NUANCES
unesp

INDOOR ENVIRONMENTAL QUALITY OF PRIMARY SCHOOLS: UNRAVELING THE IMPROVEMENTS THAT STILL NEED TO BE DONE!

QUALIDADE AMBIENTAL NO INTERIOR DAS SALAS DE AULA NO 1º CICLO: REVELANDO AS MELHORIAS QUE PRECISAM DE SER FEITAS!

CALIDAD AMBIENTAL INTERIOR DE LAS ESCUELAS PRIMARIAS: DESENTRAÑANDO LOS CAMBIOS DINÁMICOS ENTRE LAS AULAS Y LOS PERÍODOS DE TIEMPO

Neusa Sofia Guerreiro PEDRO[1]
e-mail: nspedro@ie.ulisboa.pt

Edson Pinheiro PIMENTEL[2]
e-mail: edson.pimentel@ufabc.edu.br

João PIEDADE[3]
e-mail: jmpiedade@ie.ulisboa.pt

Elisabete CRUZ[4]
e-mail: elisabete.cruz@uevora.pt

How to reference this paper:

PEDRO, N. S. G.; PIMENTEL, E. P.; PIEDADE, J.; CRUZ, E. Indoor environmental quality of primary schools: unraveling the improvements that still need to be done! **Nuances: Estudos sobre Educação**, Presidente Prudente, v. 36, n. 00, e025008, 2025. e-ISSN: 2236-0441. DOI: 10.32930/nuances.v36i00.11162

| **Submitted**: 30/05/2025
| **Revisions required**: 04/06/2025
| **Approved**: 24/06/2025
| **Published**: 21/08/2025

Editor: Prof. Dr. Rosiane de Fátima Ponce
Deputy Executive Editor: Prof. Dr. José Anderson Santos Cruz

[1] Institute of Education, University of Lisbon (UIDEF), Lisbon – Portugal. Associate Professor with Aggregation in the research and teaching area of Curriculum, Teacher Education, and Technology.
[2] Federal University of ABC (UFABC), Santo André – SP – Brazil. Faculty member of the Graduate Program in Computer Science with research in Applied Informatics in Education. Associate Professor IV, Center for Mathematics, Computing, and Cognition (CMCC).
[3] Institute of Education, University of Lisbon (UIDEF), Lisbon – Portugal. Assistant Professor in the research and teaching area of Curriculum, Teacher Education, and Technology.
[4] University of Évora, Research Center in Education and Psychology (CIEP), Évora – Portugal. Faculty member and Researcher in the area of Educational Sciences – Didactics, Curriculum Development, and Educational Technologies. Assistant Professor, Department of Pedagogy and Education.

ABSTRACT: The study addresses the Indoor Environmental Quality (IEQ) of primary school classrooms, with a focus on Carbon dioxide, Temperature, Humidity, and Illuminance. Data was collected from four classrooms in a Southern European country during May 2022. The study aims to understand differences in IEQ among classrooms and time periods. Descriptive statistics, Kruskal-Wallis tests, and pairwise comparisons were used to analyze the Conformity Rate Indicator (CRI) for each parameter, indicating adherence to desirable IEQ levels. Results show that CO2 levels are generally acceptable, except for one classroom. Temperature conforms in two classrooms, while Humidity is consistently above recommended levels. Significant differences exist among classrooms, particularly in Temperature and Illuminance. Time-period analysis reveals critical fluctuations in CO2 and Illuminance. Results show great variability in different indicators, with a severe and unstable trend of worsening indicators throughout the day, reaching dangerous rates.

KEYWORDS: Indoor Environmental Quality (IEQ). Classroom environment. School buildings. Conformity Rate Indicator.

***RESUMO**: RESUMO: O estudo foca na análise da Qualidade Ambiental Interna (QAI) de salas de aula do ensino básico, considerando parâmetros como dióxido de carbono, temperatura, umidade e iluminância. Os dados foram coletados em quatro salas de aula de um país do sul da Europa, em maio de 2022. O estudo visa compreender as diferenças na qualidade ambiental interna entre salas de aula e períodos temporais. Foram utilizadas estatísticas para analisar o Indicador de Taxa de Conformidade (ITC) para cada parâmetro, assinalando a adesão destes aos níveis desejáveis de conformidade. Os resultados mostram diferenças significativas entre as salas de aula, particularmente nos parâmetros temperatura e iluminância. A análise dos diferentes períodos temporais revela flutuações críticas nos níveis de dióxido de carbono e na iluminância. Os resultados indicam grande variabilidade nos parâmetros analisados, com uma tendência severa e instável de agravamento, atingindo índices perigosos.*

***PALAVRAS-CHAVE**: Qualidade Ambiental Interna (QAI). Sala de aula. Edifícios escolares. Indicador de Taxa de Conformidade.*

***RESUMEN**: El estudio aborda la Calidad Ambiental Interior (CAI) de las salas de clases de primaria, centrándose en el dióxido de carbono, la temperatura, la humedad y la iluminancia. Se recopilaron datos de cuatro salas de clases de un país del sur de Europa durante mayo de 2022. El estudio tiene como objetivo comprender las diferencias en el CAI entre salas y períodos de tiempo. Se utilizaron análisis estadísticos para analizar el indicador de tasa de cumplimiento (ITC) para cada parámetro, lo que indica el cumplimiento de los niveles deseables. Los resultados muestran diferencias significativas entre las salas de clases, particularmente en temperatura e iluminancia. El análisis de períodos de tiempo revela fluctuaciones críticas en el dióxido de carbono y la iluminancia. Los resultados muestran una gran variabilidad en los distintos indicadores, con una tendencia severa e inestable de empeoramiento de los indicadores, alcanzando índices peligrosos.*

***PALABRAS CLAVE**: Salas de clases. Calidad ambiental interior. Ambiente de aula. Edificios escolares. Indicador de índice de conformidad.*

Introduction

The IEQ of buildings has received increasing attention in the context of global climate change and the need for more sustainable buildings and social practices. The COVID-19 pandemic heightened concerns about air quality, reinforcing the need to ensure that indoor spaces are safe and healthy, especially in schools (Zhong; Yuan; Fleck, 2019).

According to Zomorodian, Tahsildoost, and Hafezi (2016), primary and secondary school students spend a significant number of hours within the school premises; some studies even claim that they spend one-third of their day inside schools (Almeida; Ramos; De Freitas, 2016). The literature states that indoor environmental conditions not only influence the academic performance of students but also impact their health and well-being (Al Horr *et al*., 2016; Castilla *et al*., 2017; Chatzidiakou; Mumovic; Dockrell, 2014; Griffiths; Eftekhari, 2008; Jain *et al*., 2020; Mohamed *et al*., 2021; Moldoveanu, 2015; Roskos; Neuman, 2011; Schneider, 2003; Yang; Becerik-Gerber; Mino, 2013). The quality of indoor environments is crucial not only for physical health, mental health, and well-being but also for cognitive performance and productivity. Poor indoor air quality and other subpar conditions can also lead to increased absenteeism (Apte; Erdmann, 2002; Cheryan *et al*., 2014; Zhong; Lalanne; Alavi, 2021). Specifically, within the context of education, these factors contribute to a decrease in student learning and development, as well as to the pedagogical performance of teachers (Al Horr *et al*., 2016; Griffiths; Eftekhari, 2008; Mohamed *et al*., 2021; Yang; Becerik-Gerber; Mino, 2013).

Various studies have found a direct relationship between academic outcomes and the physical characteristics of school buildings and their IEQ (Castilla *et al*., 2017; Griffiths; Eftekhari, 2008; Jain *et al*., 2020; Lewinski, 2015; Roskos; Neuman, 2011). Factors such as lighting (amount of light), thermal comfort (temperature and humidity), acoustics (noise), and indoor air quality are essential characteristics of indoor environments that can impact not only student health and well-being (Castilla *et al*., 2017; Chatzidiakou; Mumovic; Dockrell, 2014; Lewinski, 2015; Schneider, 2003) but also academic achievement and cognitive development, often due to discomfort, sickness, and subsequent absenteeism (Chatzidiakou; Mumovic; Dockrell, 2014; Jain *et al*., 2020). Also, the consequences of exposure of children and young people to biological agents present in the air (bacteria, molds, mildew, viruses, dust, and pollen) are known to lead to school absenteeism due to asthma attacks, allergies, bronchitis, and other respiratory conditions, which directly affect academic results (Chatzidiakou; Mumovic;

Dockrell, 2014; Jain *et al*., 2020; Moldoveanu, 2015; Roskos; Neuman, 2011; Wargocki; Wyon, 2013).

Nevertheless, research shows that the above-mentioned environmental factors play a crucial role in creating a suitable context for educational development, potentially impacting academic outcomes, health, and other significant aspects such as behaviour, concentration, and student satisfaction (Chatzidiakou; Mumovic; Dockrell, 2014; Cheryan *et al*., 2014; Jain *et al*., 2020; Roskos; Neuman, 2011; Yang; Becerik-Gerber; Mino, 2013).

