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Original Research Article

INDOOR ENVIRONMENTAL QUALITY AND STUDENT PERFORMANCE IN NATURALLY VENTILATED CLASSROOMS

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A b s t r a c t

Measurements of indoor air constituent concentrations and thermal parameters were conducted in three naturally ventilated classrooms during the heating season using low-cost sensors. The presence of students significantly affected indoor air composition and microclimatic conditions, leading to elevated CO_2 levels and higher concentrations of selected pollutants. During lessons, the acceptability of indoor air quality (ACC) decreased, while the percentage of dissatisfied students (PD), determined based on ACC, increased. The newly developed 10-point Indoor Environmental Quality Index (IEQI), integrating both indoor air quality and thermal conditions, and relative work performance (RWP) also deteriorated. The poorest indoor environmental conditions were observed in the classroom with the oldest students, likely due to their physiological maturation and increased use of personal care products, both contributing to higher emissions. In this classroom, the average IEQI reached 3.0 during lessons, ACC dropped to 0.4, PD rose to 23 %, and RWP decreased by nearly 4 % compared to ideal indoor conditions. Real-time IEQI tracking provides valuable insights into air quality and thermal conditions trends, supporting more effective ventilation or air-conditioning strategies and enhancing student well-being and performance.

Keywords: classroom, indoor air quality, thermal conditions, indoor environmental quality, student performance

1. INTRODUCTION

The quality of the indoor environment (IEQ), which comprehensively defines the conditions inside a room, is primarily influenced by indoor air quality (IAQ), thermal conditions as well as by lighting and acoustic conditions [1]. IAQ is determined by indoor air pollutants which include gaseous pollutants (e.g. VOCs, inorganic compounds), particulate matter (PM) and bioaerosols (biological elements), which, when inhaled, can negatively impact the health of room occupants [2]. The main parameters used

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to assess thermal conditions (TC) determining thermal comfort in rooms are temperature (T), relative humidity (RH) and air velocity. Ventilation characteristics also play an important role. The assessment of lighting is closely related to light intensity, color, and lighting uniformity [3], while the evaluation of acoustic quality is linked to the noise level in the room [4, 5].

Due to the complexity of IEQ, various definitions and terms for it can be found in the literature. Often, the concepts of IEQ, IAQ and TC are used interchangeably. Numerical indices are commonly used to assess IEQ calculated based on the values of indoor environmental parameters that significantly impact it. These indices are developed for specific indoor environments such as offices, residences, classrooms, medical rooms, and public transport. For example, Burek et al. [6] proposed the AKC index to evaluate the microclimate of educational and office spaces. The IAQ index based on the concentration of typical pollutants in air-conditioned offices such as total volatile organic compounds (TVOCs), CO_2, CH_2O, radon (Rn), PM, bacteria as well as T, RH and air velocity was presented by Wong et al. [7]. Wang et al. [8] defined an IAQ index based on the concentration of 11 pollutants in various types of buildings. Their methodology followed the US EPA's ambient air quality index formula [9]. Sarbu and Pacurar [10] assessed IAQ in university classrooms according to the European Standard CEN CR 1752 [1]. Pereira et al. [11] evaluated the environmental quality in school classrooms based on subjective surveys and Fanger's comfort indices such as the predicted mean vote (PMV) and predicted percentage of dissatisfied people (PPD) [12]. Mainka and Zajusz-Zubek [13] calculated IAQ indices in classrooms based on measurements of PM and CO_2 comparing the measured concentrations with relevant WHO guideline values. The IEQ index based on environmental parameters such as indoor air temperature, lighting intensity, noise level, CO_2, CH_2O and PM_{10} concentrations, which also considered users' subjective satisfaction and reported health symptoms, was presented by Li et al. [14]. Koufi et al. [15] evaluated IAQ in a ventilated room through computer simulations using the difference between the average CO_2 concentration in the room and the exhaust air concentration as the quality indicator. Piasecki and Kostyrko [16] determined the IAQ index using the MADM decision model incorporating concentrations of six typical pollutants and assigning subjective or objective weights. This index was part of a broader IEQ index that also considered TC, acoustic comfort, and daylight quality. The index method based on assigned weighted coefficients for measured concentrations of typical pollutants and phthalic acid esters (PAEs) was used by Sun et al. [17] to assess air quality in residential buildings.

Numerous previous studies have shown that low IEQ is associated with increased health risks, decreased well-being, and reduced work and learning performance among building occupants [18–20]. This is particularly relevant in schools where children and adolescents spend the majority of their time [21,22]. However, quantitatively assessing the influence of IEQ and individual indoor environmental parameters on student academic performance remains a complex and unresolved challenge. It is still unclear which parameters have the greatest influence and how they interact, especially since even optimal indoor conditions may not guarantee better learning outcomes [23]. As a result, IEQ requirements for educational facilities have not yet been clearly defined in legal regulations. In most cases, general WHO guidelines on indoor air pollution levels and thermal condition parameters for occupied spaces are applied [24].

The main objective of this study was to analyze changes in indoor environmental quality (IEQ) in classrooms occupied by students of different age groups. The analysis was based on a newly developed IEQ index that integrates the impact of typical indoor air pollutants and thermal condition parameters. The study also explores the potential use of this index as a practical tool for improving ventilation or air-conditioning control in classroom settings. Furthermore, it aimed to assess how the acceptability of air quality in classrooms varies and how these variations could influence student performance.

2. METHODS

2.1. Measurement site

Air pollutant concentrations and thermal condition parameters were measured over a two-week period during the heating season in three naturally ventilated classrooms at an elementary school in Lublin, eastern Poland. The school building, over 100 years old and three stories high, underwent thermal modernization at the beginning of the 21st century. The renovation included wall insulation and the replacement of old, leaky windows. The building is heated by a central heating system connected to the municipal district heating network. Panel radiators with thermostatic valves linked to a heat exchange unit are installed in classrooms and corridors. During the measurement period radiators were set to maintain an indoor temperature of 20 °C.

2.2. Classroom characteristics

The measurements were carried out in three selected classrooms located on the second floor. The classrooms were cuboidal in shape, each with three double-glazed windows, and had identical dimensions of 7.5 m × 6.5 m × 3.5 m (length × width × height). Each classroom was equipped with a teacher's desk, student tables, and chairs for 24 students (Figure 1). In each classroom, natural ventilation occurred through air infiltration via the windows and the door, with air being discharged through two rectangular ventilation grilles (0.15 m × 0.20 m) installed on the interior wall near the ceiling. These grilles were connected to a ventilation duct. The classrooms were used for various subjects throughout the day.

Classroom 1 was designated for students in grades IV–VIII with a maximum of two lessons per day held for the same group. Classroom 2 was occupied by students in grades I–III, who had all of their lessons in that room. Classroom 3 was used by kindergarten children (grade 0), who spent nearly the entire school day there.

