

Article

Improving Indoor Air Quality in a Higher-Education Institution Through Biophilic Solutions [†]

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Abstract: Schools are vital infrastructures where students acquire essential skills and foster social values. Indoor air quality (IAQ) is of paramount importance in schools, given that students spend a considerable amount of time indoors. This study examines the influence of a natural green structure (NGS) on IAQ in an Eco-Campus classroom. The IAQ of a classroom with an NGS was compared to that of an adjacent classroom without an NGS. The thermal conditions were monitored, including air temperature (T) and relative humidity (RH), as well as indoor pollutants, including carbon dioxide (CO₂), volatile organic compounds (VOCs), and particulate matter (PM_{2.5} and PM₁₀). The findings indicated a substantial improvement in indoor air quality in the classroom where the green structure was installed. This study lends support to the incorporation of biophilic solutions as sustainable approaches to fostering healthier learning environments, which in turn can lead to improvements in student performance and well-being.

Keywords: sustainable education environment; biophilic solutions; indoor air quality in classrooms; student health; well-being



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1. Introduction

According to information published by the United Nations (UN), atmospheric pollution is responsible for around 7 million deaths annually. The World Health Organization (WHO) states that atmospheric pollution exists when an environment is contaminated, whether internal or external, by a chemical, physical, or biological agent, which is responsible for modifying the natural characteristics of the atmosphere [1]. Indoor air quality (IAQ) in buildings has a very significant influence on the health of the occupants and contributes significantly to sick building syndrome. This aspect becomes especially relevant given that 87% to 90% of the global population's time is spent inside buildings [2]. These environments often lack adequate air quality due to synthetic materials used on furniture

and surfaces, insufficient ventilation, inadequate temperature, and humidity conditions. Poor IAQ can cause discomfort or health problems, such as respiratory issues, and have negative impacts on a population, cognitive abilities, and productivity.

Schools are one of the most important infrastructures in society, serving as learning places where children and young people develop essential skills and knowledge, promoting equal opportunities for all students, and acting as social elevators. Furthermore, schools provide one of the earliest contexts in which children engage in social activities and develop values of citizenship and inclusion, preparing them to actively participate in society. Schools also have a fundamental role in providing a positive and welcoming environment, helping students feel valued and supported. Nowadays, children and young people spend most the majority of their time in an indoor environment, namely school, highlighting the importance of proper IAQ. It has been found that poor IAQ in schools, in addition to its adverse effects on health [3–7], can also impact productivity, concentration, and performance [8–11]. Moreover, environments with good air quality have been demonstrated to contribute to reducing absenteeism, maintaining high school attendance. It is therefore essential to invest further in the improvement of schools' air quality to ensure the creation of healthy, safe, and welcoming learning environments. Among the various internal contaminants, particularly in schools with high classroom occupancy rates, it is imperative to conduct a comprehensive analysis of the several contaminants to assess IAQ, namely, carbon dioxide (CO₂), total volatile organic compounds (VOC_T), and suspended particulate matter (PM_{2.5} and PM₁₀).

It is known that elevated levels of CO₂ have been linked to higher levels of drowsiness, reduced cognitive function, inflammation, and kidney and bone issues [12,13]. These effects are of significant concern, particularly in educational facilities, which are characterized by a high density of occupants. Indeed, the density in such institutions can reach levels up to four times higher than that of office buildings [14]. Given the pivotal role of this factor, there has been a notable increase in the number of studies conducted on a global scale [15–20], including in Portugal [21–23], where this study was conducted. However, studies on indoor air quality (IAQ) are more often concern primary-school buildings since children are more vulnerable to indoor air pollutants [6,9,10,17,20,24].

Volatile organic compounds (VOCs) are a varied group of organic chemicals that are commonly found in urban environments. They originate from both biogenic and anthropogenic sources and can be present in indoor and outdoor environments. Exposure to these pollutants can lead to numerous harmful health effects. For instance, benzene and tetrachloroethylene are classified as Group 1 carcinogens by the International Agency for Research on Cancer [25]. Exposure to VOCs can lead to symptoms such as eye, nose, and throat irritation; headaches; nausea; asthma; and potential damage to the liver, kidneys, and central nervous system [26–29].

It is well established that particle exposure can lead to numerous health issues, including respiratory symptoms, cardiovascular diseases, reduced lung function, and premature death [30–33]. The health effects of suspended particulate matter are closely linked to the size of the particles [34,35]. The impact of PM_{2.5} on human health has been researched for over a decade, with the results showing that it contributes to lung and cardiovascular issues [36,37].

With these impacts in mind, it is critical to develop and implement strategies for improving IAQ, especially in schools, in order to promote preventive health measures that will have short-, medium-, and long-term impacts on public health and in health systems. Achieving good indoor air quality involves several approaches, such as air purification, increasing ventilation to bring in fresh air, diluting contaminants/pollutants, and eliminating or minimizing sources of pollution. In a recent development, the Italian

Society of Environmental Medicine (SIMA) and UNESCO's Chair on Health Education and Sustainable Development put forth recommendations for enhancing indoor air quality in schools. One notable suggestion was the adoption of biophilic solutions, which involve using plants as natural filters to help absorb indoor pollutants [38].

In the last few years, nature-based solutions and biophilic design have been receiving an increasing amount of attention in the field of architecture due to increasing environmental challenges. In 1984, the National Aeronautics and Space Administration (NASA) introduced botanical systems as an alternative method for treating indoor air pollutants as part of a research program that aimed to develop "Biological Life Support Systems" for long-term space habitation. This research showed that potted plants could effectively remove a wide variety of VOCs. Subsequent studies at the Mississippi National Space Technology Laboratory further developed a biological air purification system using houseplants, designed for closed environments, like space stations and energy-efficient homes [39].

In recent times, there has been growing emphasis on biophilic design, spurred by numerous studies highlighting the benefits of plants. These benefits range from visual comfort and stress reduction to improved psychological and physical well-being, ultimately enhancing productivity. Furthermore, plants have been linked to quicker thinking, enhanced attention, and superior cognitive development, all of which are particularly pertinent in educational settings [40]. A study conducted at Harvard University's Smith Campus found that when plants are incorporated into interior green-wall designs, they can effectively decompose and absorb VOCs, improving air quality while providing aesthetic benefits [20]. Also, a study from Harvard in 2021 stated that there is "emerging evidence that air pollution has an impact on our brain" and showed that increases in small particle ($PM_{2.5}$) levels were associated with large reductions in cognitive function [41]. In Figure 1, a schematic diagram is presented, illustrating the fundamental air-quality-related environmental and building conditions that lead to healthy (or sick) occupants of spaces.

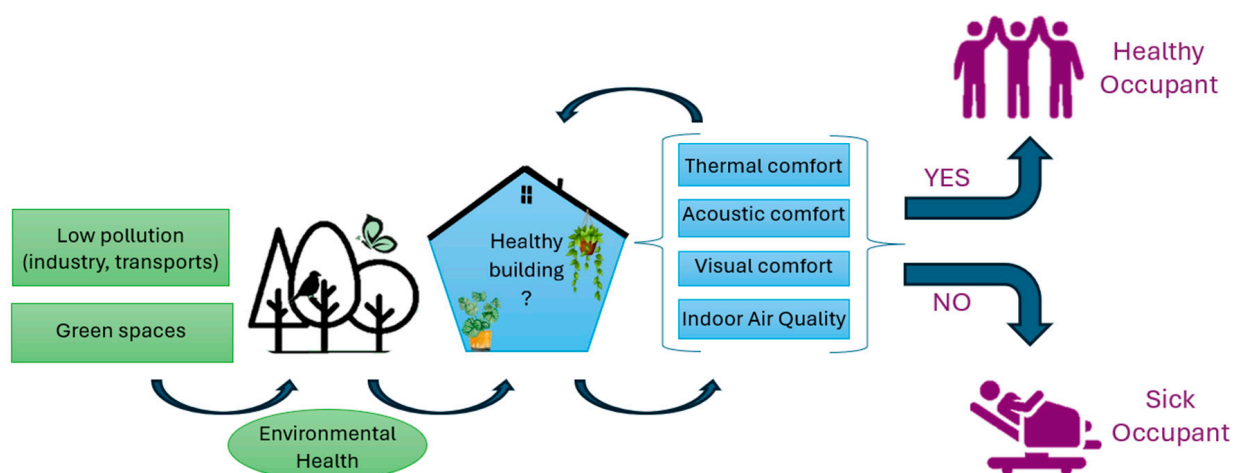


Figure 1. Diagram depicting the fundamental air-quality-related conditions that need to be met to achieve a healthy building with healthy occupants.

