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Thermal comfort evaluation in a naturally ventilated classroom using novel indexes

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ABSTRACT

Continuous measurements of indoor parameters, including temperature (T) and relative humidity (RH) were conducted in a naturally ventilated classroom during the heating season. Thermal conditions were assessed using three newly developed 10-point thermal comfort indexes: TCI 1 based on hygrothermal parameters; TCI 2, calculated from acceptability of air quality (ACC) and the percentage of dissatisfied persons (PD); and TCI 3, based on Fanger's indices (PMV and PPD). The analysis showed that thermal conditions and comfort were generally favorable but some deterioration was observed during lessons and periods with higher CO_2 concentrations due to student presence. During these periods, T and RH reached peaks of 25 °C and 51.3%, respectively, with TCI 1, TCI 2, and TCI 3 reaching values of 5, 3.4, and 2.1. The results suggest that continuous monitoring of TCI 2 and TCI 3 which showed good correlation with hygrothermal parameters enables an objective real-time assessment of thermal comfort. This approach could be applied to optimize thermal conditions not only in the monitored classroom but also in similar indoor environments.

Keywords: indoor air quality, thermal conditions, indoor environment, thermal comfort index.

INTRODUCTION

The comfort of indoor environments in buildings primarily depends on thermal conditions and indoor air quality (IAQ). Acoustic and lighting environments also play significant roles (ISO 17772, 2017; Fathi and O'Brien, 2024). The assessment of thermal conditions inside rooms is influenced by parameters such as air temperature, relative humidity, airflow velocity, and radiant temperature. Maintaining these parameters at optimal levels largely relies on the heating, ventilation, and air conditioning (HVAC) systems used, which, in turn, have a significant impact on building energy consumption. Approximately half of the energy generated in Europe is used for heating and cooling. Although winters have recently been milder due to global warming, most of this energy is still used for space and process heating (Heat Roadmap Europe, 2017).

Thermal comfort is a state in which a person feels that their body is in thermal balance, meaning they do not experience sensations of heat or cold. According to ASHRAE 55 (2020), it is a state of mind that reflects satisfaction with the surrounding thermal conditions. Various models are used to assess thermal comfort in indoor environments. The most widely applied is the static heat balance model developed by Fanger (1972), which involves calculating the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) indices. PMV predicts the average thermal sensation vote of a large group of individuals on a seven-point scale ranging from -3 (feeling cold) through 0 (neutral) to +3 (feeling hot). It is determined based on the human body heat balance meaning that the heat generated within the body is balanced by heat losses to the environment. PPD, in turn, estimates the percentage of people likely to be dissatisfied with the thermal conditions, meaning those who perceive the environment as either too cold or too warm. In addition to PMV and PPD, criteria for local thermal discomfort are also considered. These factors arise from issues such as draughts, vertical temperature differences, warm or cold floors, and radiant temperature asymmetry (PN-EN ISO 7730, 2005). Thermal comfort can also be assessed using adaptive models. Examples include the model incorporating the "adaptation factor" proposed by Yao et al. (2009) and the model described in EN 16798 (2019), which accounts for users' varied adaptation to conditions in naturally ventilated spaces. A machine learning-based adaptive thermal comfort model, utilizing artificial neural networks (ANN) and random forest (RF) algorithms, was proposed by Hoz-Torres et al. (2024).

Numerical indices are frequently used to assess indoor thermal conditions and comfort, most of which primarily rely on microclimate parameters such as indoor air temperature and humidity. In some cases, they also incorporate personal factors, including clothing insulation and physical activity (PN-EN ISO 7730, 2005). These indices are typically developed for specific indoor environments, although some more universal models with broader applicability have also been proposed. For example, Burek et al. (2006) proposed an equation for evaluating the microclimate of educational and office spaces. They introduced the concept of indoor air acceptability (AKC) in relation to specific enthalpy and relative humidity of the air, providing a method for instrumentally assessing perceived indoor air quality and for controlling air conditioning systems. Leyva et al. (2016) developed an IAQ index based on ASHRAE standards and specifications for cultural heritage objects (Thomson, 1984; ASHRAE, 2011), employing color-coded visualization to represent air quality inside a chapel. Lucero-Gómez et al. (2020) formulated an indoor climate index based on temperature and relative humidity measured inside a historical museum building. The indoor air comfort index (IAC), which incorporates among others temperature and relative humidity, was introduced by Pasaribu and Yuwono (2021). Pereira et al. (2014) evaluated the environmental quality based on Fanger's comfort indices, namely PMV and PPD. Similarly, Li et al. (2016) developed an index based on Weber-Fechner's law and PMV, incorporating air temperature, other indoor environmental factors, subjective satisfaction assessments from occupants, and reported health symptoms. Laouadi (2022) proposed a general formula for PMV taking into account the metabolic rate required to achieve comfort under given environmental conditions. More recently, Wang et al. (2024) introduced an index for the simultaneous evaluation of energy efficiency and thermal comfort, also utilizing PMV and PPD. Kliangkhlao et al. (2025) in turn applied machine learning to predict indoor microclimate conditions based on thermal comfort. Using heat index calculations, they identified the optimal single-point reference for representing and predicting variations in multi-zone indoor microclimates.