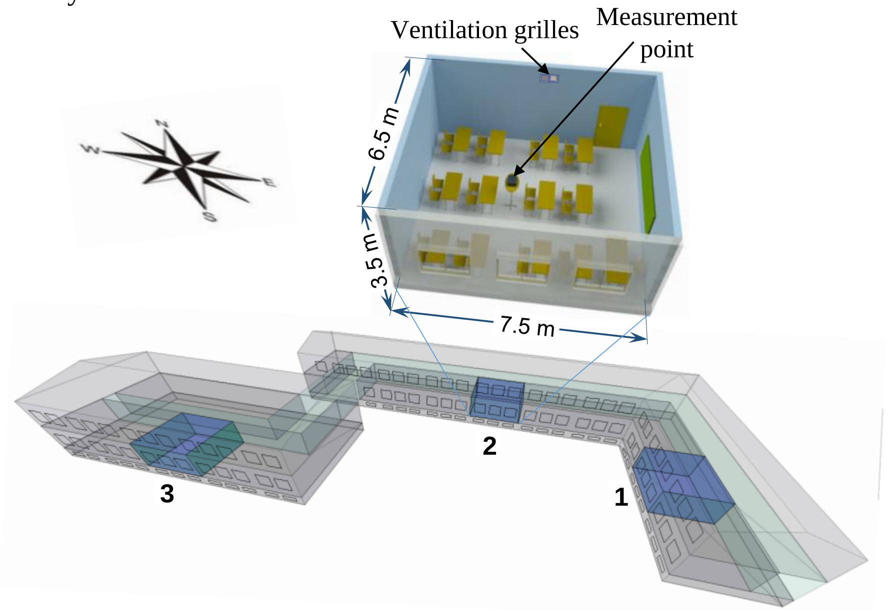

Fig. 1. Schematic view of the school building showing the monitored classrooms on the second floor. Numbers 1, 2, and 3 indicate Classroom 1 (grades IV–VIII), Classroom 2 (grades I–III), and Classroom 3 (kindergarten), respectively. The locations of the ventilation grilles and the measurement point in each classroom are also shown.

2.3. Classroom occupation and ventilation

Classroom lessons lasted 45 minutes and were typically separated by 5-minute breaks. They were conducted according to a fixed schedule from Monday to Friday, usually between 8:00 a.m. and 4:00 p.m. A comparable number of students participated in lessons and activities across all three classrooms. Ventilation was infrequent and, when applied, was generally limited to slightly opening the windows. This practice occurred almost exclusively during breaks and only sporadically during lessons. Such limited and irregular ventilation likely contributed to the accumulation of indoor air pollutants and the deterioration of thermal condition parameters during periods of student occupancy.

2.4. Measurements and data analysis

The measurements were conducted using a set of calibrated low-cost sensors placed in the central part of each classroom, at a height of 1.1 m above the floor. These sensors continuously measured and recorded, at 1-minute intervals, the concentrations of indoor air pollutants ($PM_{2.5}$, PM_{10}, CH_2O, VOCs) and CO_2 (as an occupancy/ventilation indicator), as well as indoor air temperature (T) and relative humidity (RH). The technical specifications provided by the sensor manufacturers are summarized in Table 1.

Table 1. Summary of sensor specifications

Parameter	Sensor model	Measurement range	Accuracy	Resolution
CO_2	Figaro CDM7160	300–5000 ppm	±50 ppm + 3 % of reading	1 ppm
$PM_{2.5}$ / PM_{10}	Plantower PMS5003	0–500 μg/m³	±10 μg/m³ (0–100 μg/m³); ±10 % (100–500 μg/m³)	1 μg/m³
CH_2O	Mambrapor CH2O-C-10	0–10 ppm	±0.1 ppm	0.01 ppm
VOCs	Alphasense PID-AH2	0–50 ppm	±3 % of reading	1 ppb
Temperature (T)	Bosch BME280	−40 – +85 °C	±0.5 °C (0–65 °C); ±1.25 °C (−20–0 °C); ±1.5 °C (−40 – −20 °C)	0.01 °C
Relative humidity (RH)	Bosch BME280	0–100 %	±3 % (20–80 %)	0.008 %

Note: All sensors were factory-calibrated and additionally verified against reference instruments prior to the measurement campaign.

Based on the recorded data, the indoor environment quality index (IEQI) was calculated in real-time for each classroom. This index, expressed on a 10-point scale, was determined using Equation (2.1) as the arithmetic mean of the indoor air quality index (IAQI) and the thermal conditions index (TCI):

$$\mathrm{IEQI} = \frac{\mathrm{IAQI} + \mathrm{TCI}}{2} \tag{2.1}$$

In calculating the IAQI, the methodology developed by the U.S. Environmental Protection Agency for the outdoor air quality index (AQI) was applied and adapted for indoor conditions [8]. For each measured indoor air constituent (p) whose concentrations were recorded every minute in the monitored classrooms the individual pollutant index ($IAQI_p$) was calculated in real-time using a linear interpolation formula, as shown in Equation (2.2):

$$IAQI_p = \frac{(C_p - C_l) \cdot (I_h - I_l)}{(C_h - C_l)} + I_l \quad (2.2)$$

where C_p is the measured concentration of indoor air constituent p, C_l is the concentration breakpoint less than or equal to C_p, I_l is the index value corresponding to C_l, C_h is the concentration breakpoint greater than or equal to C_p, and I_h is the index value corresponding to C_h.

Table 2. Breakpoints for indoor air constituent concentrations (C_l–Ch) and their corresponding index values (I_l–I_h) along with the assigned indoor air quality (IAQ) categories

CO_2 [ppm]	$PM_{2.5}$ [µg/m^3]	PM_{10} [µg/m^3]	CH_2O [ppb]	VOC [ppm]	I_l–I_h	IAQ category
C_l–C_h						
0–400	0–10	0–15	0–30	0–0.05	0–1	Good
400–600	10–20	15–25	30–50	0.05–0.1	1–2	
600–1000	20–30	25–40	50–75	0.1–0.2	2–3	Moderate
1000–1500	30–40	40–55	75–110	0.2–0.3	3–4	
1500–2000	40–50	55–75	110–150	0.3–0.5	4–5	Poor
2000–2500	50–60	75–95	150–200	0.5–0.8	5–6	
2500–3000	60–80	95–120	200–300	0.8–1.3	6–7	Unhealthy
3000–4000	80–100	120–150	300–500	1.3–2	7–8	
4000–5000	100–150	150–200	500–800	2–3	8–9	Hazardous
>5000	>150	>200	>800	>3	9–10	

The breakpoints for measured indoor air constituent concentrations, their corresponding index values and the assigned IAQ categories are presented in Table 2. When converting the concentration of a given indoor air constituent to $IAQI_p$ values, a 10-point scale from 0 to 10 was applied. IAQ categories reflect increasing levels of health concern with rising concentrations of the measured constituent in indoor air and were classified as follows: Good (0-2), Moderate (2-4), Poor (4-6), Unhealthy (6-8), and Hazardous (8-10).