Although several studies have analyzed IAQ and the impact of biophilic solutions in schools, as mentioned, most of them were related to kindergartens and elementary and high schools, and a few studies were carried out at higher-education institutions (HEIs), where students spend a large part of their time and often find themselves in situations of psychological stress [20]. The implementation of biophilic solutions at HEIs could prove to be an easy and interesting strategy with a positive impact on both physical and psychological health, contributing to the well-being of students.

In the present study, a biophilic solution was implemented to assess the effectiveness of plants in removing indoor air pollutants in a real-life setting, namely, an HEI. A natural green structure (NGS) was installed in an Eco-Campus classroom, whose indoor air quality was compared to that of an adjacent classroom without an NGS. Several parameters were measured, namely, carbon dioxide (CO_2), total volatile organic compounds (VOC_T), suspended particulate matter ($\text{PM}_{2.5}$ and PM_{10}), and, as comfort is significantly affected by thermal conditions, temperature and relative humidity.

The Sustainable Development Goals (SDGs) defined by the UN 2030 Agenda are of great importance in the field of education, providing a global framework for addressing a range of social, economic, and environmental challenges. In this study, we also sought to integrate the SDGs into the educational curricula at ISEL, with the goal of enhancing community awareness about environmental sustainability. This study places particular emphasis on the promotion of good health and well-being, improving air quality through biophilic solutions, and urban sustainability. The authors believe that education and research conducted at HEIs, in alignment with the SDGs, are essential for fostering innovation. This alignment contributes to the development and implementation of concrete solutions that contribute to the creation of resilient and healthier communities.

2. Materials and Methods

2.1. Building Characterization

To carry out this study, two classrooms were selected from an HEI Eco-Campus, namely, Instituto Superior de Engenharia de Lisboa (ISEL). These classrooms will be designated from now on as green room (GR—a classroom with a natural green structure (NGS), i.e., with plants) and neutral room (NR—a classroom without a natural green structure (NGS), i.e., without plants). The classrooms were selected based on the following criteria: the classrooms had to be contiguous, with the aim of having the same sun exposure with identical glazing area; have equal area; and have a high student occupancy rate (maximum of 50 occupants). Both classrooms presented identical furniture, desks, and chairs for students and professors.

Regarding materials, in both classrooms, the floor was covered with wooden parquets, walls were plastered and painted, and there was a whiteboard fixed to the wall and projection equipment fixed to the ceiling. In both classrooms, the window frames were made of iron, and the windows themselves were single-glazed glass; these windows were located on two opposite side walls, presenting different dimensions and solar orientations. The southwest facade had casement windows that were hinged at the side and fitted in triple panels, with a total area of 12.84 m^2 (Figure 2a). These windows, in both classrooms, were equipped with adjustable curtains for shading, which were installed three months prior to the IAQ monitoring. At the top of the northeast facade, there were awning windows that opened outward from a top-frame hinge (Figure 2b), with a total area of 3.90 m^2 . Although these windows had no shading devices, the northeast-facing façade receives minimal sunlight, limited to just a few minutes in the early morning. There was no air conditioning, and the classroom was only ventilated naturally through the windows and the door, which opened directly onto an outside patio (Figure 2c). During the monitoring period, the windows were always kept closed, and the rooms were ventilated exclusively by opening the door. Each classroom had an area of 74 m^2 , an average ceiling height of 3.25 m , and a volume of 241 m^3 . Figure 2d provides a schematic representation of the green room (GR) and neutral room (NR). It is important to acknowledge that these classrooms were not equipped with air-conditioning or heating systems, which are important for maintaining optimal thermal comfort. Additionally, the glazed areas were characterized by the presence of single-pane glass, which often required the doors and windows to

remain closed for extended periods during the winter months to keep the classrooms warmer. This practice impacts indoor air quality, an aspect that we also aim to assess in this study.

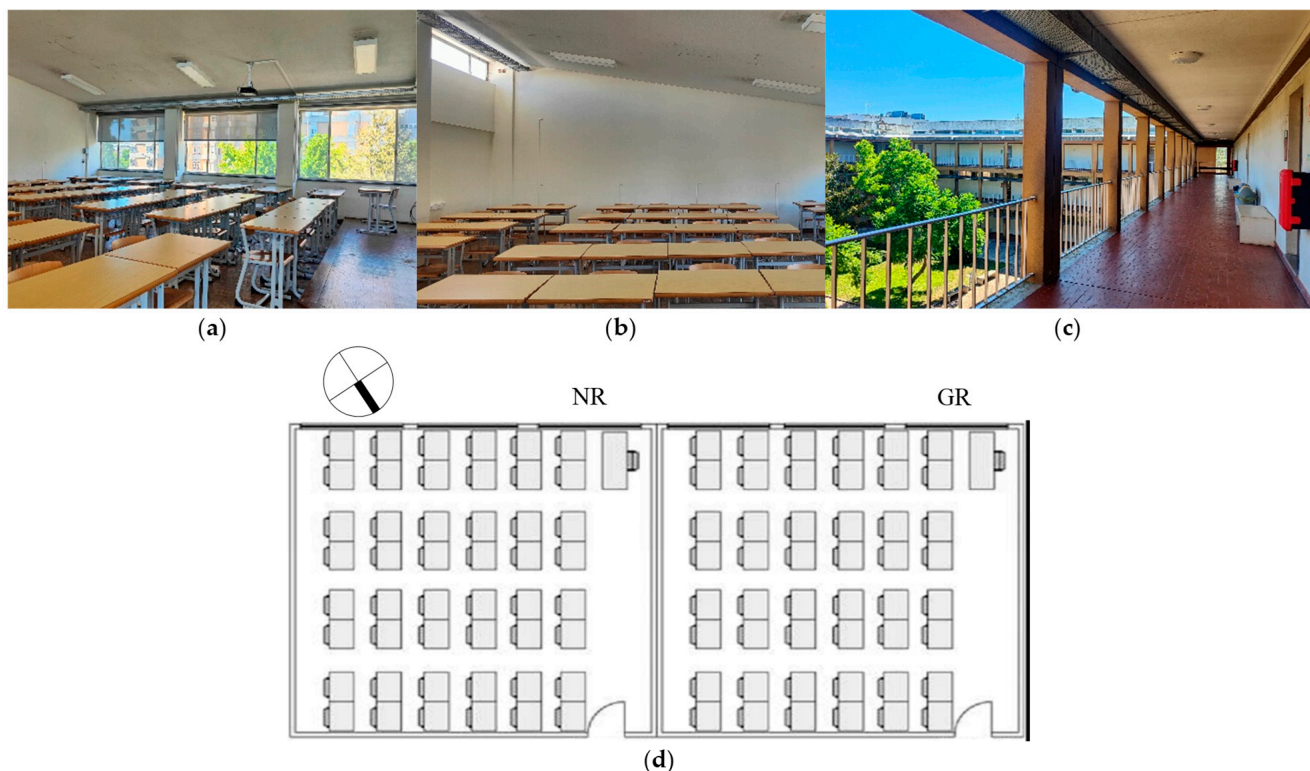


Figure 2. Classrooms studied: (a) southwest facade with triple-pane casement windows; (b) northeast facade with awning windows; (c) hallway that provides direct access to the classrooms and an outdoor patio; (d) schematic representation of the GR and NR.