According to Wargocki and Wyon (2013), the environmental conditions in primary schools, even in economically developed countries, are often inadequate and frequently worse than those found in professional settings. These authors suggest that if good environmental conditions were established in classrooms, student performance could improve by up to 30% (Wargocki; Wyon, 2013, p. 588). Several studies have sought to measure the impact of elements such as air quality, temperature, and lighting in learning environments, particularly in classrooms. Chatzidiakou, Mumovic, and Dockrell (2014) state that low ventilation rates and consequently high indoor carbon dioxide concentrations can negatively affect attention capacity, concentration, and promote student fatigue. Poor indoor air quality can cause various health problems, including headaches, fatigue, lethargy, and cardiac arrhythmia, as well as difficulties in attention, memory, and in tasks requiring higher cognitive effort (Apte; Erdmann, 2002; Griffiths; Eftekhari, 2008; Lewinski, 2015; Portugal, 2013; Wargocki; Wyon, 2013; Yang; Becerik-Gerber; Mino, 2013). This situation also affects a teacher's ability to teach and increases absenteeism (Cheryan *et al*., 2014). Regulation 353-A/2013, issued by the Ministries of Environment, Territorial Planning, and Energy; Health; and Solidarity, Employment, and Social Security of Portugal, stipulates an upper limit of 1250 ppm for carbon dioxide concentration levels for new buildings, with a tolerance of 30% for existing buildings or those without heating, ventilating, and air conditioning (HVAC) systems (Portugal, 2013).

The thermal environment is determined by air temperature, average radiant temperature, relative humidity, and air velocity (Chatzidiakou; Mumovic; Dockrell, 2014). Thermal comfort is influenced by the hydric-thermal conditions of the environment and each person's individual adaptation to the environment. It also depends on other factors such as buildings' geographical location and architectural structure, climate, time of year, and the biological and physical characteristics of individuals (gender, age, etc.), as well as the specific activity being undertaken (Al Horr *et al*., 2016; Chatzidiakou; Mumovic; Dockrell, 2014). Some studies (Earthman, 2004; Liu; Yoshino; Mochida, 2011) have concluded that temperature is the most determinant attribute regarding student perception of classroom quality (Yang; Becerik-Gerber; Mino, 2013). Several authors suggest that the temperature range best suited for children and their learning is between 20 °C and 24 °C (68 °F – 74 °F), more specifically, between 20 °C and 22 °C during winter and 22 °C and 24 °C during summer (Chatzidiakou; Mumovic; Dockrell, 2014; Cheryan *et al*., 2014; Earthman, 2002, 2004; Lewinski, 2015). Earthman (2002) also suggests that 50% relative humidity in the air is an acceptable value for classrooms. In Portugal, thermal comfort levels inside buildings should be between 18 °C and 24 °C, respectively for winter and summer, considering the average relative humidity value between 35% and 70% (DGAE, 2004, p. 9).

In addition to thermal comfort, recent research has also highlighted the importance of lighting in creating suitable, stimulating, and more productive learning environments (Barkmann; Wessolowski; Schulte-Markwort, 2012; Samani; Samani, 2012). Lighting conditions influence task visibility, visual performance, comfort, and visual impressions of spaces, people, and objects (Boyce, 2014). Regarding lighting in Portugal, the norms for school buildings (DGAE, 2004; Parque Escolar, 2017) state that, in a regular classroom, the lighting levels on the work plane should be between 300 and 500 lux, with the ideal range between 350 and 400 lux.

Despite various studies that have investigated the impact of school environmental indicators on learning and health, the monitoring of environmental quality in classrooms has been sporadic. The available studies are mainly found in academic journals related to building design and environment (Aguilar *et al*., 2022; Almeida; Ramos; De Freitas, 2016; Zhong; Yuan; Fleck, 2019; Zomorodian; Tahsildoost; Hafezi, 2016), with few studies focusing on educational issues. Moreover, despite the existence of norms that establish ideal parameters for various environmental quality indicators, regular monitoring of these indicators to support efforts aimed at enhancing environmental conditions in schools, especially in classrooms, is lacking. In this context, Pulimeno *et al*. (2020) indicate that guidelines from various organizations, including the Unesco Chair in Education for Health and Sustainable Development, recommend actions such as: (i) informing teachers and other school staff about how indoor air quality affects student health and academic performance; (ii) encouraging the adoption of protocols and measures to monitor indoor air quality in all schools; and (iii) ensuring that classrooms are adequately ventilated before classes start and during each break.

With this context as a reference, this study aims to present and discuss the results of a comparative assessment of the internal environmental quality of four primary school classrooms in Portugal, focusing on four indicators: carbon dioxide, temperature, humidity, and illuminance. The legally established standards and those considered desirable by the literature for each indicator were considered.

The study addressed the following research questions:

I. Are there differences in the internal environmental quality of the classrooms?
II. Are there differences in the internal environmental quality among classrooms across different time periods of the day?

Materials and methodology

This section aims to present the means and procedures used for data collection. Initially, the characteristics of the data collection locations and the specifications of the equipment used to register environmental parameters are presented. After this, the process of structuring the collected data and the procedures used for its analysis are described.

This study used only measurements captured by environmental sensors and not user self-report surveys. This factor distinguishes this study from other works in the field, where thermal comfort is measured through indices such as Thermal Sensation Vote (Aguilar *et al*., 2022) and Predicted Mean Vote (Brink *et al*., 2022), which are considered less reliable. For this study, the metric Conformity Rate Indicator (CRI) was created to assess classrooms' internal environmental quality. The CRI is calculated as a percentage based on the number of times the measurement for a given indicator falls within the desirable value range during a specific period. The desirable levels are presented in Chart 1. For example, a CRI of 33% for the illuminance indicator shows that in 33% of the measurements obtained during a given period, the values were between 300 and 500 lux.

Based on the limits and recommended values established by Portuguese legislation and the analysis of literature on environmental indicators, desirable levels for classroom IEQ were defined (Chart 1) as a reference in this study.

Chart 1 – Desirable Levels for Classroom IEQ Indicators

Indicators	Unit of Measure	Desirable Levels for Indoor Environments	References
CO2	Ppm	Up to 1250 ppm for new buildings. Up to 1625 ppm para for old buildings.	(Portugal, 2013)
Temperature	°C	Between 18 °C and 24 °C (Summer and Winter).	(DGAE, 2004)
Humidity	% HR	Between 45% and 55%.	(DGAE, 2004; Earthman, 2002)
Illuminance	Lux	Between 300 and 500 lux (on the work plane).	(DGAE, 2004; Parque Escolar, 2017)

Source: prepared by the authors.

The research was organized into two main phases: (1) measurement of indoor environmental conditions in classrooms throughout the day, including before and after classes; (2) evaluation of the internal environmental quality of classrooms based on the data collected in phase 1 and on parameters established to obtain the CRI for each indicator per classroom, to examine the variation across different class period schedules. The quantification of the moments when the indicators showed percentages above or below the desirable levels was performed to enable the planning of short-, medium-, and long-term actions that would contribute to maintaining the indicators within ideal limits and thus benefit the well-being and performance of the individuals involved.

Characteristics of Schools and Classrooms

The data analyzed in this study were collected from four primary school classrooms (3rd year of primary education) located in three different schools in the North region of Portugal in May 2022. The month of May falls at the end of spring, and Portugal's climate is classified as Mediterranean (Mediterranean hot summer climate [Csa] in the south and Mediterranean warm summer climate (Csb) in the north, according to the Köppen–Geiger climate classification), making it one of the most temperate countries in Europe. According to official data, May 2022 in Portugal was classified as extremely hot and very dry (IPMA, 2022). The average maximum temperature was 26 °C, and the average minimum temperature was 13.3 °C. The maximum recorded temperature for this month was 32.8 °C (on May 27).

Table 1 – Classroom Characteristics

School	Classroom	Construction year	Room area	Total of students	Average Occupancy Ratio (m2/person*)
A	C1	1948**	~50m^2	18	2.6
B	C2	1930	~50m^2	18	2.6
C	C3	2017	~50m^2	25	1.9
	C4	2017	~50m^2	24	2.0

Source: prepared by the authors.
Note: * The number of people was taken to be the total number of students plus one teacher; ** Classroom refurbished in 2013.

The classrooms in schools A and B are located in older buildings, while the classrooms in school C are in a more recent building (built in 2017). All classrooms have a single entrance/exit and windows with blinds/curtains. None of the classrooms has HVAC systems. The two classrooms in school C have radiant floor heating. All the classrooms' lighting systems consist of manually switched fluorescent light tubes (T8 or T12).

Characteristics and Preparation of Collected Data

The sensor units were programmed to record data at intervals of approximately 20 to 30 seconds, resulting in a total of 8.391 million sets of data collected. Once collected, the data for carbon dioxide, temperature, relative humidity, and illuminance inside and outside the classrooms underwent pre-processing. The data from the four classrooms were initially standardized by converting them into one-minute intervals using average, maximum, and minimum values. The Python programming language was used for data pre-processing, and further processing was conducted in the Google Colab environment, also using Python.