For a given time, the arithmetic mean of all $IAQI_p$ values calculated for the five air constituents was considered as the indoor IAQI value, as shown in Equation (2.3):

$$IAQI = \frac{\sum IAQI_p}{5} \quad (2.3)$$

In determining the TCI the acceptability of air quality (ACC) was used with values ranging from -1 (not acceptable air quality) to +1 (acceptable air quality). Based on the ranges of temperature and relative humidity measured in the classrooms, ACC was calculated using Equation (2.4):

$$ACC = aT + bRH + c + \varepsilon \quad (2.4)$$

where a, b, c are empirical constants determined separately for each classroom (Table 3) and ε represents the random error term accounting for unmodeled variations and measurement uncertainties.

Table 3. Empirical constants (a, b, c) used to calculate the acceptability of air quality (ACC)

Classroom	Empirical constant		
	a	b	c
1	-0.0487	-0.0124	2.0139
2	-0.0487	0.0038	1.4040
3	-0.0487	-0.0069	1.8976

The calculated ACC values were then used to determine the percentage of dissatisfied students (PD) according to Burek et al. [25], as shown in Equation (2.5):

$$PD = \frac{100}{1 + \exp(3.15 \cdot ACC + 0.043)} \tag{2.5}$$

The resulting PD values were divided by 10 to obtain the TCI value, which is expressed on a 10-point scale from 0 (very good thermal comfort) to 10 (very poor thermal comfort).

The relative work performance (RWP), which is influenced by the ACC, and the associated productivity loss (PL) were estimated using Equations (2.6) and (2.7) [26]:

$$RWP = 0.0983 \cdot ACC + 0.926 \tag{2.6}$$

$$PL = 1 - RWP \tag{2.7}$$

The formulas presented above were applied under the assumption that the indoor environmental conditions in the classrooms continuously affected the students during the monitoring period.

Descriptive statistics were used to characterize changes in indoor environmental conditions in the monitored classrooms as well as the comfort levels and student performance.

3. RESULTS

3.1. Indoor air pollutant levels and microclimate parameters

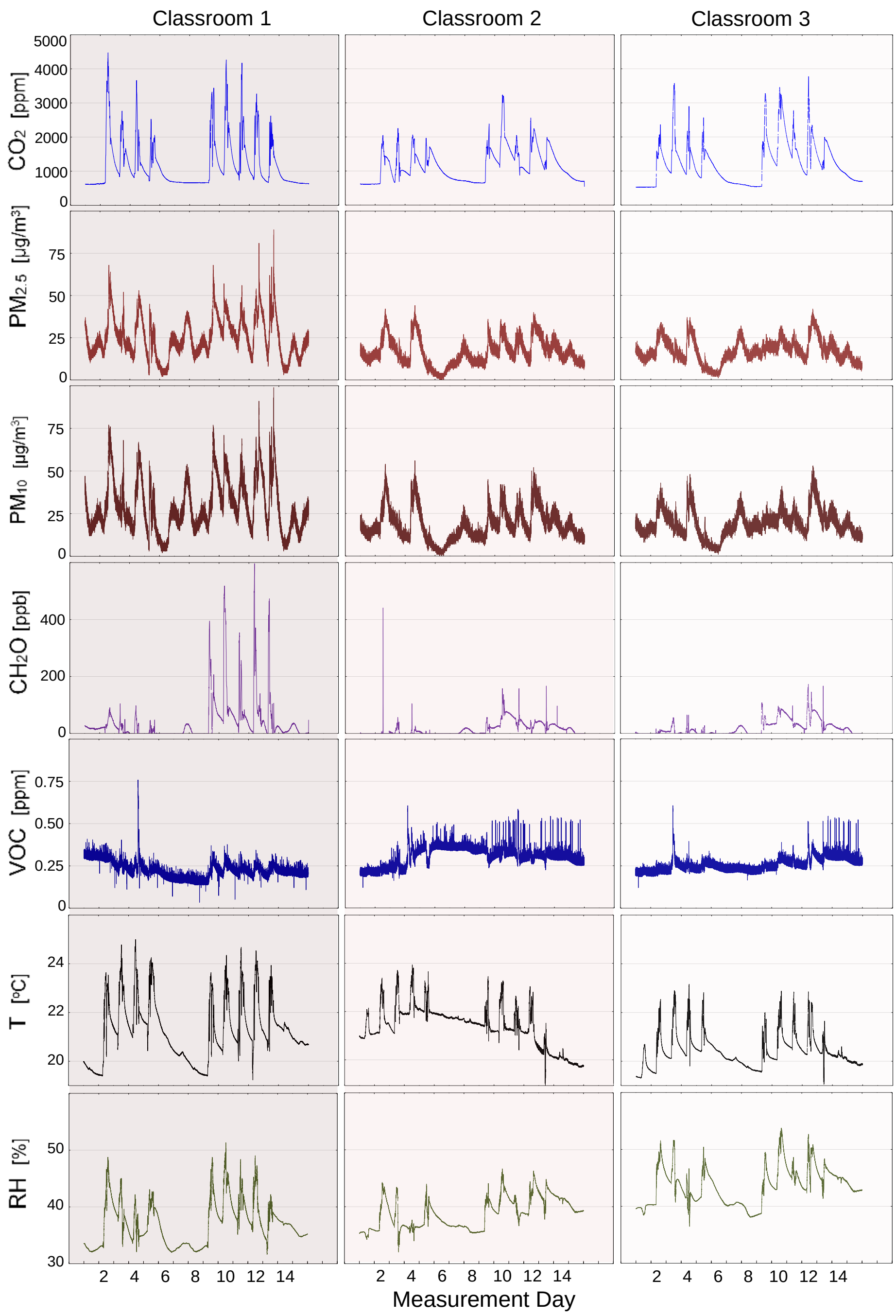

Fig. 2. Changes in the concentrations of CO_2, $PM_{2.5}$, PM_{10}, CH_2O, VOCs, and values of temperature (T) and relative humidity (RH) in the monitored classrooms over the measurement period

Graphs illustrating changes in the concentrations of CO_2, $PM_{2.5}$, PM_{10}, CH_2O, VOCs along with T and RH recorded in the monitored classrooms over the course of the study are shown in Figure 2. It can be observed that in all classrooms, on the days when lessons or activities took place, concentrations of these air constituents, as well as T and RH, noticeably increased when students entered the rooms and began their scheduled classes, typically around 8 a.m. The highest levels of these parameters during the day were generally observed towards the end of classroom occupancy which most often occurred around 4 p.m. The most dynamic fluctuations and the highest values for almost all parameters were recorded in Classroom 1, which, according to the school schedule, was regularly used by the oldest group of students.

Table 4 presents descriptive statistics for the concentrations of indoor air constituents, T, and RH in the classrooms during lessons/activities, nights (10 p.m. to 6 a.m.), and throughout the entire measurement period.