2.2. Natural Green Structure

To carry out this study, a natural green structure (NGS) was designed, considering the classrooms' geometries and the arrangement of the furniture, with the aim of having the least impact on students' circulation. In consideration of the aforementioned factors, the number and type of plants selected, along with the various forms of support, were defined. These included vases on the floor (of different dimensions and volumes), vases suspended from the ceiling, and trellises for climbing plants. In all vases, in addition to the substrate, expanded clay particles were added in order to lighten the substrate and maximize water storage and retention capacity.

The selection of plant species to be integrated into the GR was based on their documented capacity to absorb specific indoor pollutants, as evidenced by numerous research studies, referenced in Table 1. The species chosen were (Figures 3 and 4 and Table 1) *Dracaena trifasciata* or *Sansevieria trifasciata*; *Chlorophytum comosum*; *Scindapsus aureus*; *Dypsis lutescens*; *Aloe vera*; and *Ficus benjamina*.

The NGS was installed on the back wall (the wall opposite the whiteboard) and on the side walls (some near the ceiling) of the GR. Table 2 presents the scientific names of the species, vase designations and quantities, the number of vases used for plant installation, and their respective dimensions.

Photosynthesis is a biological process wherein plants convert light energy into chemical energy through light-dependent reactions in the thylakoid membranes. Carbon fixation (Calvin cycle), in which CO_2 is converted into sugars, happens in the stroma [42]. C3 plants have been observed to fix CO_2 directly via Rubisco into 3-phosphoglycerate (3-PGA) during

daylight hours, exhibiting optimal growth in moderate climates [43]. CAM plants have been shown to open their stomata at night in order to convert CO₂ into malate and store it for subsequent use during the day, thus minimizing water loss in arid conditions [44]. C3 plants demonstrate efficiency under conditions of elevated CO₂ [45], while CAM plants perform optimally in drought-tolerant environments [46]. The photosynthesis mechanisms of the studied plants are shown in Table 1.

Table 1. List of plants selected for the case study.

Scientific Name	Common Name	Importance as an Indoor Plant	Mechanisms of Photosynthesis
<i>Dracaena trifasciata</i> or <i>Sansevieria trifasciata</i> or <i>Sansevieria laurentii</i>	Mother-in-law's tongue or snake plant	Ability to absorb VOCs [47–50] Ability to absorb PM [48,51,52]	CAM [40,53]
<i>Chlorophytum comosum</i>	Spider plant	Ability to absorb VOCs [47,49,54–57] Ability to absorb PM [52,58] High ability to absorb CO ₂ [59]	C3 [53]
<i>Scindapsus aureus</i> (Europe) or <i>Epipremnum aureum</i> (USA and Canada)	Golden pothos or Devil's ivy	Ability to absorb VOCs [47,54] Ability to absorb PM [51,52] High ability to absorb CO ₂ [59]	C3 [40]
<i>Dyopsis lutescens</i>	Areca palm	Ability to absorb VOCs [60]	C3 [40]
<i>Aloe vera</i>	Aloe vera	Ability to absorb VOCs [49,50] Ability to absorb PM [52]	CAM [61]
<i>Ficus benjamina</i>	Ficus	Ability to absorb VOCs [50,62,63]	C3 [40]

To aid comprehension of the locations of the plants, a number was assigned to each species/location (Table 2 and Figure 3).

Table 2. Compositions of the NGSs installed in GR.

Species	Designation N.º	N.º of Vases	Location	Vases' Dimensions (cm) Length × Depth × Height or Diameter (Ø) × Height
<i>Dracaena trifasciata</i>	1	2	Side wall—southwest facade	100 × 40 × 40
<i>Chlorophytum comosum</i>	2	2	Side wall—southwest facade	100 × 40 × 40
	and 7	3	Back wall	100 × 40 × 40
<i>Scindapsus aureus</i>	3 and	4	Suspended side walls: 2 by southwest façade, and 2 by northeast facade	Ø 37 × 22
	8	3	Back wall (trellises)	100 × 40 × 40
<i>Dyopsis lutescens</i>	4	2	Back wall	40 × 40 × 65
<i>Aloe vera</i>	5	2	Back wall	Ø 60 × 43.5
<i>Ficus benjamina</i>	6	2	Back wall	Ø 50 × 100

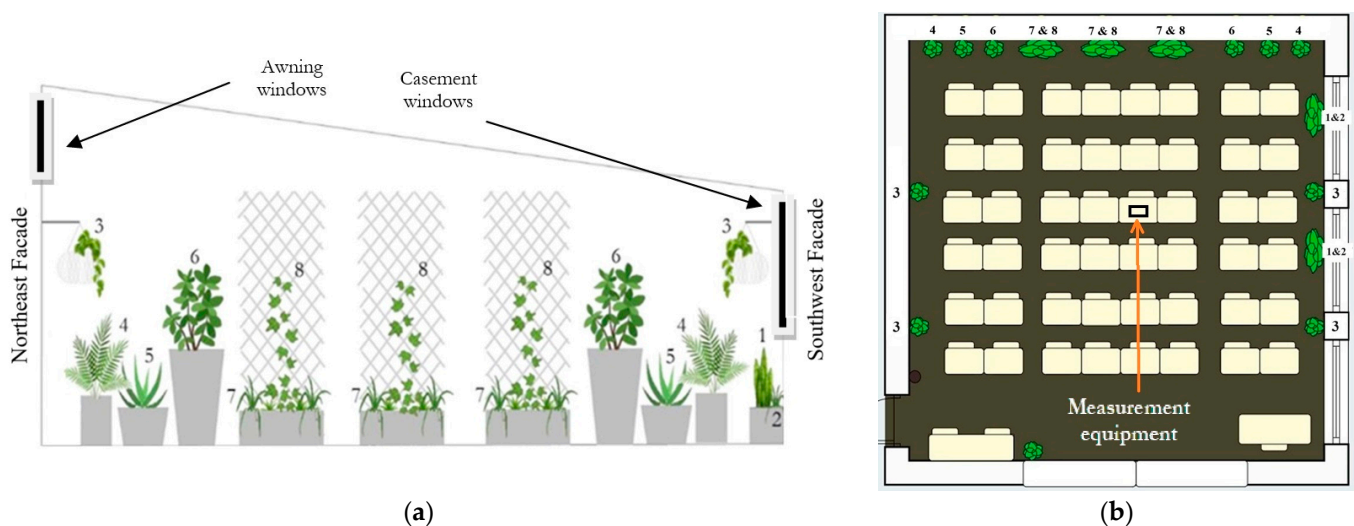


Figure 3. Schematic representation of the NGS installed in the GR, showing the plants' locations: (a) back wall (adapted from [64]); (b) classroom plan. 1—*Dracaena trifasciata*; 2 and 7—*Chlorophytum comosum*; 3 and 8—*Scindapsus aureus*; 4—*Dypsis lutescens*; 5—*Aloe vera*; and 6—*Ficus benjamina*.