To facilitate comparisons, the collected data from the two internal fixation points (front and back) in each classroom were unified using the simple arithmetic mean for each classroom. A new attribute was generated to identify the class period to which each record (hour and minute) belonged. Five 45-minute periods were defined and encoded with labels 1 to 5, according to the time ranges presented in Chart 2. It should be noted that the state schools (C1 and C2) had a slightly different schedule from the private schools (C3 and C4). Two intervals were considered: one between periods 2 and 3, the mid-morning recess, and another between periods 3 and 4, the lunch break. Organizing and encoding the data by time periods allowed the study to focus on analyzing variations at different moments of classwork and to facilitate comparisons between classrooms during these periods. To create a homogeneous dataset among the four classrooms, only data from May 17 to May 30, 2022, were considered.

Chart 2 – Characteristics of Class Periods

Class Periods	Class shifts	Timetables by classrooms	
		C1 and C2	C3 and C4
1	Morning	09:15 – 09:59 AM	09:45 – 10:29 AM
2	Morning	10:00 – 10:44 AM	10:30 – 11:14 AM
3	Lunch	11:15 – 11:59 AM	12:15 – 12:59 AM
4	Afternoon	01:30 – 02:14 PM	02:30 – 03:14 PM
5	Afternoon	02:15 – 02:59 PM	03:15 – 03:59 PM

Source: prepared by the authors.

To support data analysis, two different types of datasets were generated. The first type includes the basic data as collected, minute by minute.

The second type of dataset was generated from processing the Type-1 dataset, with each indoor measurement converted to the respective conformity level described in Chart 3, namely: (4) at the optimal level, (3) at the recommended levels, (2) outside the recommended levels, and (1) at dangerous levels. After conversion, a count of levels 4 and 3, the ones considered acceptable, was calculated for each period.

Chart 3 – Reference Ranges for the analysis of Collected Data

Carbon dioxide (ppm)		**Temperature (°C ±1) (summer)**		**Humidity (%)**		**Illuminance (lux)**	
Range	**Level**	**Range**	**Level**	**Range**	**Level**	**Range**	**Level**
<984	4	<22	3	<35	1	<200	1
>=984, <=1500	4	>=22. <=24	4	>=35. <45	2	>=200. <300	2
>1500, <=1625	3	>24. <25	3	>=45. <=49.499	3	>=300. <400	4
>1625, <=2000	2	>=25	1	>49.4999. <50.5	4	>=400. =500	4
>2000	1			>=50.5. <=55	3	>500. <1000	2
				>55;<=70	2	>=1000	1
				>70	1		

Source: prepared by the authors.

The attributes of the Type-2 dataset, in the CRI unit, are listed in Chart 4. The dataset consists of 200 records, with an equal distribution of 50 records for each of the four classrooms.

Chart 4 – Characteristics of Data in CRI Unit (Type-3)

Attribute	**Description**	**Unit of measurement**
Day	Collection day (1 to10)	Values from 1 to 10
Classroom	Class identification	Label (text)
Period	Class Periods (1 to 5)	Values from 1 to 5
indexCO2	CO2: percentage of occurrences of level 3 or 4	Percentage
indexTemp	Temperature: percentage of occurrences of level 3 or 4	Percentage
indexHumid	Humidity: percentage of occurrences of level 3 or 4	Percentage
indexLumin	Illuminance: percentage of occurrences of level 3 or 4	Percentage

Source: prepared by the authors.

This article chose to focus the analysis on the Type-3 dataset. The other dataset was also used in this study to support analyses, either through statistics or graphs. To better select the data to be used and the statistical tests to be performed, the normality of the Type-3 dataset (aggregated by classroom) was initially verified. The statistical analyses were carried out using IBM SPSS software v.27 (SPSS Corporation, Chicago, IL, USA).

Results and Discussion

This section aims to present the results obtained after processing the previously described data. Although this article focuses mainly on the Type-3 dataset, it is necessary to first present the descriptive statistics and comparative graphs of the measurements obtained for each indicator to better understand the subsequent CRI analyses.

Environmental Measurements per Classroom

Table 2 shows the descriptive statistics (median, mean, standard deviation, minimum, and maximum), which include the averages of each indicator per classroom and period. The results show the following:

- Carbon dioxide: The median and mean values tend to be within the recommended reference values (<= 1625 ppm) in all four classrooms;
- Temperature: The median and mean values tend to be within the recommended reference values (>=18 and <= 25 ºC) in C1 and C2, but not in C3 and C4;
- Humidity: The median and mean values are above the recommended reference values (>= 45 and <= 55 %RH) in all four classrooms;
- Illuminance: Only in classroom C3 did the median and mean values remain within the recommended reference values (>= 300 and <= 500 lux).

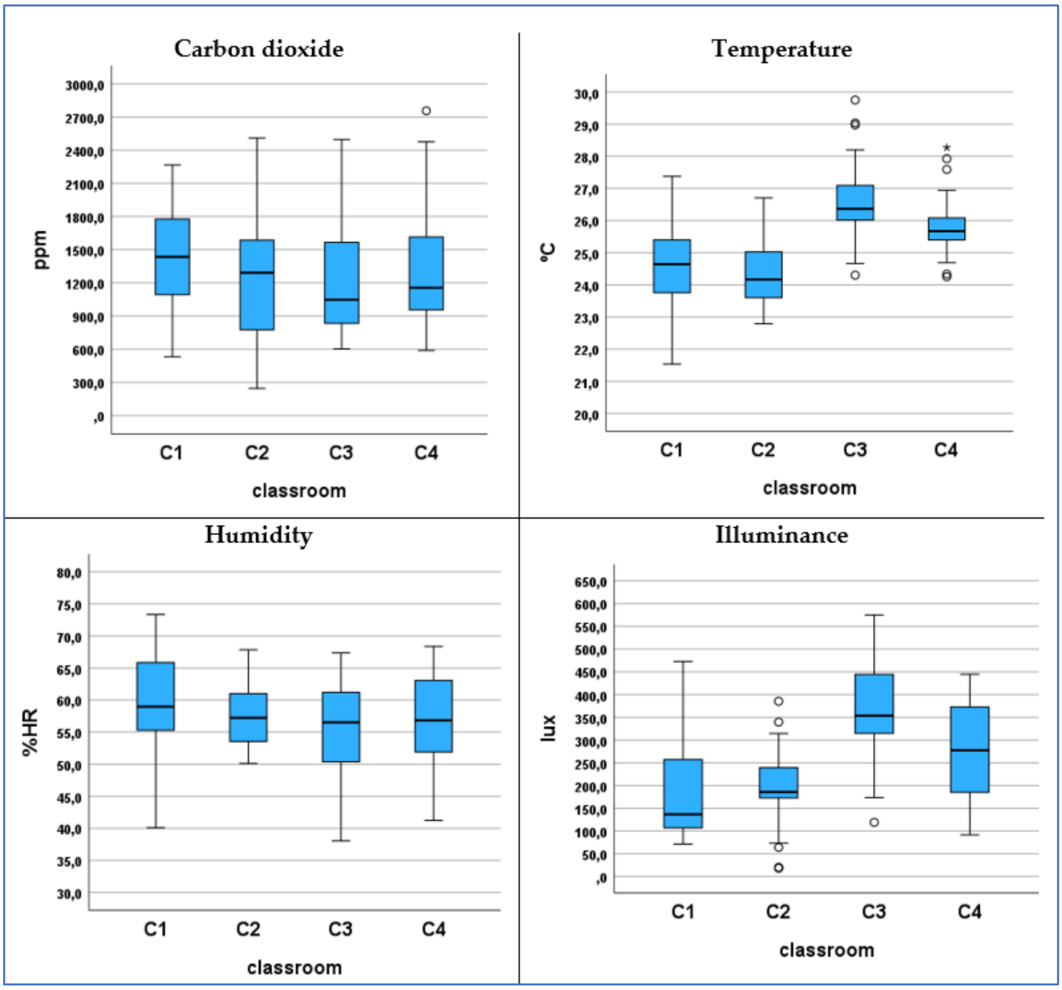
Table 2 – Descriptive Statistics of Type-2 dataset (averages per classroom)

Classroom	Descriptive Statistics	Carbon Dioxide	Temperature	Humidity	Illuminance
C1	Median	1435.627	24.641	58.963	136.722
	Mean	1437.327	24.661	59.942	194.094
	Standard deviation	411.497	1.150	7.277	118.202
	Minimum	531.606	21.529	40.092	71.500
	Maximum	2266.776	27.373	73.343	472.633
C2	Median	1291.799	24.166	57.246	185.678
	Mean	1194.695	24.314	57.811	192.200
	Standard deviation	552.596	.952	4.939	72.231
	Minimum	245.468	22.789	50.111	18.067
	Maximum	2510.838	26.704	67.829	385.133
C3	Median	1047.776	26.362	56.522	353.589
	Mean	1245.535	26.561	55.436	374.111
	Standard deviation	513.273	1.032	7.107	106.732
	Minimum	603.199	24.300	38.038	118.911
	Maximum	2496.915	29.750	67.350	575.089
C4	Median	1156.727	25.668	56.840	277.500
	Mean	1325.348	25.780	57.101	276.984
	Standard deviation	507.885	.784	6.875	99.721
	Minimum	588.793	24.249	41.237	91.378
	Maximum	2756.866	28.271	68.386	444.700

Source: prepared by the authors.