To date numerous studies have assessed thermal conditions in various indoor spaces. For instance, Sharifi et al. (2019) examined these conditions in air-conditioned multilevel residential buildings, Wu et al. (2019) in naturally ventilated dormitories, and Zhai et al. (2019) in a naturally ventilated office space. With regard to educational buildings, relevant studies have been conducted by Heracleous et al. (2021) in a secondary school, Wang et al. (2021) in naturally ventilated university classrooms, and Bhandari et al. (2023) in naturally ventilated lecture halls. Despite differences in building function and occupancy levels, thermal comfort remains a critical factor influencing overall satisfaction with the indoor environment. This is particularly important in classrooms, where students and teachers spend a considerable portion of the day. In such contexts, thermal conditions significantly affect well-being, health, and learning performance. However, specific thermal comfort requirements for educational buildings are not explicitly defined within current regulations or legal standards. Instead, general recommendations provided by the World Health Organization (WHO) regarding hygrothermal conditions in occupied indoor environments are commonly referenced (WHO, 2010; Liu et al., 2024). According to these guidelines, the temperature should range from 18 °C to 24 °C in residential spaces and 20 °C to 26 °C in office spaces, while relative humidity should be maintained between 30% and 60%.

Inadequate thermal conditions in school classrooms can significantly reduce student comfort, well-being, and productivity (Corgnati et al., 2007; Guevara and Mino-Rodriguez, 2021). Therefore, ensuring proper thermal management in these spaces is essential. Achieving optimal thermal conditions in classrooms requires appropriate heating, cooling, and ventilation systems, including air conditioning where necessary. Moreover, the effectiveness of these systems depends on their proper regulation and control, which not only enhances comfort but also improves energy efficiency.

The main purpose of this work was to evaluate thermal comfort in a naturally ventilated classroom during the heating season using continuous measurements of hygrothermal parameters. The study introduces and compares three novel 10-point thermal comfort indexes developed based on these measurements and data estimating student thermal sensations. It also examines the potential application of these indexes for optimizing thermal conditions in the monitored classroom and similar indoor environments.

RESEARCH METHODS

Measurements of indoor environmental parameters were conducted during the heating season in a classroom at a primary school in Lublin, located in eastern Poland. The three-story school building constructed before World War II with external walls made of perforated bricks underwent thermal modernization which included the installation of thermal insulation and the replacement of old wooden window frames with tighter-fitting plastic ones.

The school is heated by a central heating system supplied by the municipal district heating network. Panel radiators connected to a heat exchanger unit are installed in the classrooms and corridors. Natural (gravitational) ventilation is used with air entering through windows and doors and exiting through ventilation ducts.

The classroom selected for thermal condition monitoring was located on the second floor of the school building. This cuboidal room measured 7.5 × 6.5 × 3.5 m (length × width × height), featured three double- glazed windows and was furnished with a teacher's desk as well as tables and chairs for 24 students (Figure 1). Natural ventilation occurred through air infiltration via the windows and door, with air being discharged through two rectangular ventilation grilles (0.15 × 0.20 m) installed on the interior wall near the ceiling. These grilles were connected to a ventilation duct.

Classes were held in the classroom according to the regular timetable from Monday to Friday, usually between 8:00 a.m. and 4:00 p.m. The 45-minute lessons, attended by a consistent number of students, were usually separated by 5-minute breaks. Occasionally, the classroom was ventilated during breaks or even during lessons by partially opening the windows. The indoor temperature was controlled by thermostatic radiator valves set to 20 °C.