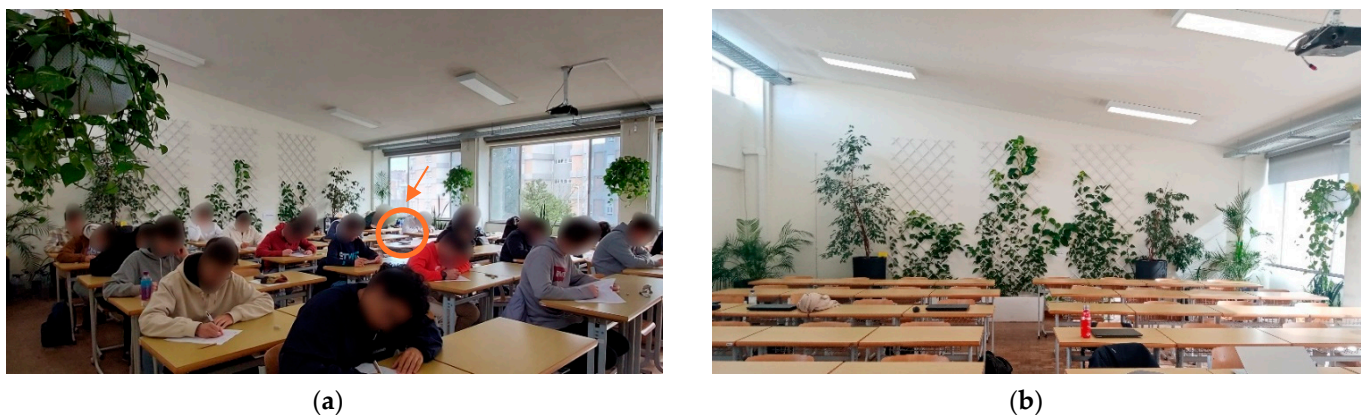


Figure 4. Green room (GR) studied, indicating the location of the IAQ-measuring equipment in (a) January 2024 [65] and (b) October 2024.

2.3. Air Quality Monitoring

Prior to conducting the monitoring procedures within the classrooms, the equipment was positioned in the corridor that connects the classrooms to a patio (see Figure 2c). At the same time, the doors and windows of the two classrooms under observation were left open for a period of 45 min in order to facilitate ventilation and ensure that the parameter values approximated those of the outdoor environment. The outdoor values recorded were 420 ppm for CO₂ and 7 µg/m³ for VOCs. On the day of monitoring, the maximum temperature recorded was 14 °C, while the minimum temperature was 5 °C. It is worth noting that the CO₂ and VOCs values recorded in the outdoor environment exhibited a high degree of similarity to those recorded in the classroom at the beginning of the monitoring period, prior to the entry of the occupants into the classrooms (see Results, Section 3.1). While minor infiltration of outdoor air through the building envelope is possible, these low outdoor levels suggest there is a minimal impact on indoor air quality measurements, considering the maximum values recorded.

IAQ monitoring was conducted in accordance with the methodology stipulated in ISO 16000-1 [66]. The measuring equipment was placed on a flat table surface at a height of 0.77 m in order to simulate the breathing zone. This was deemed the most appropriate

position for the equipment, given its stability when positioned on a table in the middle of the classroom (see Figure 3a). The objective of this study was to conduct a comparative analysis between the two classrooms, ensuring that the equipment was in the same position in order to maintain identical conditions. In accordance with the standard, the sampling point must be situated at a minimum distance of 1 m from sources of contamination (windows and doors) at the level of the respiratory tract. In accordance with Portuguese Legislation, Order No. 138-G/2021 [67], direct reading is defined as a method of measuring the parameters in a representative sample of locations and periods that reflect typical activities.

The monitoring of IAQ parameters was conducted in both classrooms prior to the installation of the natural green structures and in the absence of occupants. This monitoring was conducted in the month of May in 2022, at 8:00 am, following a period of complete closure of the classrooms starting at 11:00 pm the previous day (the time at which the previous class concluded), with doors and windows securely sealed and without any ventilation. The values recorded in the GR were 453.0 ppm for CO₂ and 858.9 µg/m³ for VOCs. In the NR, the values obtained were 498.0 ppm for CO₂ and 777.1 µg/m³ for VOCs [64]. It is imperative to emphasize the similarity of the values in the two classrooms, both with regard to the CO₂ parameter and the VOCs. This similarity can be attributed to the fact that the classrooms are entirely analogous in terms of their area, solar exposure, furniture, and type of flooring, as explained before.

For the present study, the IAQ was monitored in both classrooms during an exam period in January 2024 (which corresponds to the winter season in Portugal), with 25 occupants in each classroom (Figure 4a). The day was marked by the absence of clouds and the presence of sunlight. Indoor air quality was monitored continuously and simultaneously, with readings of the different variables collected every minute over a period of approximately 3 h (between 1:40 pm and 4:30 pm) in both classrooms (GR and NR) using portable continuous direct-reading equipment. To ensure synchronized opening and closing of doors and optimal occupancy levels in each classroom, two designated members of academic staff, by maintaining constant communication via mobile phone, ensured synchronized door operation, thus guaranteeing there were equal conditions in both rooms in terms of natural ventilation.

The equipment used was of the Kaiterra brand, specifically the Sensedge Mini 5-in-1, which was accompanied by a calibration certificate. The thermal conditions and air pollutants measured were temperature (T), with a relative error <2.3%; relative humidity (RH), with a relative error <2.3%; carbon dioxide (CO₂), with a relative error <0.13%; total volatile organic compounds (VOC_T), with a relative error <1.9%; and suspended particulate matter measuring 2.5 and 10 µm (PM_{2.5}, PM₁₀), with a relative error <1.3%. All measurements were recorded in the cloud of the “Kaiterra” platform and could be consulted whenever necessary.

The Sensedge Mini specifications for the different parameters are given below:

- Temperature (T): sensor, digital sensor; accuracy, ±1 °C; resolution, 0.01 °C;
- Relative humidity (RH): sensor, digital sensor; accuracy, ±5% RH; resolution, 0.01%RH;
- CO₂: sensor, non-dispersive infrared (NDIR); accuracy, ±10%; resolution, 1 ppb;
- VOC_T: sensor, multi-pixel metal oxide sensor (MOx); accuracy, ±15% ± 8 ppb; resolution, 1 ppb;
- Particulate matter sensor: sensor, laser particle sensor; accuracy, 0 to 30 µg/m³: ±3 µg/m³; resolution, 1 µg/m³.

Prior to the utilization of the pieces of equipment, we compared them with respect to the parameter values measured, with the devices positioned side by side. This comparison revealed that the results obtained were within the specified resolution range and exhibited a high degree of similarity.

During IAQ monitoring, the number of occupants in each classroom was kept constant to ensure the monitored variables were consistent. The ventilation and shading conditions in both classrooms were identical, the doors were opened and closed simultaneously in a controlled manner (as explained previously), and the windows were kept closed throughout the monitoring period. Regarding thermal conditions, air movement inside the classrooms was not measured since there was no mechanical ventilation system and, during the whole monitoring period, the windows were closed and the door was open for only 20 min (12% of the monitoring time), as recorded in Table 3.

Table 3. Monitoring methodology for the green room (GR) and neutral room (NR).

Hour	Number of Occupants in the Classroom	Observations/Action	Period
1:40 pm to 2:10 pm	24 25	Occupants enter. Door closes. Door opens. One person enters. Door closes	1st period
2:11 pm to 2:45 pm	25 25	Door remains closed. Door opens.	2nd period
2:46 pm to 2:50 pm to 3:10 pm	25 25 0	Door remains opened. Door closes. Door opens. All occupants leave the classrooms.	3rd period
3:11 pm to 3:20 pm	0 25	Door remains opened. Occupants enter. Door closes.	4th period
3:21 pm to 4:30 pm	25 0	Door remains closed. Door opens. All occupants leave the classrooms.	5th period

The equipment used to monitor thermal conditions and air pollutants was calibrated, and errors and uncertainties were minimized by minimizing the influence of environmental factors, as windows and doors were kept closed 88% of the time (Table 3), the classrooms were half-occupied for the test, and the equipment was positioned, correctly configured, and not moved as per the methodology defined in ISO 16000-1 [66]. Since changes in environmental conditions occurred during IAQ monitoring due to the opening and closing of classroom doors, we decided to divide the original dataset into five different time periods. Each period was divided based on the opening or closing of the door, as shown in Table 3.

2.4. Statistical Methods

Initially, the results observed for the different time periods were analyzed using descriptive statistical measures. To evaluate the assumption of normality, the results of a Shapiro–Wilk test were used (Table A1 in Appendix A).

