most challenging situation was observed in room 118, located in the vocational wing, with a volume of 160 m<sup>3</sup>. During the first measurement, with 17 students present, the CO<sub>2</sub> concentration was 2609 ppm at the beginning of the class, rising to 3087 ppm by the end (Figure 4). Of particular note are the extremely high initial concentrations recorded just before the start of classes (e.g., 2609 ppm in room 118). These values clearly demonstrate that the classrooms were completely devoid of air exchange (ventilation) during breaks between classes. The accumulation of pollutants from previous classes meant that students began their next lesson in conditions that initially failed to meet any hygiene criteria. With the presence of one additional student, the situation worsened; the initial concentration was 2530 ppm, and the final concentration exceeded 3400 ppm (Figure 5). This indicates that, from the outset, in both cases, the air in the rooms was ineffective for learning, exceeding the norm by more than twofold. Furthermore, the negative impact of pollution was exacerbated by elevated temperatures that reached 25 °C, exceeding the comfort range. This situation was caused by insufficient or absent ventilation during breaks, as evidenced by the high initial CO<sub>2</sub> concentrations. Relative humidity remained within acceptable limits most of the time, occasionally approaching the upper limit of standard [19].

An interesting situation was observed in the smallest room, room 120, with a volume of 82.5 m<sup>3</sup>. During the first measurement, when 11 people were in the room, the CO<sub>2</sub> concentration increased from 1153 ppm to 2200 ppm, and the limit value was exceeded halfway through the class period (Figure 6, Table 1). During the second measurement the same day, when the number of people increased to 30, the initial concentration was 1540 ppm (indicating poor ventilation during the break), and by the end it reached a value almost twice as high as before (Figure 7, Table 1). This demonstrates the relationship between the number of people and the concentration of pollutants in an enclosed room. The temperature then rose to 26 °C.

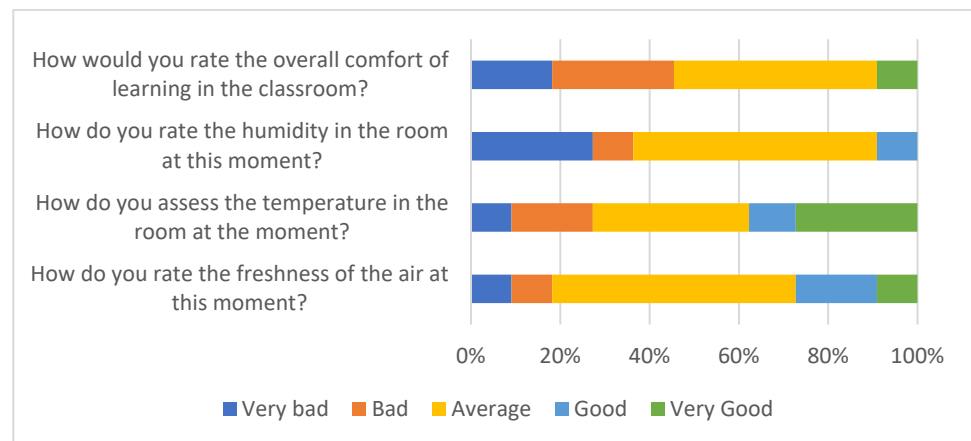
This example clearly demonstrates that poor room planning forces students to study in disastrous conditions. Most rooms have a volume of 150 m<sup>3</sup>, and significant variability in results is evident even with similar numbers of people. Comparing rooms 103 and 105 (Table 1), where the difference in the number of students was only one, the dynamics of concentration growth and the maximum levels achieved differed significantly. In room 103, with fewer students, a greater spread between the minimum and maximum values was observed than in room 105. This phenomenon indicates that the final CO<sub>2</sub> concentration, in addition to volume and the number of sources, is also influenced by less measurable factors, such as ventilation accuracy and occupant metabolic activity.