Table 4. Descriptive statistics for CO_2, $PM_{2.5}$, PM_{10}, CH_2O, and VOCs concentrations, temperature (T), and relative humidity (RH) in the classrooms during lessons/activities (8:00 a.m.–4:00 p.m.), nights (10 p.m.–6 a.m.), and the entire monitoring period; n represents the number of measurements in each classroom

Parameter	Classroom 1	Classroom 2	Classroom 3
	Lessons/activities		
	n=4214	n=4227	n=4098
CO_2 [ppm]	2312/2216 (32)	1695/1698 (29)	2006/1861 (32)
$PM_{2.5}$ [µg/m^3]	35.4/35.0 (27.1)	21.5/22.0 (40.0)	20.1/20.0 (35.2)
PM_{10} [µg/m^3]	42.8/43.0 (30.6)	24.2/24.0 (42.0)	22.5/22.0 (35.7)
CH_2O [ppb]	109.3/63.0 (119)	25.9/17.0 (132)	35.1/27.0 (101)
VOC [ppm]	0.25/0.25 (19.4)	0.30/0.30 (17.8)	0.28/0.27 (17.2)
T [°C]	23.0/23.1 (3.8)	22.2/22.3 (4.0)	21.4/21.4 (3.3)
RH [%]	41.8/41.5 (8.4)	40.3/40.8 (7.0)	46.4/46.5 (6.7)
	Nights		
	n=6802	n=6835	n=6675
CO_2 [ppm]	858/868 (22)	1035/995 (29)	1027/1020 (36)
$PM_{2.5}$ [µg/m^3]	21.7/21.0 (35.7)	15.5/16.0 (39.3)	17.1/17.0 (34.9)
PM_{10} [µg/m^3]	24.3/23.0 (38.7)	16.8/17.0 (39.6)	18.8/19.0 (35.4)
CH_2O [ppb]	18.1/16.0 (104)	15.7/7.0 (122)	17.9/7.0 (122)
VOC [ppm]	0.22/0.21 (18.3)	0.32/0.32 (17.4)	0.26/0.25 (13.9)
T [°C]	20.8/20.9 (3.4)	21.2/21.3 (3.2)	20.2/20.2 (1.7)
RH [%]	35.8/35.8 (6.5)	38.5/38.7 (5.8)	43.0/43.3 (5.6)
	Entire monitoring		
	n=21386	n=21513	n=21008
CO_2 [ppm]	1175/896 (61)	1156/1048 (41)	1217/1103 (52)
$PM_{2.5}$ [µg/m^3]	25.2/23.0 (46.4)	16.3/15.0 (48.3)	17.0/16.0 (40.5)
PM_{10} [µg/m^3]	29.2/25.0 (51.8)	18.0/16.0 (50.8)	18.9/18.0 (41.1)
CH_2O [ppb]	39.3/17.0 (195)	15.6/5.0 (148)	19.3/8.0 (136)
VOC [ppm]	0.23/0.22 (21.6)	0.31/0.31 (18.3)	0.26/0.25 (15.7)
T [°C]	21.3/21.2 (5.7)	21.4/21.5 (4.0)	20.4/20.3 (3.3)
RH [%]	37.0/36.8 (10.5)	38.8/38.8 (6.9)	43.6/43.5 (7.4)

Arithmetic average/median (coefficient of variation)

ANOVA test results indicated that during lessons in Classroom 1, the mean concentrations of all measured pollutants and the mean values of T and RH were significantly higher ($p < 0.001$) than those in Classrooms 2 and 3. Moreover, average concentrations of certain indoor air constituents exceeded the levels recommended by the World Health Organization (WHO 2010) for indoor environments. For example, mean CO_2 concentrations during lessons were more than 2.3 times higher than the recommended 1000 ppm threshold in Classroom 1, almost 1.7 times higher in Classroom 2, and over 2 times higher in Classroom 3. Notably, even during nights, mean CO_2 concentrations remained above acceptable levels in Classrooms 2 and 3 and were only slightly below in Classroom 1 (858 ppm). The highest CO_2 concentration recorded in Classroom 1 exceeded 4000 ppm. In the same classroom, the mean concentrations of particulate matter and VOCs also exceeded the maximum levels recommended by WHO, which are 10 μg/m³ for $PM_{2.5}$, 25 μg/m³ for PM_{10}, and 0.062 ppm for VOCs. The greatest excess levels were observed during lessons and activities. In the case of $PM_{2.5}$ and VOCs, their mean concentrations were more than 3.5 and 4 times higher, respectively, than the acceptable limits. Also in Classroom 1 during lessons the mean CH_2O concentration exceeded its short-term (30-minute) permissible level of 81.43 ppb. This level was occasionally exceeded in the other two classrooms as well. In contrast, the average values of T and RH in all classrooms remained within WHO-recommended ranges for office environments, i.e., between 20–26 °C and 30–60 %, respectively.

3.2. IEQ and student comfort and productivity

Changes in the values of the real-time calculated IEQI, ACC, PD, RWP, and PL in the monitored classrooms are presented in Figure 3, Figure 4, and Figure 5. Marked fluctuations in these indicators can be observed during periods of student occupancy, with noticeable differences in these patterns between classrooms.

Descriptive statistics relating to values of IEQI, ACC, PD, RWP, and PL in the classrooms during lessons/activities, nights, and over the entire monitoring period are presented in Table 5. This table provides mean values, standard deviations, medians, and maximum values of these parameters.

During lessons in Classroom 1, the values of all assessed indicators differed significantly ($p < 0.001$) from their respective means in Classrooms 2 and 3. Figure 6 shows the values of IEQI, ACC, PD, RWP, and PL in the classrooms during lessons and nights. Night-time values of ACC, PD, RWP, and PL are reported as a reference for classroom conditions without occupancy, illustrating how these indicators would behave if students were present under the same environmental conditions.

It is evident that the most unfavorable values of the considered parameters occurred during periods of student occupancy. Lesson or activity periods were almost always characterized by the lowest acceptability of indoor air quality and the highest percentage of dissatisfied students. The highest mean value of IEQI, amounting to 3.0 and indicating the worst indoor environmental quality was observed in Classroom 1 during lessons. In the other two classrooms the mean IEQI values during lessons or activities were around 2. In Classroom 1 the mean ACC during lessons was 0.4, and the mean PD reached 23 %. In Classrooms 2 and 3 during lessons or activities the mean ACC values were 0.5, while the mean PD values were 17.6 % and 15.1 %, respectively. The values of the above parameters directly affect the working conditions of teachers and the learning effectiveness of students. During lessons or activities, the mean value of RWP was lower than at nights, and in Classroom 1, this difference reached up to 2 %. Compared to ideal indoor environmental conditions, the mean value of RWP in Classroom 1 during lessons was almost 4% lower. In the case of PL the relationships were reversed and as expected the highest decrease in student productivity (PL = 3.7 %) was also recorded in Classroom 1 during lessons.