Figure 1 shows boxplot graphs of the data distribution per classroom, allowing a visual assessment of differences and similarities for each indicator. For example, the Temperature graph indicates that C1 and C2 differ from C3 and C4, based on the distance between the box limits. The same applies to the Illuminance graph, where the boxes for C1 and C2 are farther from C3. The significance of these differences is subsequently verified through statistical tests.

Figure 1 – Boxplot Graphs of Measurement Distribution per Classroom



Source: prepared by the authors.

Characteristics of the Distribution of the Conformity Rates dataset

The Kolmogorov-Smirnov test applied to the Type-3 dataset indicates that the data distribution for each classroom is not normal for the four considered attributes ($p < 0.001$ for $\alpha = 0.05$). The Shapiro-Wilk test showed similar results to the Kolmogorov-Smirnov test, although it is more discriminative, especially for reduced sample sizes (Table 3).

Table 3 – Normality Test for the type-3 data set per classroom

Indicators	Classroom	Kolmogorov-Smirnov			Shapiro-Wilk		
		Statistic	**gl**	**Sig.**	**Statistic**	**gl**	**Sig.**
Carbon dioxide	C1	.310	50	<.001	.755	50	<.001
	C2	.318	50	<.001	.720	50	<.001
	C3	.342	50	<.001	.665	50	<.001
	C4	.360	50	<.001	.654	50	<.001
Temperature	C1	.323	50	<.001	.684	50	<.001
	C2	.416	50	<.001	.598	50	<.001
	C3	.498	50	<.001	.267	50	<.001
	C4	.359	50	<.001	.527	50	<.001
Humidity	C1	.427	50	<.001	.580	50	<.001
	C2	.354	50	<.001	.669	50	<.001
	C3	.372	50	<.001	.670	50	<.001
	C4	.367	50	<.001	.658	50	<.001
Illuminance	C1	.398	50	<.001	.548	50	<.001
	C2	.486	50	<.001	.431	50	<.001
	C3	.148	50	.008	.899	50	<.001
	C4	.216	50	<.001	.786	50	<.001

Source: prepared by the authors.

The homogeneity of variance test (Levene's test) was also applied to the Type-3 dataset. The variances among classrooms were found to be homogeneous for Carbon Dioxide and Humidity based on the median, since the significance values are greater than 0.05 ($p = 0.319$ and $p = 0.178$, respectively), but not for the mean ($p = 0.03$ and $p < 0.001$, respectively). As for Temperature and Illuminance, the variances among the groups were not homogeneous (Table 4).

Table 4 – Homogeneity of Variance Test (Levene's test)

		Levene Test	df1	df2	Sig.
Carbon dioxide	Based on mean	3.048	3	196	.030
	Based on median	1.178	3	196	.319
Temperature	Based on mean	46.502	3	196	<.001
	Based on median	10.367	3	196	<.001
Humidity	Based on mean	8.001	3	196	<.001
	Based on median	1.658	3	196	.178
Illuminance	Based on mean	18.330	3	196	<.001
	Based on median	16.154	3	196	<.001

Source: prepared by the authors.

Considering the results of the normality and homogeneity of variance tests, non-parametric tests will be used.

Descriptive Statistics of CRI and Comparative Analysis per Classroom

Table 5 shows the descriptive statistics (median, mean, and standard deviation) of the Type-2 dataset, with emphasis on the median since non-parametric statistical tests will be used. Table 5, with values expressed in percentages, allows us to verify the following:

- Carbon dioxide: The rates were predominantly in conformity with desirable values in all four classrooms, with the lowest median (98%) in C1;
- Temperature: The rates were predominantly in conformity in C1 and C2 (with medians of 99% and 100%, respectively), but not in C3 and C4 (median = 0.00);
- Humidity: The rates were predominantly not in conformity (median = 0.00) in all four classrooms;
- Illuminance: The rates were moderately in conformity in C3 and C4 (with medians of 62% and 53%, respectively) and tended to be non-acceptable values for C1 and C2 (median = 0.00).

Table 5 – Descriptive Statistics of the CRI

Indicators	Descriptive statistics	C1	C2	C3	C4
CO2	**Median**	**97.778**	**100.000**	**100.000**	**100.000**
	Mean	64.356	76.844	75.778	75.289
	Standard deviation	41.448	33.114	37.223	38.429
Temperature	**Median**	**98.889**	**100.000**	**.000**	**.000**
	Mean	58.489	73.289	4.889	12.311
	Standard deviation	47.367	42.798	19.636	26.432
Humidity	**Median**	**.000**	**.000**	**.000**	**.000**
	Mean	19.556	33.556	37.778	31.289
	Standard deviation	35.863	44.606	46.510	43.694
Illuminance	**Median**	**.000**	**.000**	**62.222**	**53.333**
	Mean	19.067	8.089	58.889	51.378
	Standard deviation	36.708	21.577	34.506	43.698

Source: prepared by the authors.

These results indicate that, in general, all classrooms presented acceptable carbon dioxide levels, with no significant risk to the quality of the learning environment. However, it is worth noting that the median in C1 is slightly lower compared to the other classrooms, suggesting a possible difference in air ventilation. As for temperature, only classrooms C1 and C2 showed rates within conformity levels, while the observed values in C3 and C4 indicate that the temperature did not conform to desired standards. Regarding humidity, the results show that the levels recorded in all classrooms were persistently below the desirable standards. As for illuminance, the results show that the levels recorded in C1 and C2 were critical, while the results from C3 and C4 were only moderately aligned with the desirable standards. Table 5 also shows that all the environmental parameters analyzed had high standard deviations, indicating considerable dispersion in the recorded values.

To analyze the differences in the CRI among classrooms, the Kruskal–Wallis test was conducted. The results showed no statistically significant differences between classrooms for carbon dioxide [$X^2(3) = 3.828$; $p = 0.281$] and humidity [$X^2(3) = 3.662$; $p = 0.300$]. However, there were significant differences among classrooms regarding temperature [$X^2(3) = 77.730$; p

< 0.001] and Illuminance [$X^2(3) = 69.354$; $p < 0.001$]. Subsequently, the pairwise comparison test with Bonferroni correction was performed for each indicator. The results showed that, for both temperature and illuminance, the differences occurred between the private school classrooms (C3 and C4) and the state school classrooms (C1 and C2), as shown in Table 6.

Table 6 – Pairwise Comparison by Classroom – Temperature and Illuminance

Temperature					
Sample 1-Sample 2	**Test Statistics**	**Standard Test Statistics**	**Test Statistics**	**Sig.**	**Adj. Sig.[a]**
C3-C4	-16.330	10.508	-1.554	.120	.721
C3-C1	62.000	10.508	5.900	.000	.000
C3-C2	80.590	10.508	7.669	.000	.000
C4-C1	45.670	10.508	4.346	.000	.000
C4-C2	64.260	10.508	6.115	.000	.000
C1-C2	-18.590	10.508	-1.769	.077	.461
Illuminance					
Sample 1-Sample 2	**Test Statistics**	**Standard Test Statistics**	**Test Statistics**	**Sig.**	**Adj. Sig.[a]**
C2-C1	16.730	10.933	1.530	.126	.756
C2-C4	-61.890	10.933	-5.661	.000	.000
C2-C3	-79.060	10.933	-7.231	.000	.000
C1-C4	-45.160	10.933	-4.131	.000	.000
C1-C3	-62.330	10.933	-5.701	.000	.000
C4-C3	17.170	10.933	1.570	.116	.698

Source: prepared by the authors.