Continuous variables were presented as medians and inter-quartile ranges (25th percentile and 75th percentile) since most of the analyzed samples presented deviations from normality (Table A2 in Appendix A). To visualize the data, time plots were used to display data points for each parameter collected in a time sequence. In addition, boxplots were employed to ascertain the shape of the distribution and identify any potential outliers.

After this preliminary stage, two approaches were considered. The distributional characteristics of each sample (GR and NR) were compared using the Kolmogorov–Smirnov test for two independent samples (Table A3 in Appendix A).

To compare whether the observed differences were statistically significant, at each point in time, the Wilcoxon Signed Rank Test for related samples was employed (Table A4 in Appendix A).

The level of significance was set as follows: $\alpha = 0.05$. Statistical data analysis was conducted using SPSS 22.0 (IBM Corp. Released 2013. IBM SPSS Statistics for Windows. Armonk, NY, USA: IBM Corp).

3. Results and Discussion

3.1. IAQ-Parameter-Monitoring Results and Statistical Analysis

The thermal profiles of the two monitored classrooms, specifically air temperature (T) and relative humidity (RH), over time under the conditions specified in Table 3 are presented in Figures 5 and 6, with the latter providing boxplots for the aforementioned parameters in the different periods.

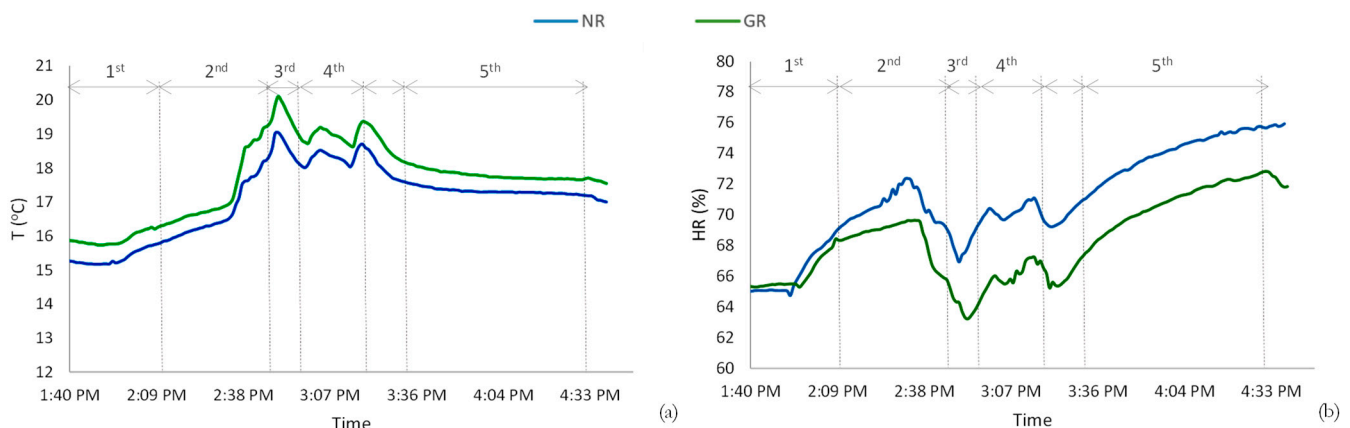


Figure 5. Comparison between green room (GR) and neutral room (NR): (a) air temperature (T) and (b) relative humidity (RH).

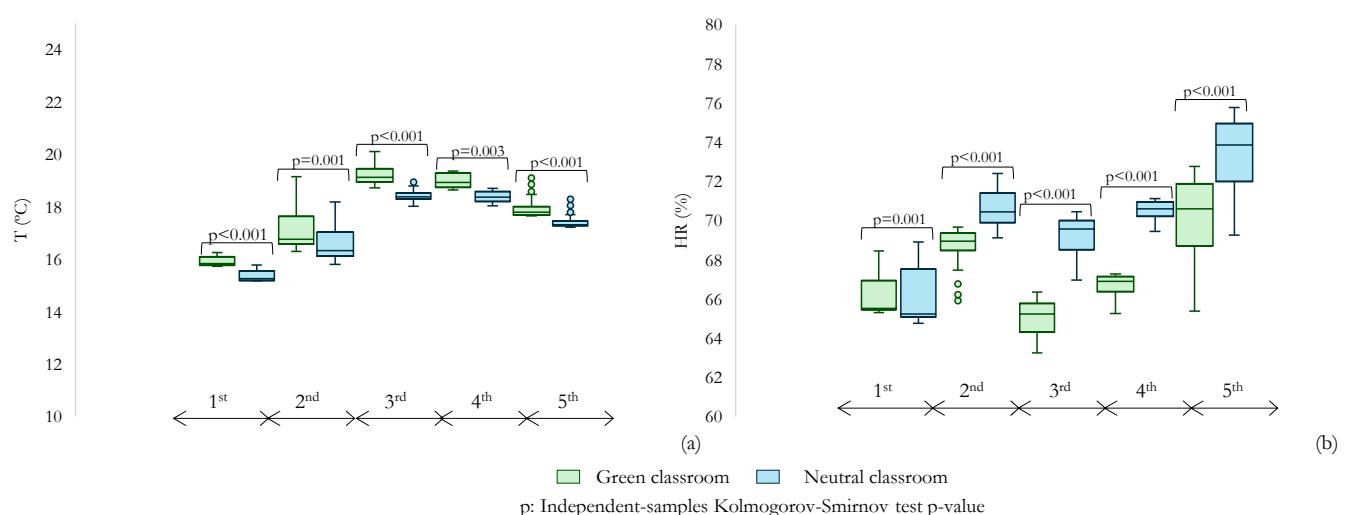


Figure 6. Boxplots depicting conditions in both classrooms (green room (GR) and neutral room (NR)): (a) air temperature (T) and (b) relative humidity (RH); 1st: 1:40–2:10 pm; 2nd: 2:11–2:45 pm; 3rd: 2:46–3:10 pm; 4th: 3:11–3:20 pm; 5th: 3:21–4:30 pm.

In both classrooms, a rise in T and RH was observed immediately after the door was closed (Figure 5). At 2:10 pm, a brief opening of the door allowed the entry of a single occupant, resulting in no appreciable change in indoor thermal conditions. In contrast, between 3:10 pm and 3:20 pm, the door remained open for approximately 10 min to accommodate the gradual exit of multiple occupants. This prolonged period in which the door was open promoted increased thermal exchange with the colder outdoor environment, leading to observable fluctuations in air temperature. Given that monitoring took place in the winter, the outdoor temperature continued to decrease after this period, inhibiting any further increase in indoor temperature (as shown in Figure 5a). From approximately 3:20 pm onwards, the indoor temperature stabilized. Meanwhile, RH continued to rise, likely driven by persistent moisture generation from human respiration in conjunction with reduced ventilation rates [68].

Concurrently, the behavior of the paired observed values within each period could be highlighted and compared between the two classrooms using the results of the Wilcoxon tests described in Table A4 (Appendix A). As illustrated in Figure 6, the boxplots represent the distribution of the parameters across different periods. A close examination of the temperature series in the GR and NR (Figure 5a) reveals a marked increase in temperature in the GR in comparison to the NR, with $p < 0.001$ (Figure 6a), as shown in Table A4. Additionally, there was a gradual increase in indoor air temperature from the moment the door was closed (periods 1, 3, and 5) and a decrease when the door was opened (periods 2 and 4) in both classrooms. It is also evident that the temperature variation was identical in both classrooms, as shown in Figure 6a, with similar temperature variations in all periods since identical IQR values are given in Table A2 (Appendix A). Notwithstanding, the minimum, median, and maximum temperatures in each period were higher in the GR than in the NR, exhibiting a discrepancy ranging from 0.5 to 1 °C, as shown in Table A2. Similar differences between the values in the GR and NR were observed for all periods. There was greater variability in the temperatures in the second period for both classrooms, but this variation was more pronounced in the GR, wherein the distribution of values exhibited positive asymmetry, indicating a rightward slant with a ‘light tail’ distribution. Additionally, it appears that, among the five periods analyzed, the third and fourth periods present a more symmetrical and regular distribution of temperature values.