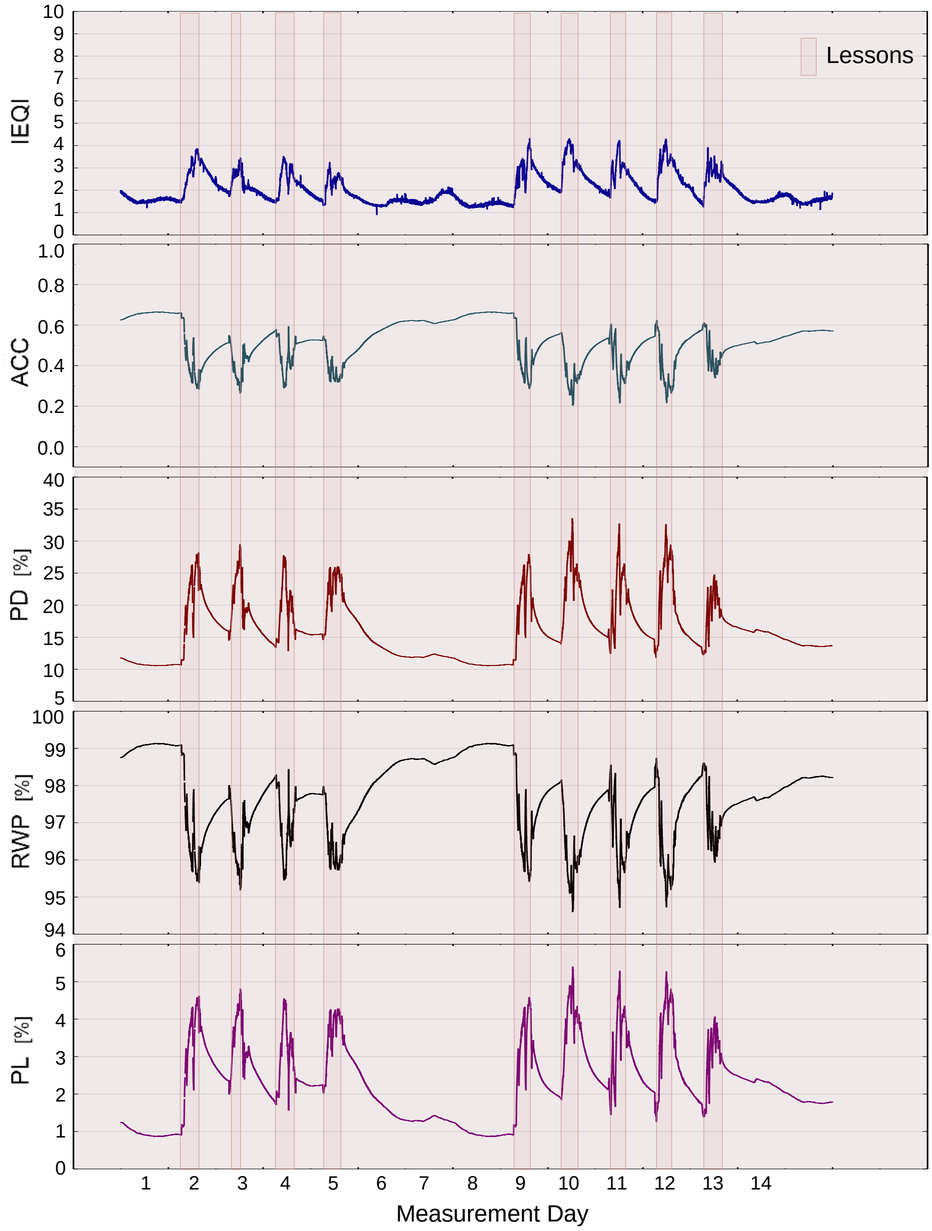

Fig. 3. Changes in the indoor environment quality index (IEQI), acceptability of air quality (ACC), percentage of dissatisfied students (PD), relative work performance (RWP), and productivity loss (PL) in Classroom 1