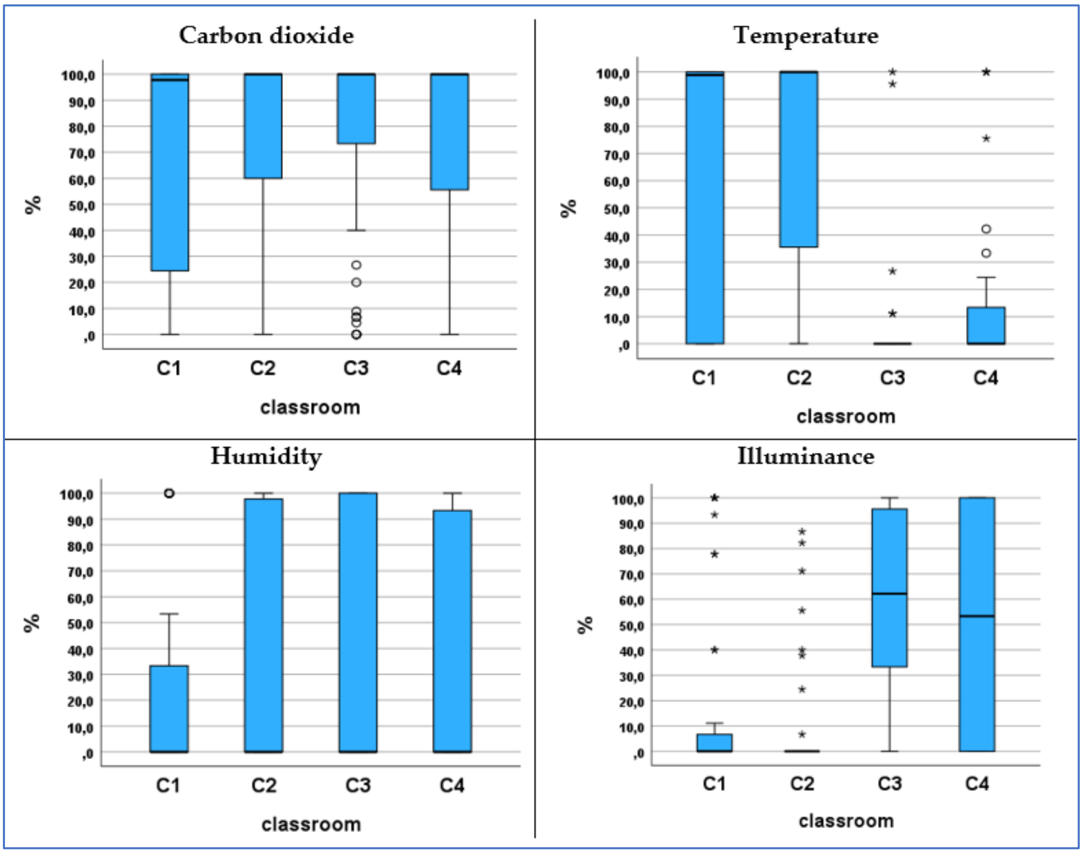
Each line tests the null hypothesis (H0) that the distributions of Sample 1 and Sample 2 are equal. The asymptotic significances (two-sided test) are shown. The significance level is 0.050. The significance values have been adjusted using the Bonferroni correction for multiple tests.

The results of the Kruskal-Wallis tests and the pairwise comparisons can also be visualized in Figure 2, which shows the boxplot graphs of the 'Conformity Rate Indicator' (CRI) distribution of data per classroom for carbon dioxide, temperature, humidity, and illuminance. The graphs on the right (temperature and illuminance) clearly show the differences between C1–C2 and C3–C4. For example, in the temperature graph, C3 and C4 have a distribution significantly different from C1 and C2. The same occurs in the illuminance graph, but in the opposite direction compared to the trend observed in temperature.

Comparison of CRI by Class Period

The graphs in Figure 2 present the variations in carbon dioxide, temperature, humidity, and illuminance during the time considered valid for this analysis (10 days) in the four classrooms, now categorized by class periods (X-axis).

Figure 2 – Boxplot graphs of the distribution of acceptable rate levels per Classroom

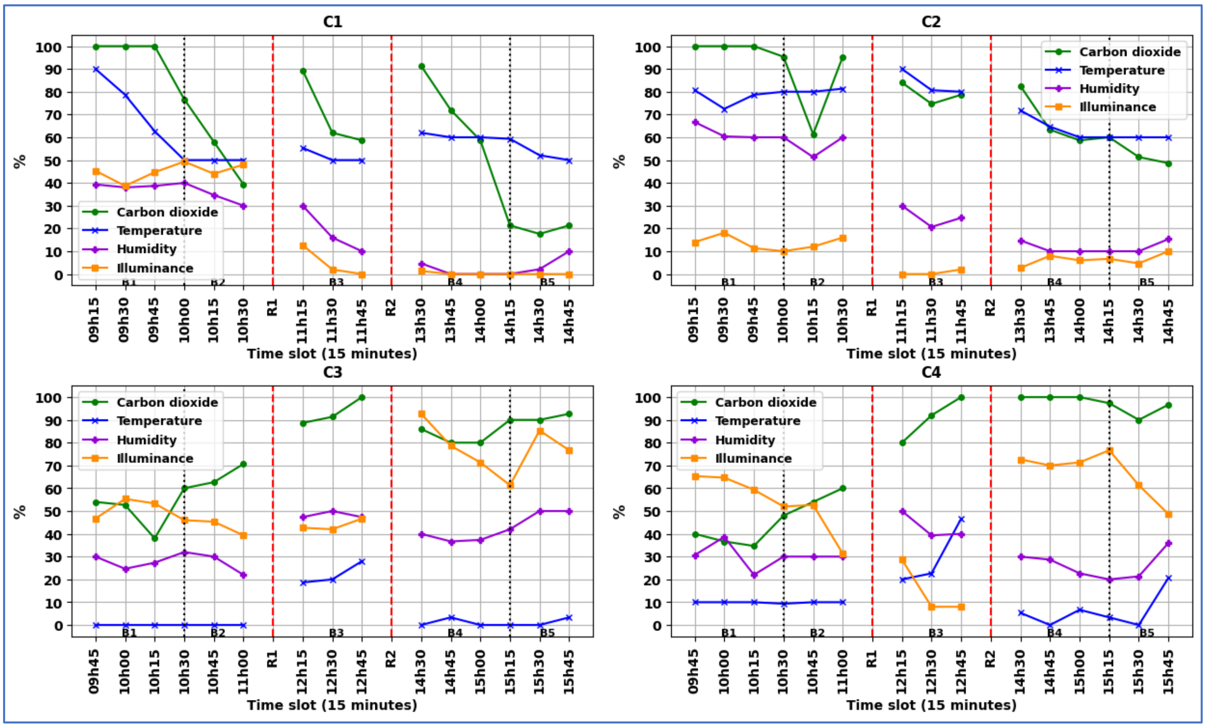


Source: prepared by the authors.

The vertical dashed red lines highlight two intervals: R1 – mid-morning recess; R2 – second recess or lunch break, periods when students are out of the classrooms. The vertical dashed black lines delimit periods B1/B2 and B4/B5. Analyzing Figure 3, the following observations can be highlighted regarding the CRIs detected for each indicator:

- Carbon dioxide (green line): In classroom C1, the rate starts at 100% in period B1 and drops to 40% by the end of period 2, indicating that carbon dioxide levels deteriorate drastically throughout the day. After R1, at the beginning of period 3, the carbon dioxide rate starts at 90% and drops to 60% after 45 minutes. Also, after R2, at the beginning of period 4, the carbon dioxide rate starts at 90% and drops to 20% by the end of period 5. The behavior of this parameter in C2 is similar. In classrooms C3 and C4, which are in the same school, carbon dioxide rates show different behavior compared to C1 and C2. They start between 40% and 50% (period B1) and improve until the end of period 2. In both C3 and C4, the carbon dioxide rate improves after period 3 and continues improving in the afternoon, during periods 4 and 5. This is considered to be associated with the opening of classroom doors and windows;

Figure 3 – CRI per class period (Average per classroom over the 10 days analysed)



Source: prepared by the authors.

- Temperature (blue line): In classroom C1, the rate starts at 90% in period 1 and drops to 40% by the end of period 2, indicating that temperature levels deteriorate compared to acceptable values. In period 3, the rates remain around 50%, and at the beginning of period 4, they are close to 60%, falling slightly by the end of period 5. In classroom C2, the rates start at 80% in period 1 and remain relatively stable until the end of period 3. In the afternoon, period 4 starts with a rate of 70% and drops to 60%. In classrooms C3 and C4, the rates of acceptable temperature levels start with low values, between 0 and 10%, and show improvements throughout the day (due to the south-facing location of the building);
- Illuminance (orange line): In classroom C1, the rate remains around 45% in periods 1 and 2 and drops to levels close to zero from period 3 onwards. The behavior is similar in C2, but with values below 20% starting from period B1. In C3 and C4, the values remain above 50% until the middle of period 2. In C4, the rate drops below 30% in period B3. In both classrooms, the rates rise above 60% in period 4 and start to fall again at the end of period 5.

Differences between CRI regarding periods were also examined using the Kruskal–Wallis test. Regarding the complete dataset, without separation by classroom, the results showed no significant differences between periods for all indicators ($p > 0.05$): (i) Carbon dioxide [$X^2(4) = 8.084$; $p = 0.089$]; (ii) Temperature [$X^2(4) = 3.271$; $p = 0.514$]; (iii) Humidity [$X^2(4) = 6.925$; $p = 0.140$]; (iv) Illuminance [$X^2(4) = 6.764$; $p = 0.149$]. Considering the division by classroom, as shown in Table 7, significant differences were found in relation to the "Time Period" variable, except for Temperature.