### 3.2. Analysis of Internal Conditions in Classrooms—Surveys

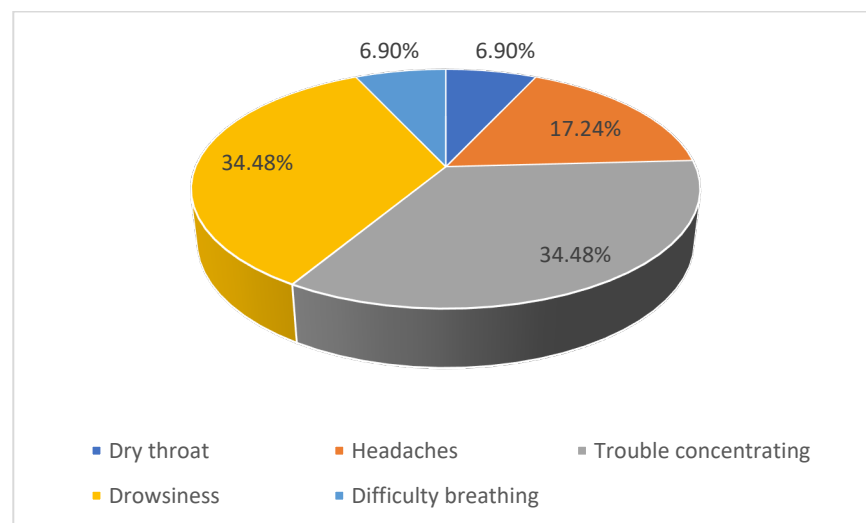
The next stage of the research was to conduct surveys among students to learn about their subjective assessments of classroom conditions and the presence of possible discomfort symptoms.

The reliability and validity of the survey were confirmed by the results from room 120, where measurements revealed very poor conditions, with 41 people surveyed. Student responses fully confirmed this: 96.67% rated the air quality as “poor” or “very poor” (Figure 8), and all indicated the room was “too hot.” Furthermore, almost all stated the air was “too humid.” Regarding symptoms, students listed all of them, most frequently

reporting breathing difficulties and concentration problems (Figure 9). The learning experience in this room was almost unanimously rated as very poor (Figure 8). The most frequently reported symptoms were drowsiness and concentration problems. Despite this, students stated that their school learning experience was generally good. In one case, in room 120, full agreement was observed between the measurement results and the respondents' responses. In most cases, even with significantly unfavorable air parameters, students' experiences were similar to those in other classrooms. This may indicate low user awareness of the impact of indoor air quality on their bodies.