In relation to the monitoring of relative humidity in both classrooms (see Figure 5b), it can be observed that its variation over time is comparable to that of the air temperature, with oscillations when the door was opened and closed. It is evident that until 2:10 pm, the progression of the RH curve in both classrooms was identical ($p = 0.229$ in Table A4 in Appendix A), with comparable values at that time: 68.6% and 68.4% in the NR and GR, respectively. In fact, the GR initially exhibited a lower humidity level that eventually rapidly surpassed the humidity level of the NR in the first period. This was followed by a period of relatively stable humidity levels, with the GR maintaining a marginally higher level until 1:55 pm, at which juncture a reversal was observed, with the NR attaining a higher humidity level than the GR. Over the course of this first period, the minor variations observed were cancelled out. However, from this point onwards, despite the continuity of parallelism of the curves, a significant divergence in the values becomes evident, with $p < 0.001$ for almost all the values. In the neutral room, the range of RH values was generally more pronounced, mainly in the first and second periods, as evidenced by the progression of the curves in Figure 5b and the dimensions of the boxes in Figure 6b. In the initial period, the relative humidity in the GR ranged from 65.3% to 68.4% (IQR = 1.6), while in the NR, it varied between 64.8% and 68.9% (IQR = 2.5), and, in the second period, there was a variation from 65.9% to 69.7% (IQR = 0.9) and from 69.1% to 70.5% (IQR = 1.6), respectively (Table A2 in Appendix A). It is evident that in the neutral room, the relative

humidity levels were considerably higher most of the time, surpassing 70%, which exceeds the limits recommended by Portuguese legislation [69]. In the GR, the values monitored were generally below 70% RH, except for the final 40 min, during which the values reached 72.7% until the door was opened at 4:30 pm.

The results of the monitoring of contaminants, CO_2 , and VOC_T can be observed in Figure 7a,b. Figure 8 presents the boxplots for the aforementioned parameters in the different periods.

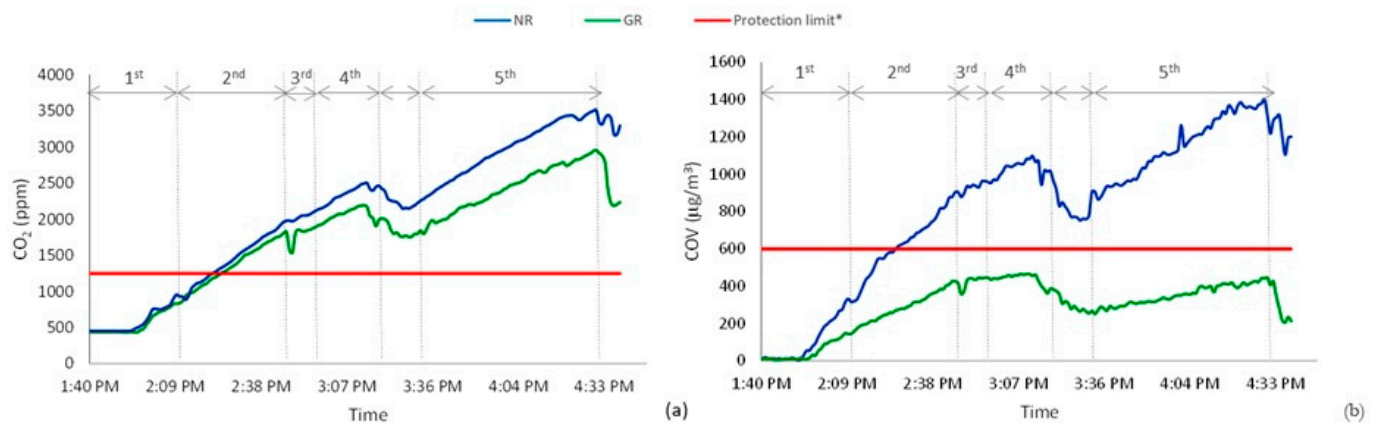


Figure 7. Comparison between green room (GR) and neutral room (NR): (a) carbon dioxide (CO_2) and (b) total volatile organic compounds (VOC_T). * Order No. 138-G/2021, 1 July [67].

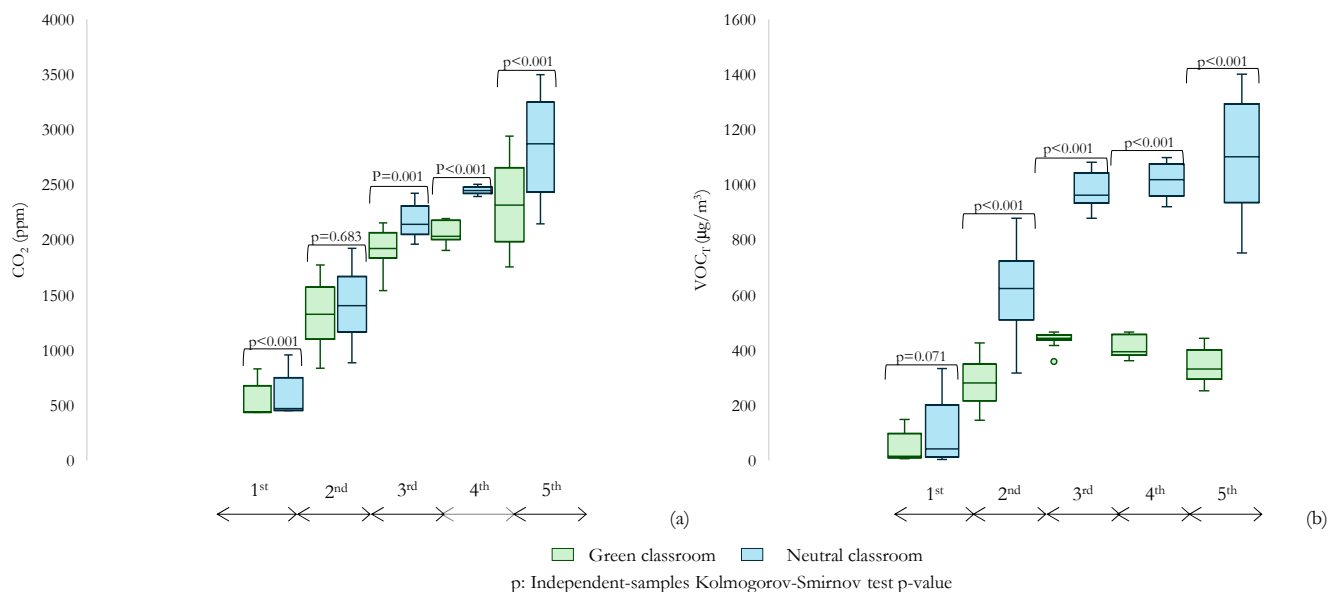


Figure 8. Boxplots of the parameters in both classrooms (green room (GR) and neutral room (NR)): (a) carbon dioxide (CO_2) and (b) total volatile organic compounds (VOC_T); 1st: 1:40–2:10 pm; 2nd: 2:11–2:45 pm; 3rd: 2:46–3:10 pm; 4th: 3:11–3:20 pm; 5th: 3:21–4:30 pm.

The results in Figure 7 show once again that the monitored values for CO_2 and VOC_T vary with the opening and closing of the door. Additionally, there is a substantial difference between the monitored values, with the concentrations of CO_2 and VOC_T being systematically higher in the NR than in the GR, with $p < 0.001$ for the majority of the analyzed periods, as can be observed in Table A4 in Appendix A. The discrepancy between the monitored values in the two classrooms is more pronounced in the case of VOC_T .