Table 7 – Indicators with differences in the Kruskal-Wallis test for the Time Period

Classroom	Indicator	Sig.[a,b]
C1	CO2	<0.001
	Illuminance	0.007
C2	Humidity	0.037
C3	CO2	0.006
	Illuminance	0.024
C4	CO2	<0.001
	Illuminance	0.049

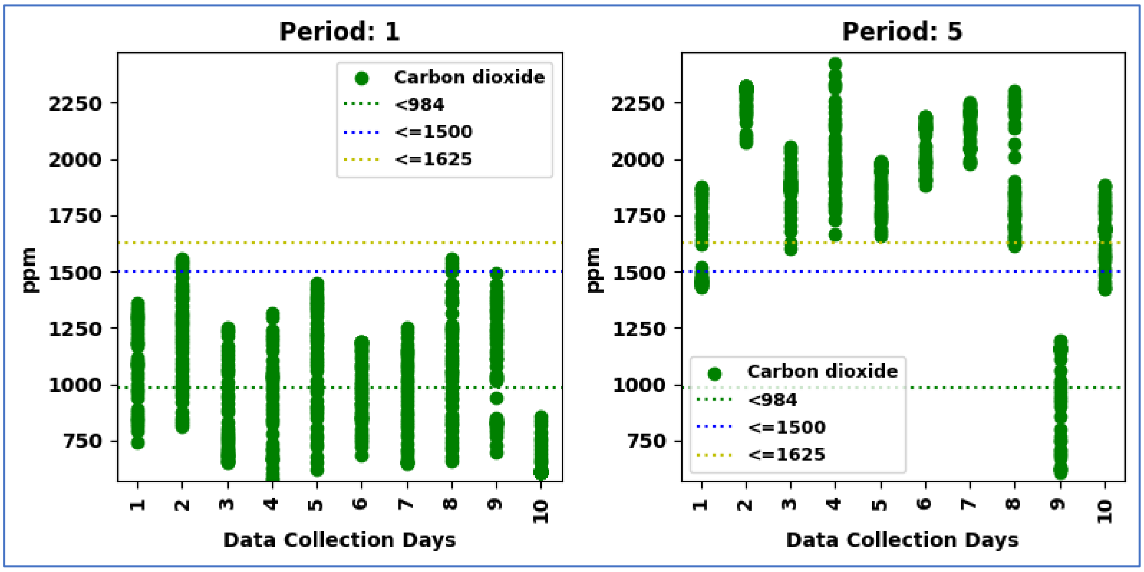
Source: prepared by the authors.

Note: Variable: a=The significance level is .050; b= Asymptotic significance is displayed.

Based on the results shown in Table 6, the pairwise comparison test with Bonferroni correction was applied, revealing the following:

- Carbon dioxide: There are statistically significant differences between periods 1 and 5 in classroom C1 (Adj. Sig. < 0.001) and in C3 (Adj. Sig. = 0.008). In classroom C4, the differences occur between periods 1 and 4 (Adj. Sig. = 0.004), 1 and 5 (Adj. Sig. = 0.016), 2 and 3 (Adj. Sig. = 0.048), 2 and 4 (Adj. Sig. = 0.003), and 2 and 5 (Adj. Sig. = 0.015). Figure 4 allows the differences between the periods in C1 to be observed. It can be noted that, in the graph of period 1, the green dots are predominantly below 1,500 ppm on all 10 days, while in period 5 (end of the day), these dots are predominantly above 1,500 ppm, reaching critical values;

Figure 4 – Comparison of carbon dioxide in classroom C1 in periods 1 and 5

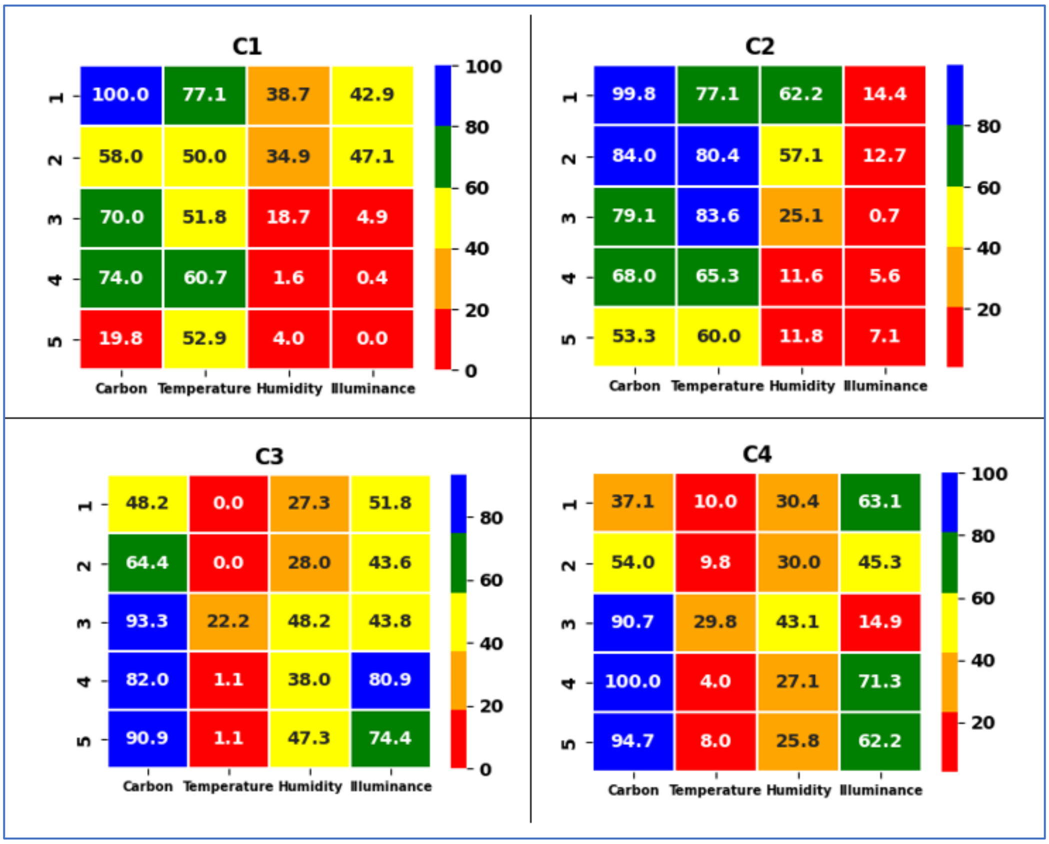


Source: prepared by the authors.

- Humidity: The differences are statistically significant only in classroom C2 and between periods 1 and 4 (p = 0.019), 2 and 4 (p = 0.034), 1 and 5 (p = 0.020), and 2 and 5 (p = 0.036), that is, between the morning and afternoon periods, indicating a significant decline during the day;

- Illuminance: The differences are statistically significant in classroom C1 between periods 1 and 5 (Adj. Sig. = 0.030), showing a substantial decline, and in classroom C4, between periods 3 and 4 (Adj. Sig. = 0.039), indicating a substantial improvement.

Figure 5 – Heatmap of Indicators by Time Period (per classroom)



Source: prepared by the authors.

Figure 5 shows heatmap graphs for each of the four classrooms (C1 to C4), using a five-colour scale representing the extent to which the rates remained within the desired parameters during each of the five periods over the total of ten days. Considering all four indicators, it can be observed that: (i) classroom C2 has the highest favourable index (CRI ≥ 60%), mainly concentrated in the Carbon dioxide and Temperature indicators; (ii) for both C1 and C2, almost all indicators for Humidity and Illuminance are below the desirable range (CRI ≥ 60%); (iii) both C3 and C4 have CRI values below 60% for Temperature and Humidity indicators.

Final considerations

Numerous studies indicate that academic performance is influenced by the IEQ of school buildings, which is positively correlated with students' learning, behaviour, satisfaction, and performance. Considering that primary school students spend many hours in the classroom, it is essential for schools to constantly monitor the internal environmental quality of these spaces and use this information to ensure a clean, healthy, and productive learning environment (Brink *et al*., 2022). This proactive approach can contribute to improving the educational experience, reducing the incidence of environmentally induced health issues, and maximizing student learning potential, as well as teachers' pedagogical activity and well-being.

However, research has shown that the evaluation of the environmental quality of classrooms faces serious limitations: (i) it tends to occur sporadically and episodically; (ii) it is primarily conducted by researchers from other scientific fields, not focusing on education sciences; (iii) it does not tend to collect real parameters but instead relies on user satisfaction surveys.

To counter these limitations, this study examined the internal environmental quality of four primary school classrooms, collecting data on Carbon dioxide, Temperature, Humidity, and Illuminance. The aim was to verify to what extent these indicators remained in conformity with the established desirable parameters. Using the Conformity Rate Indicator metric, the study sought to determine whether there were significant differences in conformity rates among the four Portuguese classrooms and among different time periods throughout the day.

The results showed that, overall, based on the calculated average values, the Carbon dioxide levels tend to fall within the recommended reference values for the four classrooms. Temperature only falls within the reference values in two of the four classrooms (C1 and C2). Humidity levels are above the reference values in all four classrooms, while Illuminance only shows values that fall inside reference ranges in one of the classrooms (C3).

These results indicate that, in general, all classrooms show some environmental values of concern, since these could have adverse consequences on comfort, well-being, and productivity, both for students and teachers. Further investigation is required to identify the causes and to implement appropriate corrective measures.

The results also showed significant differences in the environmental quality of the four classrooms, specifically in Temperature and Illuminance. These indicators showed markedly different values between the classrooms located in state schools, in historical buildings, and the two classrooms located in a private school, which had a more modern building. Illuminance values were more favourable in the classrooms in the private school. Contrary to expectations, the classrooms in the state schools exhibited more acceptable thermal values. It is important to establish that, as the results of this study show, the remarkable differences that tend to be found internationally between private and public-school buildings and working conditions are not found in the Portuguese educational system.