**Figure 8.** Student responses to questions about air parameters.

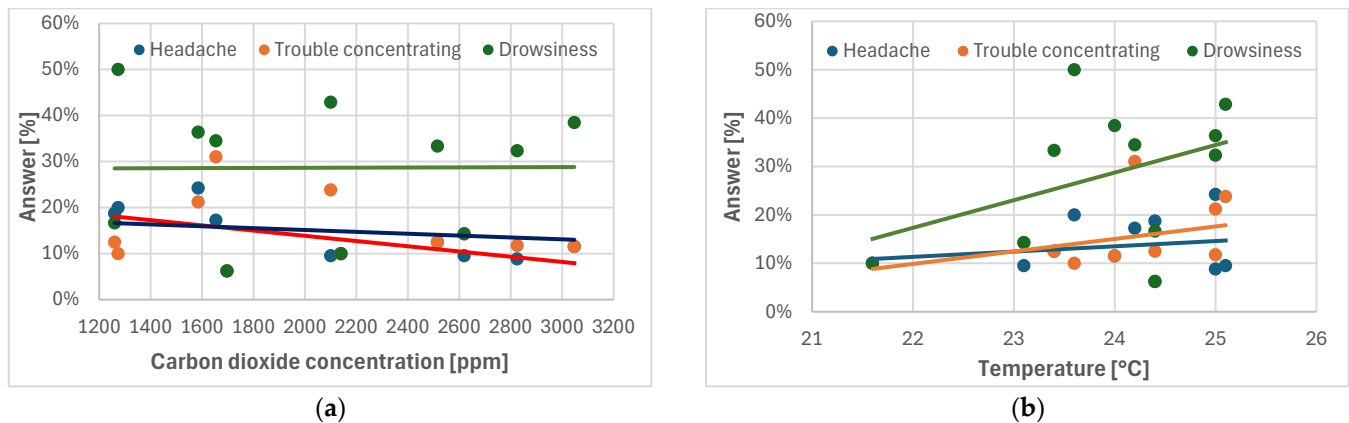


**Figure 9.** Complaints of students in room 120.

### 3.3. Analysis of Internal Conditions in Classrooms—Correlation

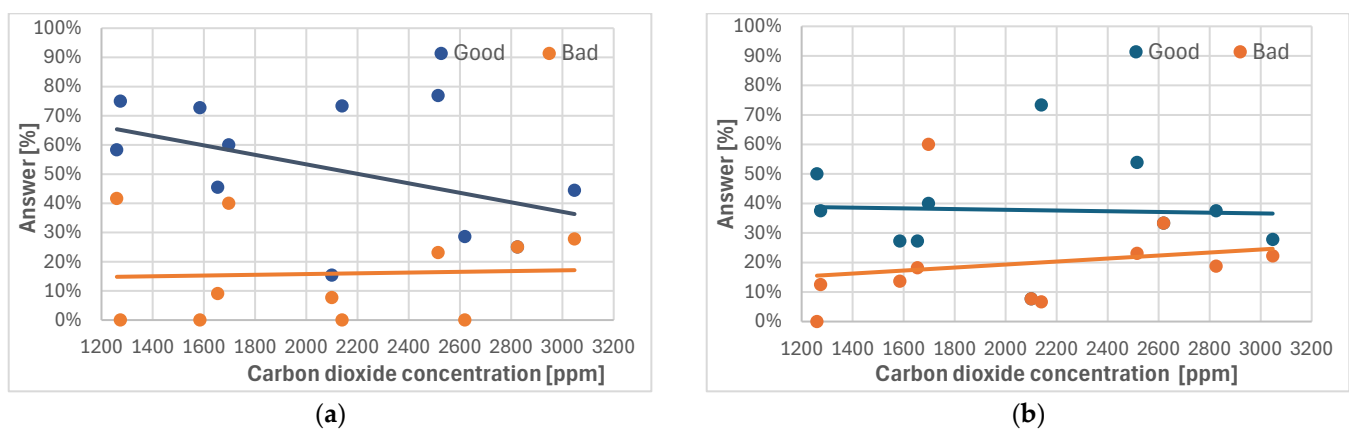
The analysis of survey data revealed certain dependencies and paradoxes.

No correlation was observed between carbon dioxide concentration and the symptoms experienced (Figure 10a). The results indicate an inverse relationship, with increasing concentration increasing the frequency of symptoms such as headaches, drowsiness, and difficulty concentrating (Figure 10b). Prolonged exposure to poor air quality weakens the body's defense mechanisms, obscuring the true impact of pollutants.



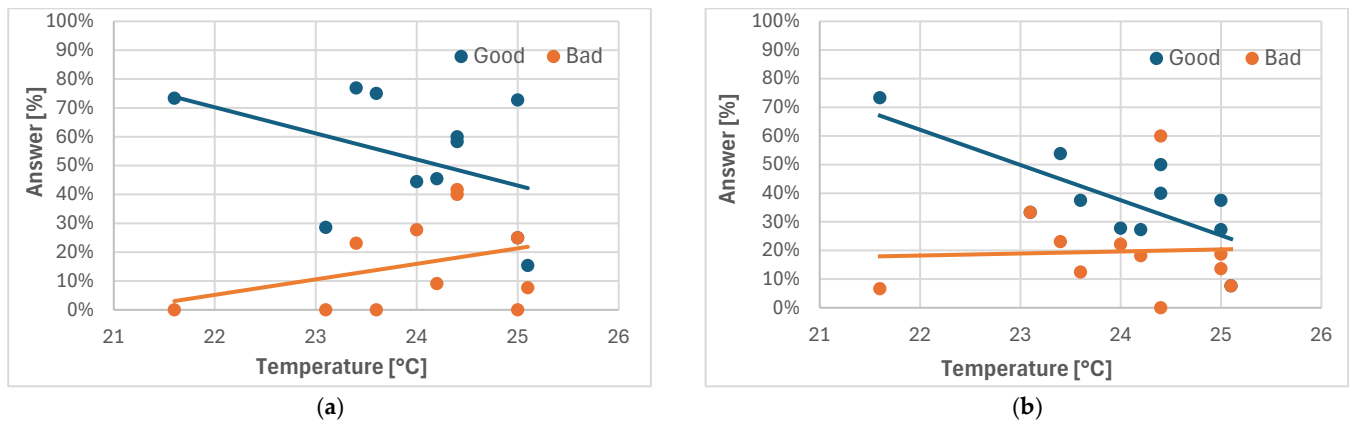
**Figure 10.** Ailments felt by students depending on CO<sub>2</sub> concentration (a) and temperature (b). The lines mark the “trend lines”.