The measurements were conducted using a set of calibrated low-cost sensors placed in the central area of the classroom. These sensors continuously measured air temperature (T), relative humidity (RH) and CO_2 concentrations. The sensor temperature resolution was 0.1 °C (range: -40 − 85 °C) with an accuracy of ±1 °C, the sensor relative humidity resolution was 0.1% with

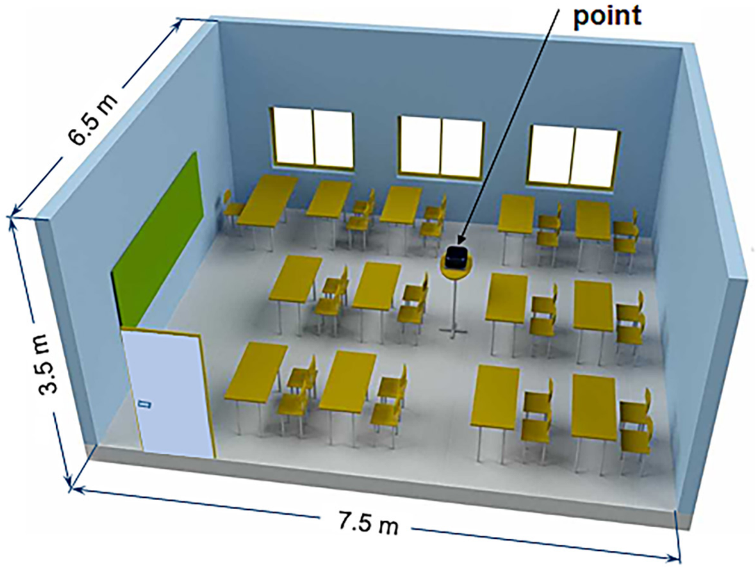

Figure 1. Schematic view of the classroom with the measurement point marked

an accuracy of ±3% and the sensor CO_2 concentration resolution was 1 ppm (range: 300–5000 ppm) with an accuracy of ±50 ppm (Dumała et al., 2024). The measurement data were recorded at 1-minute intervals. Concentrations of other gaseous air pollutants and aerosol particles were also measured, but these data were not considered in this study. During all lessons in the classroom, it was assumed that student activity was light and mainly sedentary, corresponding to a metabolic rate of 1.2 met. A typical combination of clothing appropriate for the heating season was also assumed, with a thermal insulation value of 1 clo. The general assessments of thermal conditions in the classroom based on this data did not account for local thermal discomfort caused by draughts, vertical air temperature differences, warm/cold floors or radiant temperature asymmetry.

T and RH are the most commonly monitored environmental parameters that primarily affect comfort in indoor spaces. In this study, these measurements were used to evaluate the overall thermal conditions in the monitored classroom. Three different indexes, developed specifically for this study, were used to assess thermal comfort. The first index – TCI 1 – is based on indoor thermal comfort directly related to the hygrothermal microclimate (ASHRAE 55, 2020; Auliciems and Szokolay, 2007). TCI 1 was determined for the measured and recorded T and RH at a given time using Table 1 which lists the values of this index for T ranging from 19 °C to 28 °C and RH between 20% and 70%. Its values are assigned on a scale from 0 (very good) to 10 (very poor).

The values of the second index – TCI 2 – were calculated based on the acceptability of air quality (ACC) and the percentage of dissatisfied persons (PD). ACC was calculated using the logarithmic Weber-Fechner law formula (Burek et al., 2006):

$$ACC = -k \cdot ln(h/h_0) \quad (1)$$

where: h is the air specific enthalpy, and h_0 is the threshold specific enthalpy; k and h_0 depend on RH and air pollution levels.

ACC with values ranging from -1 (not acceptable air quality) to +1 (acceptable air quality) was used to determine *PD*. Considering the ranges of T and RH measured in the classroom, the following formula was used (Burek et al., 2017):

$$PD = 100/(1 + exp(3.15 \cdot ACC + 0.043)) \quad (2)$$

The *PD* values, calculated every minute, were divided by 10, and the results, ranging from 0 to 10 on a 10-point grading scale, were used as TCI 2 values.

The third index, TCI 3, was determined using Fanger's thermal comfort indices, i.e., the predicted mean vote (*PMV*) and predicted percentage dissatisfied (*PPD*), which were calculated based on the formulas provided in PN-EN ISO 7730 (2005):

$$PMV = f(M, W, \lambda_{cl}, T_a, T_{ra}, p_a, h_c, T_{cl}, f_{cl}) \quad (3)$$

$$PPD = 100 - 95 \cdot exp(-0.003353 \cdot PMV^4 - 0.2179 \cdot PMV^2) \quad (4)$$

where: M is the metabolic rate (W/m^2), W is the mechanical work performed (W/m^2), λ_{cl} is the clothing insulation (m^{2}K/W), T_a is the indoor air temperature (°C), T_{ra} is the mean radiant temperature (°C), p_a is the water vapor partial pressure (Pa), h_c is the convective heat transfer coefficient (W/m^{2}K), T_{cl} is the clothing surface temperature (°C), and f_{cl} is the clothing surface area factor (-).