Upon analyzing the CO₂ values (Figure 7a), it becomes evident that the levels in the GR were consistently and significantly lower than those in the NR across all five periods, with $p < 0.001$, (Figure 8a and Table A4 in Appendix A). This reduction was likely due to the photosynthesis process in plants, in which plants absorb CO₂ and release O₂ during daylight hours. As shown in Figure 8a, in the second period, the distributions of CO₂ values were found to be non-significantly different ($p = 0.627$). However, when analyzing the differences for each pair of observations, in the GR and NR, over time, significantly higher levels were observed in the NR, with $p < 0.001$. The NR had a higher CO₂ concentration and exhibited a greater variation in CO₂ over the different periods, as evidenced by the size of the boxes in Figure 8a. The maximum values observed at 4:30 pm, prior to the opening of the classroom's doors, were on the order of 3512 ppm in the NR and 2955 ppm in the GR. It is important to note that in both classrooms, the windows remained closed, and the doors were closed at 3:20 pm, with 25 occupants inside each classroom. In the absence of any ventilation, an increase in CO₂ levels was expected due to human respiration.

Regarding the VOC_T values (Figure 7b), the initial readings were identical in both classrooms (9.7 µg/m³), as shown in Figure 8b, for the 1st period, with $p = 0.071$. However, after 1:55 pm, a significant divergence in the values was observed between the two classrooms, with $p < 0.001$ for almost all periods. It is interesting to note that in the green room, the variation in VOC_T was considerably lower, as illustrated by the relatively smaller size of the boxes in Figure 8b and the consistently lower IQR (Table A2 in Appendix A) values obtained in this classroom in comparison to those recorded in the neutral room, across all periods. In the GR, the values remained significantly lower, below the 600 µg/m³ limit stipulated by Portuguese legislation. In contrast, the NR exceeded this limit, failing to meet the protection standards outlined in the same legislation. For instance, at 4:30 pm, the GR registered VOC_T values of around 442.4 µg/m³, within permissible limits, while the NR showed values of around 1401.4 µg/m³, significantly surpassing the allowed threshold. In fact, during the monitoring period, the VOC_T values remained much higher in the NR than in the GR almost all the time, with a large and significant difference in values, highlighting the role of the plants selected (mentioned in Table 1) for the NGS in reducing VOC_T values.

Notably, when the door was left open for a 10 min period (3:10 pm–3:20 pm, Table 3), there was a marked decrease in CO₂ and VOC_T values, indicating the positive impact of natural ventilation. It should be noted that the classroom doors open directly onto an outdoor patio, where CO₂ and VOC_T concentrations were lower than indoors. Conversely, when the door was closed, there was a notable increase in both CO₂ and VOC_T values. Two additional door openings occurred: one at 2:10 pm prior to the entry of a single occupant and one at 2:45 pm lasting five minutes. In both instances, CO₂ and VOC_T levels showed slight decreases in both classrooms, though the reduction was more pronounced in the green room. These observations demonstrate that five minutes is not enough time to produce significant measurable differences.

The results of the PM_{2.5} and PM₁₀ monitoring can be observed in Figure 9a and Figure 9b, respectively, and Figure 10a,b present the distributions of the observed values given by the boxplots for the same parameters.

An analysis of the data relating to PM_{2.5} and PM₁₀ in both classrooms reveals a high degree of similarity in the results obtained (see Figures 9 and 10). Even so, for PM_{2.5}, we found statistically significant differences in the distribution of the values observed for the third period, and, for PM₁₀, there were differences in the shape of the distribution between the two classrooms for the second and fifth periods. There was no statistically significant variation in the values measured in either classroom, nor did the opening or closing of the doors result in any change in the measured values. This stands in contrast to the variations observed in the other monitored parameters. The highest values found in the NR and

GR were $11 \mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ and $13 \mu\text{g}/\text{m}^3$ for PM_{10} . At around 2:00 pm, there was an increase in $\text{PM}_{2.5}$ values in both classrooms in comparison to the initial values, rising from $6 \mu\text{g}/\text{m}^3$ to $10 \mu\text{g}/\text{m}^3$ in the NR and from $7 \mu\text{g}/\text{m}^3$ to $9 \mu\text{g}/\text{m}^3$ in the GR. Also, for PM_{10} , the values also increased, namely, from $6 \mu\text{g}/\text{m}^3$ to $10 \mu\text{g}/\text{m}^3$ in the NR and from $7 \mu\text{g}/\text{m}^3$ to $10 \mu\text{g}/\text{m}^3$ in the GR. It was also observed that door opening had no noticeable effect on this parameter, as it maintained the same profile.

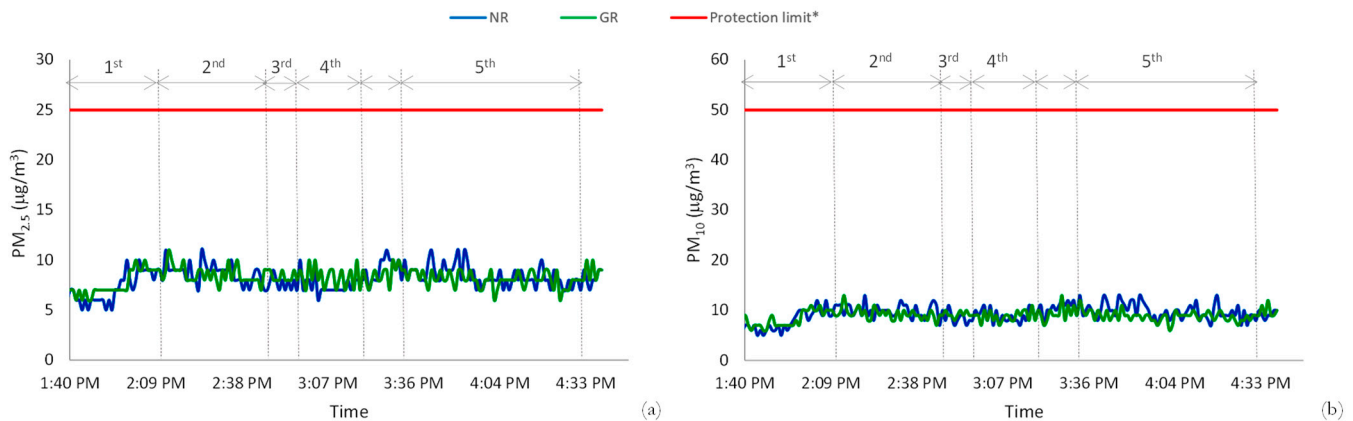


Figure 9. Comparison between green room (GR) and neutral room (NR): (a) suspended particulate matter measuring $2.5 \mu\text{m}$ ($\text{PM}_{2.5}$) and (b) suspended particulate matter measuring $10 \mu\text{m}$ (PM_{10}). * Order No. 138-G/2021, 1 July [67].