A different pattern was observed when analyzing CO<sub>2</sub> concentration and indoor comfort (Figure 11a). In this case, the correlation is clear: higher CO<sub>2</sub> concentration is associated with lower indoor comfort. Analysis of the dynamics of change showed that the perception of good comfort decreases much faster than the perception of poor comfort increases. This suggests a tendency towards a neutral perception. As pollution levels increase, students are less likely to rate the situation as extremely poor. Regarding the assessment of air freshness, only a slight upward trend was observed in responses, indicating a lack of air freshness at high CO<sub>2</sub> concentrations (Figure 11b), further confirming users’ high tolerance to poor conditions.



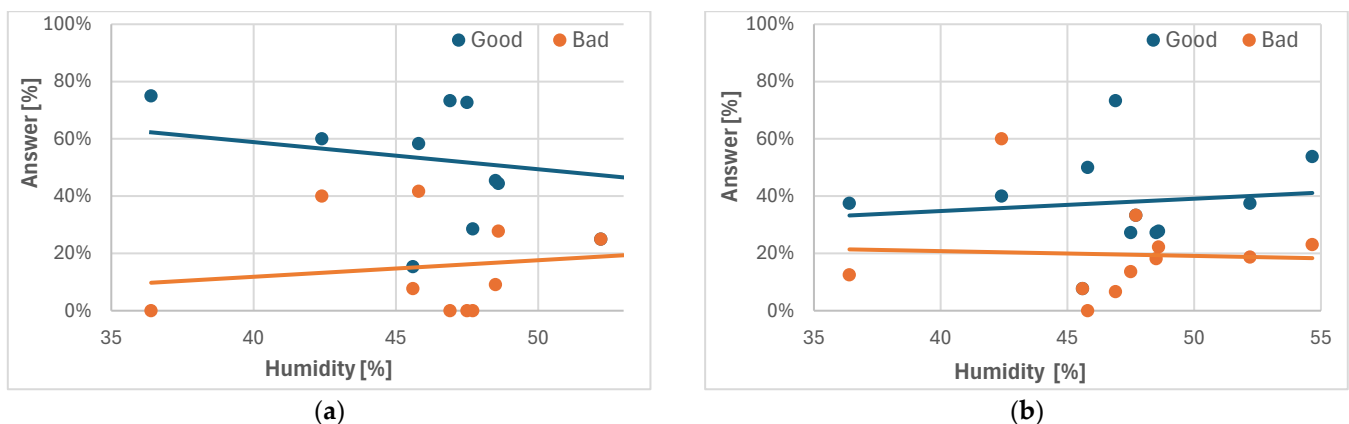
**Figure 11.** Comfort felt by students (a) and air freshness (b) depending on CO<sub>2</sub> concentration.

Temperature proved to be the parameter with the greatest impact on students. A strong correlation was observed between temperature increases and decreased comfort (Figure 12a) and symptom severity (Figure 12b). The exceptionally rapid increase in responses indicating low comfort and the direct correlation between this condition and the perception of increased temperature suggest that for students, temperature is the most measurable indicator of their feelings. Students are particularly sensitive to overheating in the room.



**Figure 12.** Comfort felt by students (a) and air freshness (b) depending on temperature.

For relative air humidity, no correlation with comfort was observed (Figure 13a), although a decreasing trend in the frequency of responses indicating “good” comfort was observed with higher values of this parameter. Comparing humidity with responses revealed several illogical observations. Among them, a strong correlation was observed between the simultaneous perceptions of the room as “too humid” and “too dry”. These two phenomena contradict each other. Another illogical relationship is the increase in reports of dry throat with increasing air humidity. This can be explained by the fact that as this parameter increases, another parameter, which was the actual cause of irritation, also increases. Surprisingly, responses regarding good air freshness were more frequent with higher humidity (Figure 13b).



**Figure 13.** Comfort felt by students (a) and air freshness (b) depending on humidity.

To verify the influence of indoor environmental parameters on students’ subjective experiences, a correlation analysis was conducted. The analysis revealed no statistically significant relationship between the instantaneous CO<sub>2</sub> concentration and the number of reported symptoms ( $r = 0.0907$ ;  $p > 0.05$ ). However, a moderately strong, positive, and statistically significant correlation was observed between air temperature and reported discomfort ( $r = 0.4314$ ;  $p < 0.05$ ). These results clearly indicate that the thermal parameter, rather than the direct carbon dioxide concentration, was the main factor determining the subjective deterioration in the subjects’ well-being.