The PMV and PPD were calculated using the monitored air temperature and relative humidity in the classroom, along with an estimated T_{ra} (T_a ± 1 °C) and air velocity (0.1 m/s) as well the assumed metabolic rate (M = 1.2 met = 69.6 W/m²) and students' clothing insulation (λ_{cl} = 1 clo =

Table 1. TCI 1 values assigned to indoor air temperature (T) and relative humidity (RH) measured in the classroom

	T [°C]										
	Values	19	20	21	22	23	24	25	26	27	28
RH [%]	70	3	2	2	3	4	5	6	6	7	8
	60	2	1	1	2	3	4	5	6	7	8
	50	1	0	0	1	2	3	4	5	6	7
	40	2	1	0	0	1	2	3	4	5	6
	30	3	2	2	2	2	3	3	4	5	6
	20	4	3	3	3	3	3	4	5	6	7

0.155 m²K/W). The PPD values were divided by 10 to derive the values of the TCI 3 index. For the TCI 2 and TCI 3 indexes, it was assumed that the classroom thermal conditions affected the thermal sensations of hypothetical students present in the classroom throughout the entire monitoring period. The values of these indexes are always greater than 0, as even under ideal thermal conditions, there is a certain percentage of students dissatisfied with those conditions.

RESULTS

The time series of T, RH, and CO_2 concentration in the classroom during the two-week monitoring period are presented in Figure 2. The graphs show that the thermal conditions in the classroom were generally good. The values of T and RH remained mostly within the recommended ranges of 20 °C to 26 °C and 30% to 60%, respectively, as per the WHO guidelines for office spaces (WHO, 2010). Each day when lessons were held the values of T and RH as well as the CO_2 concentration increased fairly quickly after the students entered the classroom. Indoor air temperature typically rose from around 21 °C to its maximum values at the end of the lessons and the students' presence in the classroom, averaging around 24 °C (on one day, T reached 25 °C). Meanwhile, RH values increased from an average of 35% to approximately 45% (with a maximum slightly over 51%). The highest RH values, similarly to T, occurred at the end of the students' time in the