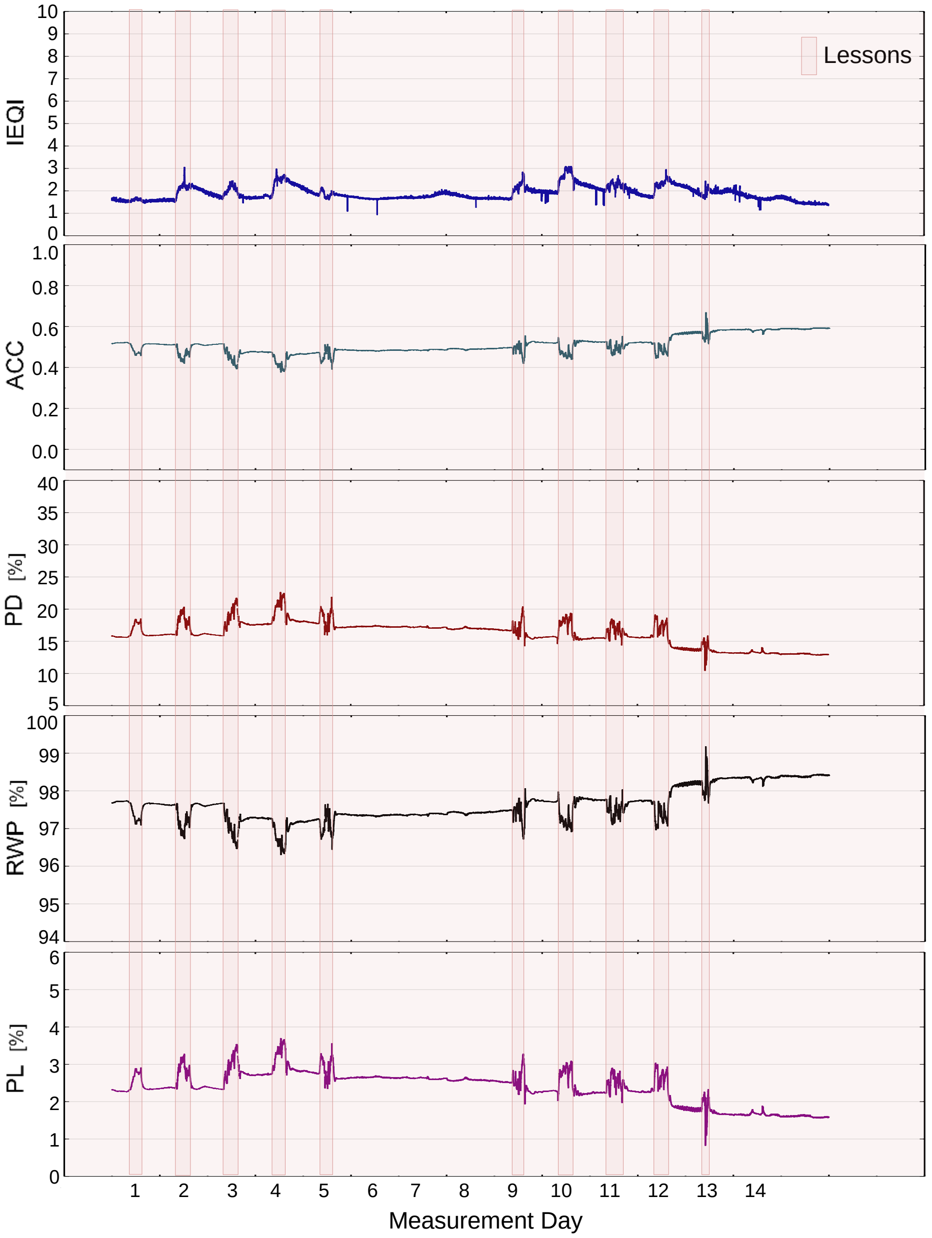

Fig. 4. Changes in the indoor environment quality index (IEQI), acceptability of air quality (ACC), percentage of dissatisfied students (PD), relative work performance (RWP), and productivity loss (PL) in Classroom 2

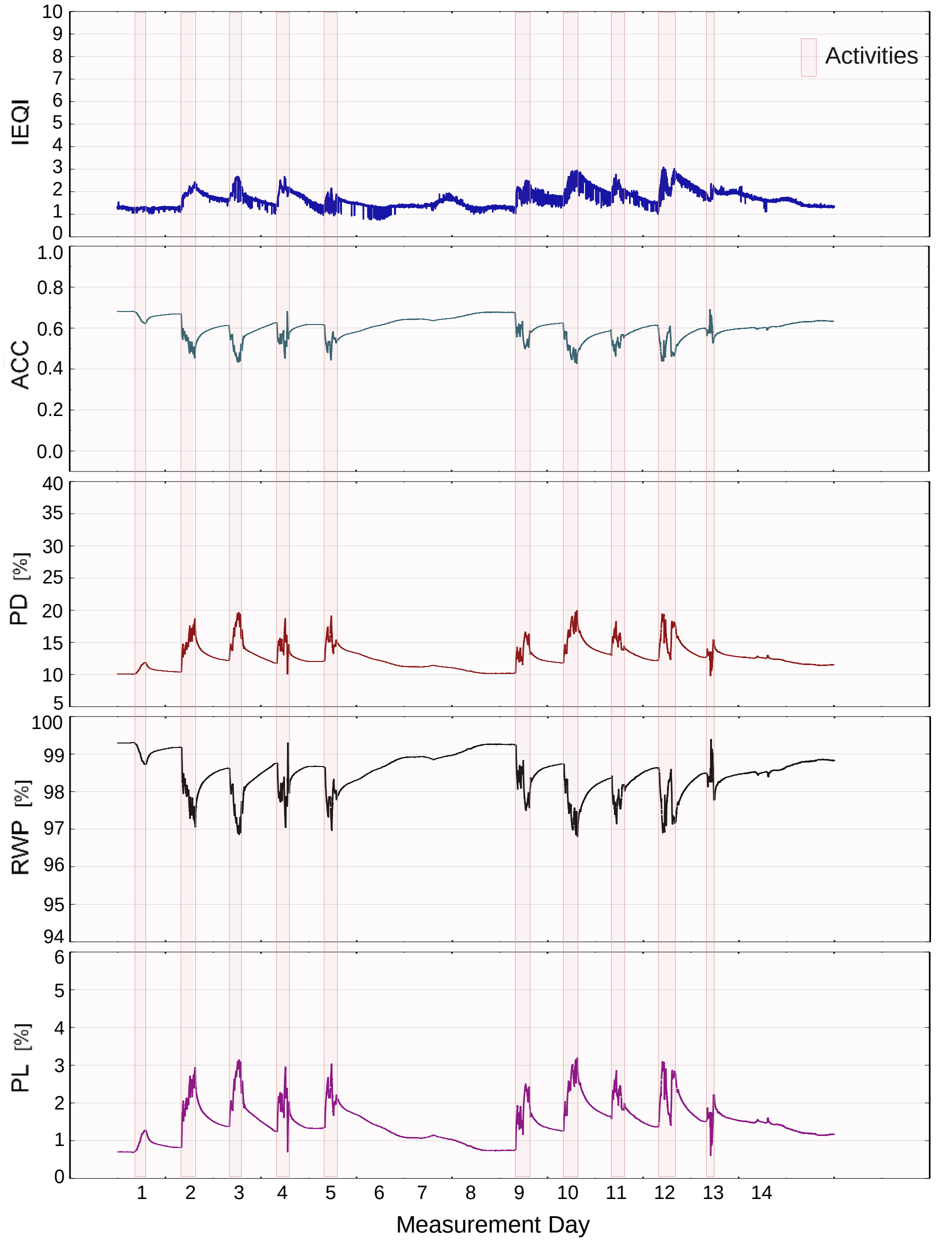

Fig. 5. Changes in the indoor environment quality index (IEQI), acceptability of air quality (ACC), percentage of dissatisfied students (PD), relative work performance (RWP), and productivity loss (PL) in Classroom 3

Table 5. Descriptive statistics for indoor environment quality index (IEQI), acceptability of air quality (ACC), percentage of dissatisfied students (PD), relative work performance (RWP), and productivity loss (PL) in the classrooms during lessons/activities (8:00 a.m.–4:00 p.m.), nights (10 p.m.–6 a.m.), and the entire monitoring period; n represents the number of measurements in each classroom

Indicator	Classroom 1	Classroom 2	Classroom 3
	Lessons/activities		
	n=4207	n=4213	n=4098
IEQI	3.0 (0.5) 3.0/4.3	2.2 (0.3) 2.2/3.1	2.1 (0.4) 2.1/3.1
ACC	0.4 (0.1) 0.4/0.5	0.5 (0.05) 0.5/0.7	0.5 (0.05) 0.5/0.7
PD [%]	22.9 (3.9) 23.2/33.5	17.6 (2.1) 17.8/22.6	15.1 (1.9) 14.9/20.0
RWP [%]	96.3 (0.7) 96.2/98.4	97.3 (0.4) 97.2/99.2	97.9 (0.5) 97.9/99.4
PL [%]	3.7 (0.7) 3.8/5.4	2.7 (0.5) 2.8/3.7	2.1 (0.5) 2.1/3.2
	Nights		
	n=6802	n=6823	n=6675
IEQI	1.8 (0.3) 1.7/2.6	1.8 (0.2) 1.8/2.4	1.6 (0.3) 1.6/2.5
ACC	0.6 (0.1) 0.5/0.7	0.5 (0.04) 0.5/0.6	0.6 (0.03) 0.6/0.7
PD [%]	14.3 (2.2) 14.8/18.5	15.8 (1.6) 16.0/18.2	12.1 (1.0) 12.1/14.2
RWP [%]	98.1 (0.6) 97.9/99.1	97.7 (0.4) 97.6/98.4	98.7 (0.3) 98.6/99.3
PL [%]	1.9 (0.6) 2.1/2.9	2.3 (0.4) 2.4/2.8	1.3 (0.3) 1.4/1.9
	Entire monitoring		
	n=21386	n=21513	n=21008
IEQI	2.0 (0.7) 1.8/4.3	1.9 (0.3) 1.8/3.1	1.7 (0.4) 1.6/3.1
ACC	0.5 (0.1) 0.5/0.7	0.5 (0.04) 0.5/0.7	0.6 (0.05) 0.6/0.7
PD [%]	16.1 (4.5) 15.4/33.5	16.2 (1.9) 16.5/22.6	12.7 (1.9) 12.4/20.0
RWP [%]	97.7 (1.0) 97.8/99.1	97.6 (0.4) 97.5/99.2	98.5 (0.5) 98.6/99.4
PL [%]	2.3 (1.0) 2.2/5.4	2.4 (0.4) 2.5/3.7	1.5 (0.5) 1.4/3.2