## 4. Discussion

High carbon dioxide concentrations recorded in the analyzed Warsaw school (regularly exceeding 2500–3000 ppm) are not an isolated phenomenon and are consistent with results from numerous studies conducted in Europe [23–27] and worldwide [28–30].

The obtained results confirm, among others, the observations of [31], who studied the microclimate in historic buildings. These authors indicated that replacing windows with airtight ones (PVC) without simultaneously modernizing the natural ventilation system drastically reduces the infiltration air flow, leading to an increase in CO<sub>2</sub> concentration above 2000 ppm already in the first lesson hour. A similar effect of “thermal tightness” in historic buildings after partial thermal modernization was also described by [32–34].

The fact that concentrations of 4025 ppm were recorded in room 120 with mechanical ventilation is reflected in studies [35,36]. These researchers showed that the mere presence of mechanical systems in classrooms does not guarantee success if they are poorly designed (with too low airflow per person) or turned off by teachers due to noise or perceived draft. According to ASHRAE [37] and European standards [12,19], the minimum airflow should be approximately 10 l/s per person, which, considering the small volume of classroom 120 (82.5 m<sup>3</sup>) and 30 students, was physically impossible to achieve without a high air exchange rate.

The observed lack of a direct linear correlation between instantaneous CO<sub>2</sub> concentration and the number of reported acute symptoms (headaches, drowsiness) should not be interpreted as evidence of negative health impacts from pollution. Rather, it stems from the methodological limitations of subjective sensory assessment under conditions of slow, gradual carbon dioxide accumulation in the classroom setting. These results indicate that occupants’ subjective perceptions do not accurately and immediately reflect actual deterioration of indoor air quality, which aligns with classical theories of sensory and olfactory adaptation by Fang, Clausen and Fanger [38]. Sensory responses to clean air and air polluted by building materials were studied across different temperature (18–28 °C) and humidity (30–70%) ranges. Statistical correlation analysis confirmed that air temperature had the strongest and most direct impact on students’ discomfort ( $p < 0.05$ ). This supports the thesis, common in the psychophysics of comfort, that people subconsciously associate the feeling of stuffiness and lack of freshness with room overheating, which results from the biological lack of receptors that directly respond to CO<sub>2</sub> concentration [37,38].

It should be emphasized, however, that the absence of subjective discomfort does not mean the absence of negative effects on the body. Studies [9] have shown that even at CO<sub>2</sub> concentrations of 2500 ppm, a drastic decline in decision-making abilities and strategic thinking (by as much as 40–50%) is observed, despite subjects’ subjective ratings of well-being as “tolerable.” This is consistent with our results, in which students, despite poor measurement results, reported overall good learning experiences in the classroom. The conclusion that temperature (and not CO<sub>2</sub>) was the primary factor determining students’ comfort is consistent with Fanger’s thermal comfort models (PMV/PPD) and research [39]. These findings indicate that humans lack receptors that directly detect carbon dioxide concentration, meaning they subconsciously associate any “stuffy” situation with room overheating.

### 4.1. Future Research

Carrying out similar measurements in May/June, when windows are constantly open (natural ventilation works differently), would allow for an assessment of the impact of seasonality on indoor air quality.

Conducting an experiment—instructing teachers to intensively ventilate classrooms for the full 10 min of each break and measuring how quickly CO<sub>2</sub> concentration returns to critical values once the lesson begins.

It would certainly be necessary to conduct microbiological tests and suspended dust tests (PM<sub>2.5</sub> and PM<sub>10</sub>), which are a major problem in Warsaw in winter.

In the context of further research, a key step should be the implementation of a methodology based on direct, objective assessments of students' cognitive functions (such as standardized tests of attention, working memory, and coordination). Replacing or supplementing subjective, declarative surveys with hard indicators of intellectual performance will allow for a precise separation of the microclimates' actual impact from users' sensory adaptation.

#### 4.2. Limitations

During correlation analysis, we observed that students who stayed in the classroom for long periods did not “feel” the high CO<sub>2</sub> concentration (unlike someone entering from outside). This limits subjective survey methods for assessing absolute air quality.

The fact that students simultaneously indicated that it was “too dry” and “too humid” suggests that young people have difficulty correctly interpreting air humidity. This is a significant methodological limitation of the research tool.