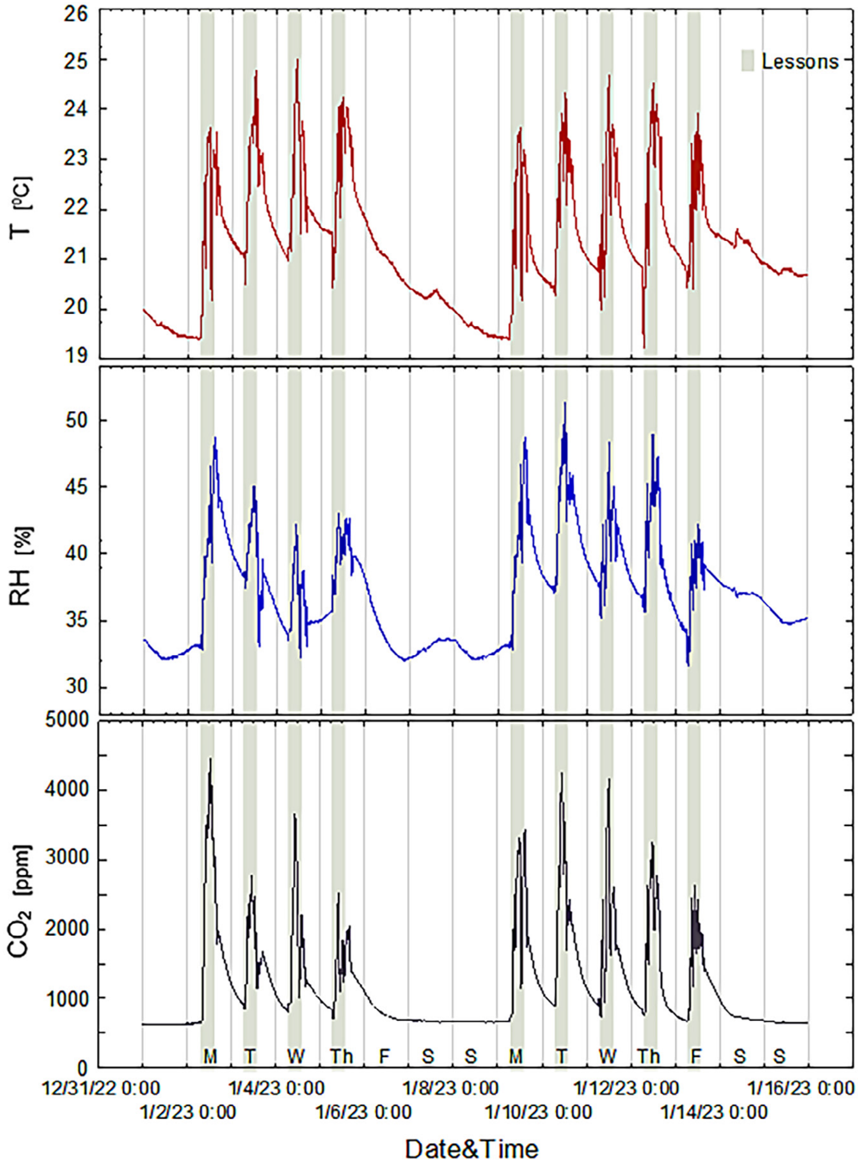

Figure 2. Time series of temperature (T), relative humidity (RH), and CO_2 concentration in the classroom

classroom. A similar pattern was observed for CO_2 concentration, a key indicator of occupancy in indoor spaces. The levels of CO_2 concentration depend on the number of occupants and the duration of their presence in the room. In the case of the monitored classroom, CO_2 was exhaled by the students and this was the only real source of that gas. On some days CO_2 concentration rose from a baseline of approximately 600 ppm to over 4000 ppm during lessons.

The variations in TCI 1, TCI 2, and TCI 3 in the classroom are presented in Figure 3. It can be observed that TCI 1 values fluctuated more abruptly and within a broader range (from 0 to 5) than TCI 2 values (< 1 to ~3.7) and TCI 3 values (0.5 to ~2). Additionally, TCI 1 seem to be less visually correlated with lesson times and the presence of students in the classroom, as indicated by the previously mentioned increases not only in CO_2 concentration but also in T and RH, as shown in the graphs in Figure 2.

Table 2 provides a summary of the mean, minimum, maximum, standard deviation, and correlation coefficients for T, RH, and CO_2 concentrations, as well as the calculated TCI 1, TCI 2, and TCI 3 values for the entire monitoring period. These data indicate that, on average, the thermal conditions in the classroom during this period were acceptable. Some deterioration in these conditions, as illustrated in Figure 2, was observed during periods of student presence. The highest TCI 2 and TCI