Arithmetic average (standard deviation) median/maximum

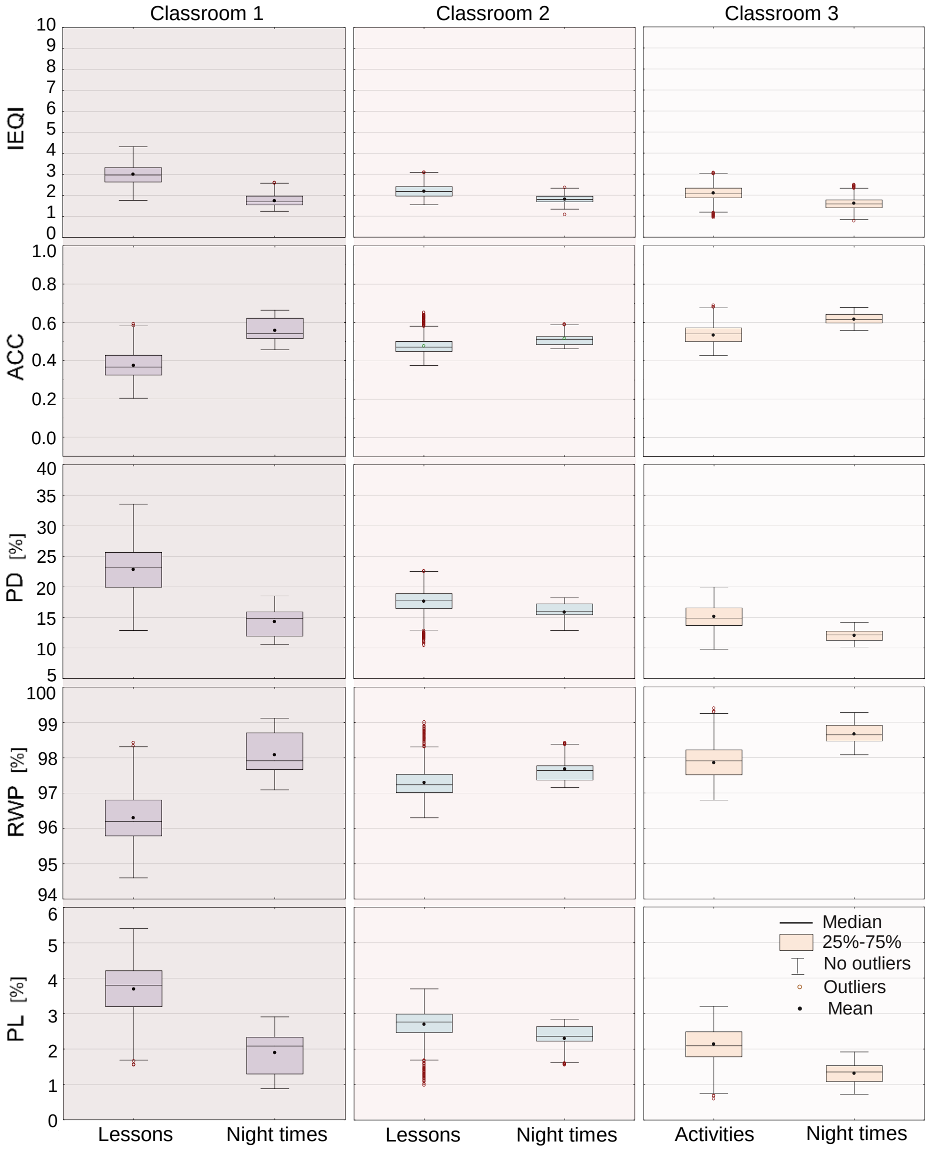

Fig. 6. Values of indoor environment quality index (IEQI), acceptability of air quality (ACC), percentage of dissatisfied students (PD), relative work performance (RWP), and productivity loss (PL) in the classrooms

The results presented clearly demonstrate that student presence in the classrooms during lessons or activities leads to a deterioration in both IAQ and TC, which in turn negatively affects the overall IEQ. ACC decreases, while the number of students dissatisfied with IAQ, as indicated by PD, increases. A consistent decrease in RWP is also observed, along with an increase in PL. Among the three monitored classrooms, the greatest deterioration in the analyzed parameters was recorded in Classroom 1, where lessons were held for the oldest student groups.

4. DISCUSSION

Environmental monitoring in schools is primarily conducted to assess indoor air quality, as well as to evaluate general environmental conditions that may affect student well-being, health, ability to concentrate, and effective knowledge acquisition. Findings from such monitoring efforts provide valuable insights that can support initiatives aimed at minimizing the negative effects of environmental factors and contribute to shaping evidence-based strategies for creating healthier and safer indoor learning environments for students as well as appropriate working conditions for teachers and other school personnel.

The subject of this study was the analysis of changes in indoor environmental quality in classrooms during lessons or activities and their impact on student performance. Continuous multi-parametric indoor air monitoring was conducted during the heating season in three classrooms of identical volume, all naturally ventilated and located on the same floor of the school building. The monitoring included several typical indoor air constituents such as CO_2, aerosol particles $PM_{2.5}$ and PM_{10}, and gaseous pollutants: CH_2O and VOCs. T and RH were also measured in the classrooms. The measured parameters served as the basis for calculating IAQI and TCI, which were then used to determine the overall IEQI. ACC and PD were also assessed, and these values were subsequently used to evaluate RWP and the related PL. It should be noted that no direct survey-based assessments or cognitive tests quantifying student academic performance or learning outcomes were conducted as part of this study.