The results reflect an extreme adverse scenario, not an average one-year scenario.

We had no influence on whether a given window in the tested room was ajar, whether the door to the corridor was open, or what the exact metabolic activity of the students was (a quiet lesson or a lesson with lively discussion).

The analysis focuses on classrooms in a single historic technical school building in Warsaw. The wall structure (the thick brickwork of the old building), volume, and technical condition are specific to this building, making it difficult to directly translate the results to contemporary school buildings.

### 5. Conclusions

The present results constitute a case study and refer to the specific characteristics of a single historic school building in Warsaw. However, they allow for the following general conclusions:

Based on the conducted research on selected air parameters and the analysis of surveys among technical school students, the following conclusions were drawn. First and foremost, significant inefficiency was observed in mechanical and natural ventilation. Current solutions are either ineffective or poorly managed, given the number of students currently assigned to classrooms. In most classrooms, permissible CO<sub>2</sub> concentrations are exceeded halfway through the lesson, and sometimes even from the beginning. This condition classifies these rooms in the worst category according to the PN-EN 16798-1:2019-06 standard [19]. The results of this case study allow for the formulation of categorical conclusions regarding implementation. A key practical recommendation is the absolute exclusion of extremely small classrooms (less than 90 m<sup>3</sup>, e.g., a 120-person classroom) from traditional teaching where group sizes exceed 10 people. The dynamics of biocontaminant accumulation in such a small space make it impossible to ensure safe learning conditions, even with basic ventilation systems in place. The conditions in the so-called professional wing are particularly disturbing, with an average CO<sub>2</sub> concentration of 2629 ppm, which clearly deviates from other average values and suggests a serious problem with air exchange, insulation from the rest of the building, and the construction and installation solutions used. Another significant finding is a serious problem with elevated temperatures despite the heating being turned off. Average temperatures of 24–26 °C exceed comfort standards

during the heating-winter season, suggesting inadequate ventilation and insulation of the building envelope. The building is highly energy-efficient in terms of heat loss, but completely dysfunctional in terms of hygiene. Survey studies have revealed the occurrence of symptoms typical of sick building syndrome (SBS), such as drowsiness and difficulty concentrating. A statistically significant correlation was found between these symptoms and deteriorating parameters of the classroom's internal environment.

At the same time, a phenomenon of students becoming accustomed to poor conditions was observed, whose answers often did not reflect the actual classroom situation; e.g., students reported feeling comfortable learning when the CO<sub>2</sub> concentration was high.

The parameter with the greatest and most clear impact on student experiences was temperature. A strong correlation was observed between increased temperature, decreased comfort and an increased frequency of reporting negative symptoms.

At the same time, a significant paradox related to carbon dioxide was observed. Unusually, there was no correlation between rising CO<sub>2</sub> concentrations and the frequency of reporting specific complaints, such as headaches or drowsiness, confirming that students are accustomed to poor conditions. However, rising CO<sub>2</sub> concentrations were clearly associated with a decline in indoor comfort. Students responded to the deteriorating conditions by leaning toward neutral assessments of the situation while avoiding extremely negative statements. Responses regarding the impact of relative humidity were highly inconsistent. They were internally contradictory and did not allow for the observation of a relationship between this parameter's value and the feeling of comfort or specific symptoms. This indicates difficulties in correctly recognizing and interpreting humidity-related stimuli, making this parameter of limited use in assessing air quality.

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

**Funding:** This scientific project was financed within the framework of science research funds at Warsaw University of Life Sciences (SGGW), Institute of Environmental Engineering and Białystok University of Technology (WZ/WB-IIS/8/2026).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** Data included as raw data.

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

## Abbreviations

The following abbreviations are used in this manuscript:

|                   |                                                                                                      |
|-------------------|------------------------------------------------------------------------------------------------------|
| BMS               | Building Management Systems                                                                          |
| CO <sub>2</sub>   | Carbon Dioxide                                                                                       |
| IAQ               | Indoor Air Quality                                                                                   |
| NOAA              | National Oceanic and Atmospheric Administration                                                      |
| PM <sub>2.5</sub> | Particulate matter 2.5 microns or less in diameter                                                   |
| PM <sub>10</sub>  | PM <sub>10</sub> is a mixture of particles suspended in the air whose diameter does not exceed 10 µm |
| WHO               | World Health Organization                                                                            |

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