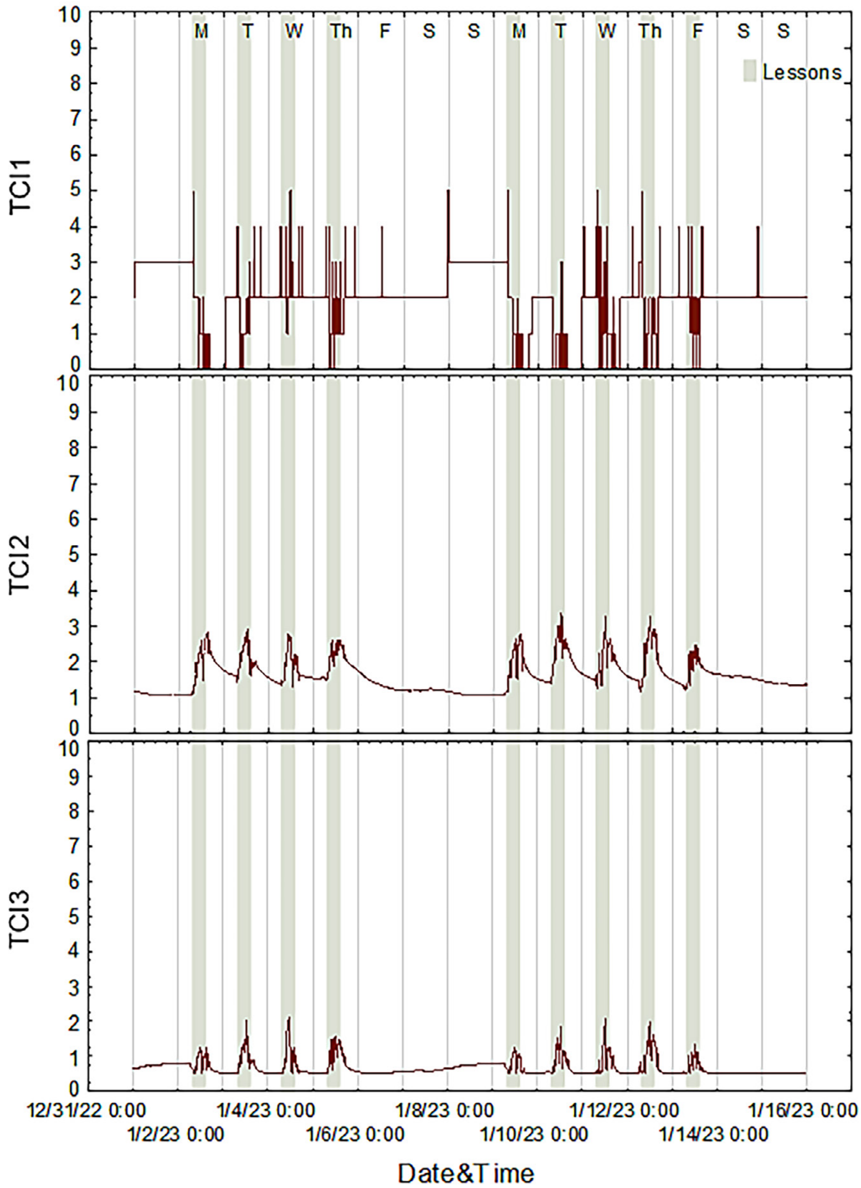

Figure 3. Changes in the thermal comfort index values (TCI1, TCI2, and TCI3) in the classroom

Table 2. Mean, minimum (Min), maximum (Max), standard deviation (SD), and correlation coefficients of indoor air temperature (T), relative humidity (RH), CO_2 concentration, and thermal comfort indexes (TCI 1, TCI 2, and TCI 3) in the classroom

Parameter	Mean	Min	Max	SD	T [°C]	RH [%]	CO_2 [ppm]	TCI 1, r	TCI 2	TCI 3
T [°C]	21.26	19.23	25.00	1.22	1.00	0.80	0.81	-0.61	0.95	0.56
RH [%]	37.00	31.64	51.33	3.87	0.80	1.00	0.84	-0.75	0.93	0.44
CO_2 [ppm]	1174	606	4473	716	0.81	0.84	1.00	-0.60	0.89	0.66
TCI 1	1.91	0.00	5.00	0.84	-0.61	-0.75	-0.60	1.00	-0.68	-0.10
TCI 2	1.61	1.05	3.35	0.45	0.95	0.93	0.89	-0.68	1.00	0.62
TCI 3	0.67	0.50	2.14	0.25	0.56	0.44	0.66	-0.10	0.62	1.00

3 values were recorded around midday on lesson days, specifically towards the end of the students' presence in the classroom. The correlation coefficients, which were statistically significant at $p < 0.001$, showed a strong positive correlation between TCI 2 and T, RH, and CO_2 concentrations ($r > 0.9$). Slightly lower correlation coefficients ($r > 0.4$) were observed for the relationship between TCI 3 and T, RH, and CO_2 concentrations. On the other hand, TCI 1 values were significantly but negatively correlated with the measured T, RH, and CO_2 concentrations, as well as with the calculated TCI 2 and TCI 3 values.

Figure 4 presents the measured T, RH, and CO_2 concentration, along with the calculated TCI 1, TCI 2, and TCI 3 values in the monitored classroom during lessons and nights. Table 3, in turn, summarizes the basic statistical information for these measured parameters and calculated indexes during classes, nights, and over the entire monitoring period. It is evident that significant differences exist between these periods. The average values of all parameters and indexes, except