Another finding of this study is related to the analysis of the values recorded for environmental quality indicators during different time periods in the school day. The results show that, when analysed collectively, the indicators tend to show acceptable values. However, when these indicators were analysed separately for the five different time periods considered, critical variations were detected.

In the comparison between periods, in each of the analysed classrooms, the results indicated significant differences in the variations of Carbon dioxide and Illuminance rates in three out of four classrooms, and Humidity in one of these classrooms. Some periods show great variability in different indicators, with a severe and unstable trend of worsening indicators throughout the day, reaching dangerous rates at some moments. Similar results have been found (Catalina *et al*., 2022; Tran *et al*., 2023). The reasons behind this high variation need to be further explored and mitigated.

This study's main contribution lies in the investigation of the time variation of IEQ in classrooms, with a focus on the calculation of conformity rate indicators, bearing in mind the desired values. Unlike opinion-based studies, which can be influenced by subjective biases, the environmental indicators used in this study provide information from reliable measurements, reducing the possibility of distortion in conclusions (Aguilar *et al*., 2022; Brink *et al*., 2022). Additionally, the data analysis procedure adopted in this study is also a relevant input for research on this topic, considering that: (i) the conformity rates of monitored indicators with the values established as desirable by legislation and relevant literature were analysed; (ii) by continuously and transversally collecting data over several working days, the study went beyond simple episodic measurement of environmental indicators. This relationship between continuously collected measurements and reference values allowed for a more profound and comprehensive analysis of the indoor environmental quality of the classrooms, which can impact the effectiveness of learning processes and their outcomes.

Finally, based on the results obtained, the following recommendations are made, primarily for teachers and school boards: (i) raise awareness among the school community about the importance of frequent and continuous monitoring of classrooms' IEQ indicators; (ii) conduct pilot studies involving teachers in data collection (possibly starting with a single indicator and later expanding) and also involving students in the data processing procedure, making it a curricular project; (iii) discuss the results with the teaching staff, also considering the benefits of extending this discussion to other users of the schools' indoor spaces, including students and other stakeholders; (iv) identify practical actions for improving the indicators; (v) develop intervention plans in buildings to improve the environmental quality of classrooms and other working spaces; (vi) create funding projects to enable the acquisition and implementation of automatic monitoring and intelligent control systems for environmental quality. These basic recommendations could significantly contribute to promoting awareness among all education stakeholders about sustainable development inside schools; at the same time, they could also contribute to the adoption of measures related to energy efficiency and sustainability of school buildings (Nakaoka *et al*., 2022).

Specifically for the four classrooms monitored and analysed in this study, the installation of smart HVAC systems is recommended to reduce the amplitude of variations in internal conditions. If installing such systems is not possible, periodic monitoring, for example, during different time periods, is recommended to guide the regular opening of doors and windows. For classrooms with inadequate lighting indicators, a review of the lighting system and ensuring an adequate balance across the entire work area for students and teachers is highly recommended.

Regarding the improvement of IEQ, some interventions that could be considered include: the reduction of students per class; the thermal insulation of walls and windows to reduce unwanted heat transfer; installation of smart thermostats capable of controlling temperature and guaranteeing comfort; installation of ventilation systems for adequate air renewal; installation of lighting systems that can be regulated in intensity to adapt to conditions. Considering energy conservation, it would also be worth studying: the use of thermostats with automatic temperature adjustment based on occupancy schedules; alerts for window/door opening when relevant indicators are unsatisfactory; use of sensors and automated control systems to adjust ventilation based on actual occupancy needs, avoiding energy waste in unused areas; prioritization of the use of natural light to reduce dependency on artificial lighting during the day, especially considering the level of sun exposure that the country offers.

As a continuation of this work, which is part of an ongoing project aimed at enhancing the analysed classrooms (Pedro *et al*., 2023), future plans involve conducting repeat measurements after implementing strategies to enhance ventilation, cooling, and lighting to ensure that children learn in a safe and healthy classroom environment. An intelligent system will be employed to respond promptly whenever indicators fall outside the recommended parameters. Additionally, it is also intended to correlate the data on environmental quality factors collected with the perceptions of students and teachers regarding the comfort of the environment and academic performance.

Limitations

Although this study has achieved significant results and drawn essential conclusions to guide potential actions for the improvement of learning environments, it is crucial to recognize certain limitations in the data collection process, as well as in the decisions made for its pre-processing and analysis.

Firstly, it is important to highlight the limited sample size used in this study, which affects the representativeness of the results. The data were collected in a restricted number of classrooms during a specific time period, in schools with particular locations, building architecture, and facilities. This restricted scope inhibits the generalization of the results even to other classrooms within the same country, due to the significant variability in primary school building characteristics. Although the study considered private and public schools, no comparative approach was taken, considering that in Portugal no significant differences in school building quality can be found between the private and public subsectors. Another critical aspect relates to the fact that the study only considered schools from the northern region of Portugal; therefore, it did not address the climatic variations across different regions of the country. Similarly, data were not collected at different times of the year to capture variability throughout different seasons (seasonal variations). These elements should receive attention in future studies.

Additionally, it is important to acknowledge that not all IEQ parameters were considered. This study did not analyse air velocity, radiant temperature, chemical or biological particles, noise, vibration levels, etc.

Lastly, while this study concentrated on analysing periods of classroom occupation (class periods), it is worth considering that quantifying and examining periods of non-occupation could offer insights into variations during those times. This could potentially enhance the effectiveness of actions aimed at improving IEQ and energy efficiency during such periods.

REFERENCES

AGUILAR, A. J.; DE LA HOZ-TORRES, M. L.; RUIZ, D. P.; MARTÍNEZ-AIRES, M. D. Monitoring and Assessment of Indoor Environmental Conditions in Educational Building Using Building Information Modelling Methodology. **International Journal of Environmental Research and Public Health**, Switzerland, v. 19, n. 21, p. 13756, 2022. DOI: 10.3390/ijerph192113756.

AL HORR, Y.; ARIF, M.; KATAFYGIOTOU, M.; MAZROEI, A.; KAUSHIK, A.; ELSARRAG, E. Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. **International Journal of Sustainable Built Environment**, [*S. l.*], v. 5, n. 1, p. 1–11, 2016. DOI: 10.1016/j.ijsbe.2016.03.006.

ALMEIDA, R. M. S. F.; RAMOS, N. M. M.; DE FREITAS, V. P. Thermal comfort models and pupils' perception in free-running school buildings of a mild climate country. **Energy and Buildings**, [*S. l.*], v. 111, p. 64–75, 2016. DOI: 10.1016/j.enbuild.2015.09.066.

APTE, M. G.; ERDMANN C. A. **Indoor carbon dioxide concentrations, VOCs, environmental sensitivity association with mucous membrane and lower respiratory sick building syndrome symptoms in the base study**: analyses of the 100 building dataset. California: Indoor Environment Group, 2002. Disponible: https://indoor.lbl.gov/publications/indoor-carbon-dioxide-1. Access: 29 Apr. 2025.

BARKMANN, C.; WESSOLOWSKI, N.; SCHULTE-MARKWORT, M. Applicability and efficacy of variable light in schools. **Physiology & Behavior**, [*S. l.*], v. 105, n. 3, p. 621–627, 2012. DOI: 10.1016/j.physbeh.2011.09.020.

BOYCE, P. R. **Human Factors in Lighting**. 3. rd. Boca Raton: CRC Press, 2014.

BRINK, H. W.; LOOMANS, M. G. L. C.; MOBACH, M. P.; KORT, H. S. M. A systematic approach to quantify the influence of indoor environmental parameters on students' perceptions, responses, and short-term academic performance. **Indoor Air**, [*S. l.*], v. 32, n. 10, p. 1–19, 2022. DOI: 10.1111/ina.13116.

CASTILLA, N.; LLINARES, C.; BRAVO, J. M.; BLANCA, V. Subjective assessment of university classroom environment. **Building and Environment**, [*S. l.*], v. 122, p. 72–81, 2017. DOI: 10.1016/j.buildenv.2017.06.004.

CATALINA, T.; GHITA, S. A.; POPESCU, L. L.; POPESCU, R. Survey and measurements of indoor environmental quality in urban/rural schools located in Romania. **International Journal of Environmental Research and Public Health**, [*S. l.*], v. 19, n. 16, p. 10219, 2022. DOI: 10.3390/ijerph191610219.

CHATZIDIAKOU, L.; MUMOVIC, D.; DOCKRELL, J. **The effects of thermal conditions and indoor air quality on health, comfort and cognitive performance of students**. London: The Bartlett, 2014.

CHERYAN, S.; ZIEGLER, S. A.; PLAUT, V. C.; MELTZOFF, A. N. Designing classrooms to maximize student achievement. **Policy Insights from the Behavioral and Brain Sciences**, [*S. l.*], v. 1, n. 1, p. 4–12, 2014. DOI: 10.1177/2372732214548677.