The study confirmed quite common findings indicating that the presence of students over time deteriorates IEQ and thermal conditions in the classroom. During lessons not only CO_2 concentrations increased – due to students' breathing – but also concentrations of other air constituents associated with their presence in the classrooms. Moreover, even though thermostatic radiator valves were set at 20 °C, an increase in both temperature and relative humidity was observed during occupancy which likely impacted TC and students’ subjective sensations. According to the literature data, the combination of these factors tends to negatively affect student performance. This was also reflected in the observed decrease in RWP values and the corresponding increase in PL. It is worth emphasizing that the most unfavorable indoor environmental conditions exerting the greatest negative influence on student productivity were recorded in the classroom where lessons were held for the oldest students. This may have been related to more intense thermoregulation processes in this age group as well as hormonal changes associated with adolescence, potentially resulting in increased perspiration and thereby higher emissions of pollutants into the indoor air [27, 28]. Additionally, greater amounts of air pollutants emitted from personal care products may have contributed to these findings, given that older students more frequently use cosmetics, including antiperspirants and scented products intended to mask unpleasant body odors [29, 30].

Considering the complexity of the IEQ issue and its impact on building occupants, one must approach the results of studies on this topic with great caution, as full understanding is still far from being achieved. This also applies to the findings of this study. In the adopted approach, it was assumed – based on the applied formulas – that observed changes in IAQ and TC were the primary drivers of variations in student performance indicators (RWP and PL), although this assumption cannot be conclusively proven within the scope of the study. Regarding typical air pollutants affecting IAQ, numerous studies suggest that they can significantly impact comfort, well-being and, consequently, the performance of building occupants. For example, Wargocki and Wyon [31] stated that IAQ, which is generally accepted by most building occupants, can reduce overall performance by 5–10 % for adults and by 15–30 % for children. Mujan et al. [18], in their review, expressed the opinion that IAQ has the main impact on the health, comfort, and productivity of occupants in office and residential buildings.

Similar conclusions were drawn by Felgueiras et al. [32] who reported that better productivity levels were registered in conditions with good indoor air quality in terms of VOCs, airborne particles, and CO_2. In the context of educational environments Stafford [33] found that improving indoor air quality in schools was associated with better student performance on standardized math and reading tests. Wargocki et al. [21] based on their analyses of classroom IAQ proposed that reducing CO_2 concentrations from 2100 ppm to 900 ppm would improve performance on psychological tests and school tasks by 12 % in terms of task completion speed and by 2 % in terms of errors. On the other hand, Astolfi et al. [34] confirmed that bio-effluents, including TVOCs, are the primary cause of sickness due to unpleasant odors in classrooms and that air quality can be effectively controlled using CO_2 as an indicator. Pulimeno et al. [35] observed that students exposed to low air quality in classrooms performed worse on standardized tests assessing reading and mathematical abilities compared to students in healthy classroom environments.

Numerous studies have shown that thermal conditions, largely determined by indoor air temperature and humidity under normal working conditions, significantly influences the productivity of building occupants. According to Seppänen et al. [36] relative work performance can be estimated based on indoor air temperature which also affects ACC as shown in equation (2.2). It is important to note that in this approach the impact of indoor air pollutants is not taken into account which raises doubts and is criticized. Some researchers argue that the relationship proposed by Seppänen et al. [36] is inadequate for predicting work performance based solely on air temperature due to its low predictive power [37]. However, many studies confirm the importance of such a relationship. For example, research conducted by Abdul Rahman et al. [38] successfully indicated that temperature has the strongest correlation with the working performance of office workers. Similarly, studies by Kaushik et al. [39] demonstrated a relationship between office workers' productivity and various environmental factors, including indoor air temperature. Geng et al. [40] found that optimal productivity occurred when workers perceived the indoor environment as thermally neutral or slightly cool, and that thermal satisfaction had a positive effect on productivity. The results obtained by Lan et al. [41] revealed that elevated temperatures led to reduced work performance, even when thermal comfort was maintained through appropriate clothing adjustments. Likewise, studies by Lin et al. [42] showed that in an office setting moderately elevated indoor temperatures above 25 °C had a significantly negative impact on work performance, whereas moderately lowered temperatures below 21 °C had no significant effect. As for spaces in educational buildings, the research in university classrooms presented by Sarbu and Pacurar [10] indicated that thermal conditions strongly affect student performance, while the study by Hoque and Weil [43] suggests that academic performance can be improved by increasing thermal comfort. Similarly, in the research by Toyinbo et al. [44] in elementary school buildings an association was found between lower mathematics test results and inadequate ventilation rates and temperatures in classrooms. On the other hand, Brink et al. [22] observed that student perceptions of the thermal environment and indoor air quality were significantly associated with their physiological and cognitive responses, with the latter being linked to their short-term academic performance. Conversely, some studies – such as that of Maciejewska and Szczurek [45] – do not fully corroborate these findings. According to them air temperature did not play a significant role in student performance. They also challenged the common belief that the better a person feels and/or the better they perceive the surrounding conditions, the more effective their work is.

This study has certain limitations related to the applied methodology for determining IEQI and estimating student performance. The calculated indices account for key factors but do not capture all potential influences on indoor environmental quality or learning outcomes. In particular, air velocity, which can vary significantly in naturally ventilated spaces, was not measured and therefore not considered in thermal comfort assessments. Measurements were taken at a single central point in each classroom, which may not detect localized variations in air constituent concentrations or microclimate conditions. Student heterogeneity, including differences in age, gender, and clothing type, was not explicitly incorporated, even though these factors may affect thermal sensation and learning performance. Moreover, the study relied on low-cost sensors; although these were factory-calibrated and additionally verified against reference instruments, their accuracy is inherently lower than high-precision devices. The results pertain to naturally ventilated classrooms with a nearly constant number of students during the heating season, and similar outcomes may not directly apply to other classroom types, occupancy patterns, or ventilation conditions. Finally, no subjective assessments or direct performance tests were conducted, which could have provided further validation of the calculated RWP and PL values. Despite these limitations, the study provides valuable insights into the relationship between student presence, indoor environmental conditions, and indicators of comfort and productivity in school classrooms.

5. CONCLUSIONS

Measurements of typical indoor air quality parameters, as well as temperature and relative humidity, were carried out in naturally ventilated classrooms. Based on the calculated IAQ and TC indices, which influence the overall IEQI, the results confirm previous findings regarding the impact of indoor environmental conditions on comfort and student performance.
The main conclusions are as follows:

1. IEQ deteriorates during lessons and activities, as CO_2 levels rise along with concentrations of typical indoor pollutants, temperature, and humidity, negatively affecting both indoor air quality and thermal comfort.
2. Lower indoor environmental quality is associated with decreased student performance, reflected in reduced RWP and increased PL.
3. The oldest student groups experienced the most unfavorable conditions, likely due to physiological factors linked to maturation and the more frequent use of personal care products, both contributing to indoor air pollution.
4. Ongoing monitoring of the IEQI provides valuable insights into air quality and microclimate trends, supporting more effective ventilation and air treatment strategies in educational buildings.

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