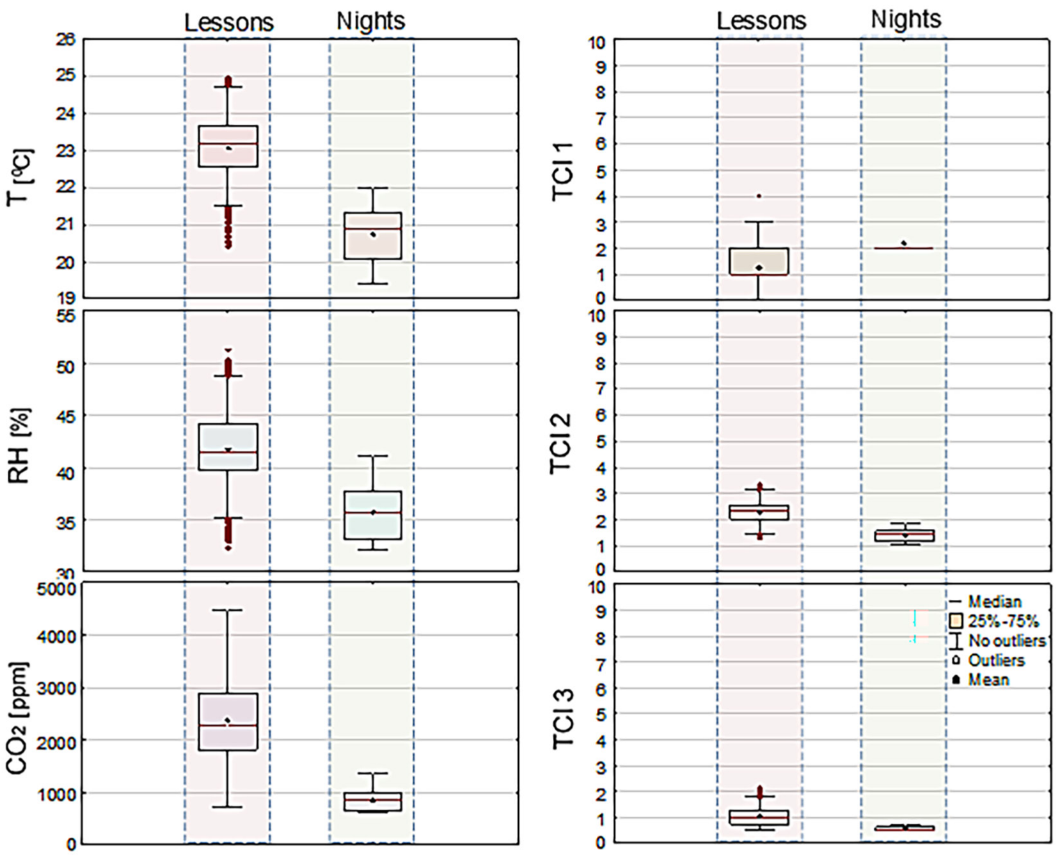

Figure 4. Indoor air temperature (T), relative humidity (RH), CO_2 concentration, and thermal comfort index values (TCI1, TCI2, and TCI3) in the classroom during lessons and nights

for TCI 1, were significantly higher ($p < 0.001$) during lessons compared to nights and the entire monitoring period. During lessons, the mean values of T, RH, and CO_2 concentration were 23.1 °C, 41.8%, and 2372 ppm, while the mean TCI 1, TCI 2, and TCI 3 values were 1.2, 2.3, and 1. Meanwhile, the maximum values of T, RH, and CO_2 concentration reached 25.0 °C, 51.3%, and 4473 ppm, whereas the maximum values of TCI 1, TCI 2, and TCI 3 were 5, 3.4, and 2.1, respectively.

The presented data suggest that TCI 2 and TCI 3 can serve as fairly reliable indicators for assessing thermal comfort in the classroom. However, some doubts arise regarding TCI 1, as its highly fluctuating values do not accurately reflect changes in thermal conditions, making it seem less useful for real-time evaluation of thermal comfort in the classroom. It would therefore be advisable to re-evaluate the method used to determine this index.