DIREÇÃO-GERAL DA ADMINISTRAÇÃO ESCOLAR. **Normas para concepção e construção de escolas básicas**. Portugal: DGAE, 2004. Disponible: http://www.centroescolar.min-edu.pt/np4/file/9/programa_ii.pdf. Acesso em: 29 abr. 2025.

EARTHMAN, G. I. **School facility conditions and studentacademic achievement**. Los Angeles: UCLA's Institute for Democracy, 2002. Disponible: https://escholarship.org/uc/item/5sw56439. Access: 29 Apr. 2025.

EARTHMAN, G. I. **Prioritization of 31 criteria for an adequate school building**. Baltimore: American Civil Liberties Union, 2004. Disponible: https://www.researchgate.net/publication/239605533_Prioritization_of_31_criteria_for_school_building_adequacy. Access: 29 Apr. 2025.

GRIFFITHS, M.; EFTEKHARI, M. Control of CO2 in a naturally ventilated classroom. **Energy and Buildings**, [*S. l.*], v. 40, n. 4, p. 556–560, 2008. DOI: 10.1016/j.enbuild.2007.04.013.

INSTITUTO PORTUGUÊS DO MAR E DA ATMOSFERA. **Boletim climático Portugal Continental – Maio/2022**. Lisboa: IPMA, 2022. Disponible: https://www.ipma.pt/resources.www/docs/im.publicacoes/edicoes.online/20220608/doEOrQOHPDDWhISEKCGO/cli_20220501_20220531_pcl_mm_co_pt.pdf. Access: 29 Apr. 2025.

JAIN, N. *et al*. Building performance evaluation: Balancing energy and indoor environmental quality in a UK school building. **Building Services Engineering Research and Technology**, [*S. l.*], v. 41, n. 3, p. 343–360, 2020. DOI: 10.1177/0143624419897397.

LEWINSKI, P. Effects of classrooms' architecture on academic performance in view of telic versus paratelic motivation: a review. **Frontiers in Psychology**, Lausanne, v. 6, p. 1–5, 2015. DOI: 10.3389/fpsyg.2015.00746.

LIU, S.; YOSHINO, H.; MOCHIDA, A. A measurement study on the indoor climate of a college classroom. **International Journal of Ventilation**, [*S. l.*], v. 10, n. 3, p. 251–261, 2011. DOI: 10.1080/14733315.2011.11683953.

MOHAMED, S.; RODRIGUES, L.; OMER, S.; CALAUTIT, J. Overheating and indoor air quality in primary schools in the UK. **Energy and Buildings**, [*S. l.*], v. 250, p. 111291, 2021. DOI: 10.1016/j.enbuild.2021.111291.

MOLDOVEANU, A. M. Biological Contamination of Air in Indoor Spaces. *In*: NEJADKOORKI, F. (org.). **Current Air Quality Issues**, [*S. l.*], p. 489–514, 2015. DOI: 10.5772/59727.

NAKAOKA, H.; SUZUKI, N.; EGUCHI, A.; MATSUZAWA, D.; MORI, C. Impact of exposure to indoor air chemicals on health and the progression of building-related symptoms: a case report. **Sustainability**, [*S. l.*], v. 14, n. 21, p. 14421, 2022. DOI: 10.3390/su142114421.

PARQUE ESCOLAR. **Especificações Técnicas de Arquitetura para Projeto do Edifício Escolar**. [*S. l.*], Parque Escolar, 2017. Disponible: https://construcaopublica.gov.pt/docs/site/pt/programa/Parque-Escolar-Manual-Especificacoes-Tecnicas-Arquitetura.pdf. Access: 29 Apr. 2025.

PEDRO, N.; SARDINHA, L.; PIEDADE, J.; CRUZ, E.; AGONÁCS, N.; PEDRO, A.; RODRIGUES, A. L. Digital Technologies and Innovative Learning Environments: a project for studying its impact on Students' performance and wellbeing. *In*: International Technology, Education and Development Conference, 17., 2023, Valença. **Proceedings** […]. Valença: IATED, 2023. p. 8031–8040.

PORTUGAL. Portaria n.º 353, de 4 de dezembro. Ministério do Ambiente. **Diário da República**: 1.ª série, n. 235, p. 6644(2)-6644(9), 2013. Disponible: https://diariodarepublica.pt/dr/detalhe/portaria/353-2013-484380. Access: 29 Apr. 2025.

PULIMENO, M.; PISCITELLI, P.; COLAZZO, S.; COLAO, A.; MIANI, A. Indoor air quality at school and students' performance: recommendations of the UNESCO chair on health education and sustainable development & the Italian society of environmental medicine (SIMA). **Health Promotion Perspectives**, [*S. l.*], v. 10, n. 3, p. 169–174, 2020. DOI: 10.34172/hpp.2020.29.

ROSKOS, K.; NEUMAN, S. B. The classroom environment. **The Reading Teacher**, [*S. l.*], v. 65, n. 2, p. 110–114, 2011. DOI: 10.1002/TRTR.01021.

SAMANI, S. A.; SAMANI, S. A. The Impact of Indoor Lighting on Students' Learning Performance in Learning Environments: A knowledge internalization perspective. **International Journal of Business and Social Science**, [*S. l.*], v. 3, n. 24, p. 127–136, 2012.

SCHNEIDER, M. **Linking School Facility Conditions to Teacher Satisfaction and Success**. Washington: National Clearinghouse for Educational Facilities, 2003. Disponible: https://eric.ed.gov/?id=ED480552. Access: 29 Apr. 2025.

TRAN, M. T.; WEI, W.; DASSONVILLE, C.; MARTINSONS, C.; DUCRUET, P.; MANDIN, C.; HÉQUET, V.; WARGOCKI, P. Review of parameters measured to characterize classrooms' indoor environmental quality. **Buildings**, Basel, v. 13, n. 2, p. 433, 2023. DOI: 10.3390/buildings13020433.

WARGOCKI, P.; WYON, D. P. Providing better thermal and air quality conditions in school classrooms would be cost-effective. **Building and Environment**, [*S. l.*], v. 59, p. 581–589, 2013. DOI: 10.1016/j.buildenv.2012.10.007.

YANG, Z.; BECERIK-GERBER, B.; MINO, L. A study on student perceptions of higher education classrooms: Impact of classroom attributes on student satisfaction and performance. **Building and Environment**, [*S. l.*], v. 70, p. 171–188, 2013. DOI: 10.1016/j.buildenv.2013.08.030.

ZHONG, L.; YUAN, J.; FLECK, B. Indoor Environmental Quality Evaluation of Lecture Classrooms in an Institutional Building in a Cold Climate. **Sustainability**, [*S. l.*], v. 11, n. 23, p. 6591, 2019. DOI: 10.3390/su11236591.

ZHONG, S.; LALANNE, D.; ALAVI, H. The complexity of indoor air quality forecasting and the simplicity of interacting with it – a case study of 1007 office meetings. *In*: Chi conference on human factors in computing systems, 21, 2021, Yokohama, Japan. **Proceedings** […]. New York: Association for Computing Machinery, 2021. p. 1–19.

ZOMORODIAN, Z. S.; TAHSILDOOST, M.; HAFEZI, M. Thermal comfort in educational buildings: A review article. **Renewable and Sustainable Energy Reviews**, [*S. l.*], v. 59, p. 895–906, 2016. DOI: 10.1016/j.rser.2016.01.033.

CRediT Author Statement

- **Acknowledgements**: None.
- **Funding**: This work was supported by National Funds through FCT—Portuguese Foundation for Science and Technology, I.P., within the scope of UIDEF – Research and Development Unit in Education and Training, UIDB/04107/2020, https://doi.org/10.54499/UIDB/04107/2020. It originated from a research project entitled "Classroom 4.0 – well-being resources: research and development of school furniture solutions that influence and monitor students' well-being and health in the classroom, promoting conditions for superior academic performance" (Ref. POCI-01-0247-FEDER-047130/LISBOA-01-0247-FEDER-047130), co-financed by Lisboa 2020, COMPETE 2020, Portugal 2020, and the European Union—FEDER.

- **Conflicts of interest**: No conflicts of interest.
- **Ethical approval**: The study was derived from the aforementioned project, which was duly submitted to the Ethics Committee of the Institute of Education, University of Lisbon, and received favorable approval.
- **Data and material availability**: Supplementary material provided.
- **Authors' contributions**: Neuza Pedro contributed to the planning of the data collection process and overall project management enabling such collection, supervised the data analysis process and results production, contributed to the elaboration of conclusions, selection of some key elements for the presented literature review, and also assumed the final review of the text and its adaptation to the formal requirements of this journal. Edson Pimentel was responsible for data preparation and analysis production, as well as the presentation of results; he also structured the central elements of the framework and drafted the preliminary version of the conclusions. The other authors equally contributed to different phases of the study's development and the production of this article proposal, particularly in conceptualization, methodology, understanding and discussion of results, and overall review of the final version produced.

Processing and editing: Editora Ibero-Americana de Educação
Proofreading, formatting, standardization and translation

EDITORA IBERO-AMERICANA