DISCUSSION

Environmental monitoring in school classrooms is usually conducted to evaluate IAQ, thermal comfort, and overall environmental conditions that may affect student well-being, health, and productivity. The results of such monitoring provide valuable insights that support the adjustment of hygrothermal parameters in classrooms, thereby creating a healthier and safer learning environment for students and suitable working conditions for teachers and school staff. These findings also have an economic dimension, as optimizing thermal conditions can lead to energy savings. This study focused on analyzing variations in thermal conditions within a naturally ventilated classroom during the heating season, both in the presence and absence of students. Measurements of hygrothermal parameters, along with values of the newly developed thermal comfort indexes – TCI 1, TCI 2, and TCI 3 – confirm widely reported findings in the literature regarding the impact of occupant presence on the indoor microclimate (Zhai et al., 2019; Kanthila et al., 2021). The presence of students, as indicated by elevated CO_2 concentrations, contributed to significant increases in temperature and humidity ultimately influencing thermal comfort. Continuous monitoring of these comfort indices, particularly TCI 2 and TCI 3, which exhibit strong correlations with measured hygrothermal parameters, enables objective, real-time assessment of thermal comfort and allows for timely responses to changing classroom conditions. This, in turn, can enhance student well-being and cognitive performance while also significantly affecting energy use in educational facilities. These conclusions are supported by findings from lecture hall studies by Sarbu and Pacurara (2015), which indicate that thermal conditions have a substantial impact on student comfort and academic outcomes. Similarly, research by Hoque and Weil (2016) suggests that improvements in thermal comfort can lead to better academic performance. Comparable results were reported by Toyinbo et al. (2016), who identified a link between lower math test scores and insufficient ventilation combined with inadequate classroom temperatures. Brink et al. (2022) further observed that student perceptions of thermal environment and air quality are strongly associated with both physiological and cognitive responses, the latter being closely tied to short-term academic performance. On the other hand, some studies (Maciejewska and Szczurek, 2025) have not confirmed a significant influence of indoor air temperature on learning outcomes. Nevertheless, when discussing thermal comfort and energy

Table 3. Indoor air temperature (T), relative humidity (RH), CO_2 concentration and the thermal comfort index values (TCI 1, TCI 2, and TCI 3) in the classroom

Parameters	Lessons	Nights	Entire monitoring
	N = 3673	n = 7171	n = 21432
T [°C]	23.1 (0.9) 23.2/25.0	20.7 (0.7) 20.1/22.0	21.3 (1.2) 21.2/25.0
RH [%]	41.8 (3.4) 41.4/51.3	35.7 (2.4) 35.7/41.2	37.0 (3.9) 36.8/51.3
CO_2 [ppm]	2372 (772) 2278/4473	845 (189) 852/1369	1174 (716) 895/4473
TCI 1	1.2 (0.8) 1.0/5.0	2.2 (0.6) 2.0/5.0	1.9 (0.8) 2.0/5.0
TCI 2	2.3 (0.4) 2.3/3.4	1.4 (0.2) 1.5/1.9	1.6 (0.5) 1.6/3.4
TCI 3	1.0 (0.4) 1.0/2.1	0.6 (0.1) 0.5/0.8	0.7 (0.3) 0.6/2.1

Note: Arithmetic average (standard deviation) median/maximum.

efficiency, analyses of results from recent studies conducted in educational buildings, such as by Ranđelović et al. (2024), should also take into account the predicted impacts of climate change (Heracleous et al., 2021).

The thermal comfort assessment indexes presented in this study, unlike many other indices proposed in the literature (e.g., Pasaribu and Yuwono, 2021; Wang et al., 2024), classify thermal comfort levels using an intuitive and easily interpretable 10-point scale. These indexes may prove useful not only for evaluating comfort in the monitored classroom but also in comparable indoor environments. In particular, TCI 2 and TCI 3, whose values consistently reflect changes in the indoor microclimate, can support the optimization of thermal conditions for instance through more efficient management of heating, ventilation or air conditioning systems.

Although the developed indexes capture variations in thermal comfort, several limitations related to their computational methodology, the formulas used, and the omission of key influencing factors may affect their reliability and accuracy. To enhance their credibility, it would be beneficial to compare their values with those of established thermal comfort indices. Furthermore, validating these indexes against actual student perceptions – an aspect not included in this study – would provide valuable insight. Future research should focus on refining these indexes to improve their practical applicability.

CONCLUSIONS

Maintaining proper thermal conditions in school classrooms is essential for student well-being, health, and learning productivity. Poorly managed thermal environments can also significantly impact energy consumption in school buildings. Continuous monitoring of hygrothermal parameters conducted in a naturally ventilated classroom during the heating season showed that the thermal conditions in the classroom were generally good throughout the entire monitoring period. Some deterioration was observed during lessons and, more broadly, during periods of student presence which were characterized by elevated CO_2 concentrations. A similar trend was observed in the assessed thermal comfort levels in the classroom based on the newly developed 10-point indexes – TCI 1, TCI 2, and TCI 3. Continuous calculation of TCI 2 and TCI 3 values which showed a fairly strong correlation with the measured hygrothermal parameters enables objective and real-time assessment of thermal comfort in the monitored classroom. This method could also be applied to effectively optimize thermal conditions in this and other similar indoor environments, for example through appropriate control of heating, ventilation or air conditioning systems.

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