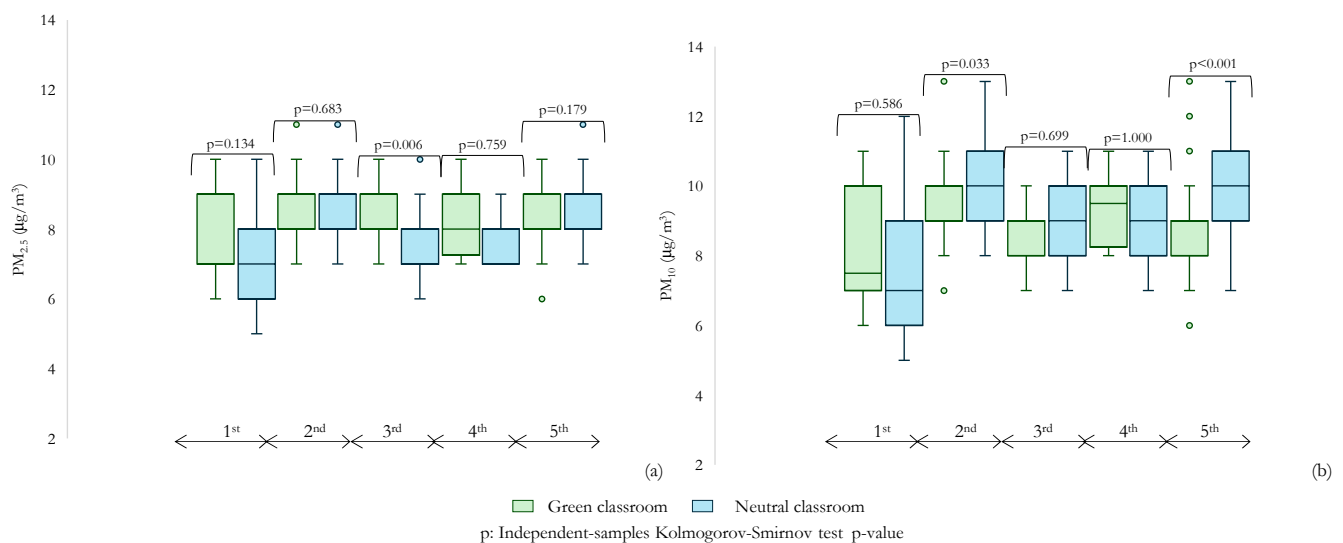


Figure 10. Boxplots for both green room (GR) and neutral room (NR): (a) suspended particulate matter measuring $2.5 \mu\text{m}$ ($\text{PM}_{2.5}$) and (b) suspended particulate matter measuring $10 \mu\text{m}$ (PM_{10}); 1st: 1:40–2:10 pm; 2nd: 2:11–2:45 pm; 3rd: 2:46–3:10 pm; 4th: 3:11–3:20 pm; 5th: 3:21–4:30 pm.

As demonstrated in Table A4 in Appendix A, the findings of the test indicate statistically significant variations in $\text{PM}_{2.5}$ for the first, third, and fifth periods and in PM_{10} for the second and fifth periods. Nevertheless, with regard to the assessment of air quality, these discrepancies are of negligible significance, given that the observed values in both classrooms are in close proximity and significantly lower than the prescribed reference values stipulated by legislative frameworks.

3.2. Discussion

The thermal environment is evaluated based on a series of parameters that facilitate the determination of thermal comfort and the suitability of thermal conditions for human activities. As previously mentioned, the environmental factors evaluated in this study were temperature and relative humidity. The quality of the thermal environment can impact the efficacy of teaching and learning processes. Low temperatures force the body to produce heat to avoid cooling, which consequently results in an increase in body activity. This, in turn, reduces students' attention and concentration, which affects their work. Conversely, elevated temperatures can induce drowsiness, fatigue, and difficulty concentrating, which may result in a decline in response efficacy and an increased propensity to make errors.

In enclosed indoor environments during the winter, the presence of multiple occupants typically results in an initial increase in both parameters (temperature and relative humidity). This is primarily attributed to the continuous emission of sensible and latent heat through human respiration and perspiration [70,71]. On average, a resting human body emits approximately 85 W of metabolic heat, and this value can reach up to 180 W during engagement in low-level occupational activities, contributing substantially to indoor heat gains when occupancy is high [70]. In addition to the presence of people, plants near windows or light sources may retain heat more effectively, contributing to a localized increase in temperature. The presence of plants can also influence air circulation and heat distribution within an enclosed space, potentially leading to slightly higher temperatures.

Relative humidity, defined as the ratio between the actual vapor pressure and the saturation vapor pressure at a given temperature, tends to increase initially as both air temperature and absolute humidity rise due to human activity. However, as the indoor temperature continues to increase—partly due to cumulative metabolic heat—the saturation vapor pressure also rises exponentially, according to the Clausius–Clapeyron relation. Consequently, if the increase in absolute humidity does not keep pace with the rise in saturation capacity, relative humidity may begin to decline, despite the ongoing introduction of water vapor into the environment [71]. However, certain plants can also absorb moisture directly from the air through their leaves or soil, reducing ambient humidity. As the temperature in the classroom with plants increased, the air's capacity to hold moisture also increased, which could have led to a decrease in relative humidity despite the presence of plants.

Order No. 138-G/2021 [67], which sets indoor air quality standards, does not specify temperature and relative humidity values. However, recommendations can be found in the General Regulation on Hygiene and Safety at Work (Decree-Law 243/86 of 20 August) [69], which suggests that workplace temperatures should ideally range between 18 °C and 22 °C, with the possibility of reaching 25 °C under certain climatic conditions, and that relative humidity should be maintained between 50% and 70% to ensure workers' well-being and protect their health. A relative humidity level falling below 40% is considered disadvantageous, as this results in the air becoming excessively dry. Consequently, this dryness causes significant irritation to the respiratory tract. Conversely, relative humidity levels exceeding 70% are conducive to the uncontrolled growth of fungi and bacteria [72].

Notwithstanding the fact that Portuguese legislation recommends a relative humidity level of between 50 and 70%, Liu et al. [73] found that academic performance is enhanced at lower levels of relative humidity, specifically at approximately 40% humidity, in conjunction with a temperature of 24 °C.

In accordance with the recommended values set forth in Portuguese legislation [69], the GR, in general, met the temperature requirements, with values consistently being above 18 °C or near it, reaching a maximum of 20.5 °C (the value recommended by legislation), while in the NR, the maximum temperature reached was 19 °C. In the GR, temperatures

remained below 18 °C during the first two measurement periods. However, in all subsequent periods, temperatures were consistently maintained at or slightly above 18 °C. It is important to note that the measurements were taken during the winter in this study. The southwest and northeast facades were set with single-glazed glass, accounting for a significant area on the southwest facade. This configuration led to a rapid exchange of thermal energy with the external environment, thereby contributing to the classroom's lower temperature during the winter months. The maximum temperature recorded during the day was 14 °C. However, given the presence of a large area exposed to sun (the southwest facade) and an occupancy of 25 people, it is not surprising that the temperature in both classrooms exceeded that of the external environment. Consequently, it can be concluded that a notable enhancement was observed in the winter regarding the NGS in the GR classroom. The monitored data suggest that plant presence may improve thermal conditions, with temperature and humidity values closer to those recommended by Portuguese legislation [69].

Carbon dioxide (CO₂), a gas classified as a simple asphyxiant, is a substance that can reduce the availability of oxygen in certain concentrations. Additionally, it can be considered a respiratory irritant. In low concentrations, adverse effects on human health are generally not observed. However, when present in higher concentrations, it can be associated with the development of certain symptoms. For instance, at levels exceeding 1000 ppm indoors, it induces impairment in cognitive performance, including decision-making, problem-solving, calculation speed, and association [74]. In the present study, elevated levels of CO₂ were detected in both classrooms. These levels were attributed to the presence of the occupants. Nevertheless, the values in the green room were found to be lower than those in the neutral room, thereby underscoring the highly favorable impact of incorporating plants in indoor spaces. Several factors should be considered regarding the reduction of CO₂. The plants may have enhanced air mixing within the classroom, even without natural ventilation. The localized effect of the plants, positioned near the walls and ceiling, may have contributed to the reduction in CO₂ levels. The photosynthetic pathways through which plants capture and fix CO₂, namely, the C3 mechanisms, can reduce CO₂ levels. Most of the indoor plants used in our study (Table 1) utilize the C3 photosynthetic pathway, where CO₂ is directly fixed by the enzyme Rubisco into a three-carbon compound during the Calvin cycle [43]. This process is efficient at moderate temperatures and higher CO₂ concentrations [45], such as those found in an indoor environment with occupants. Thus, plants using the C3 mechanism can actively reduce CO₂ levels by increasing photosynthetic activity [75]. The likely predominance of C3 plants (Table 1), combined with the elevated indoor CO₂ concentrations due to occupant presence, may have stimulated greater photosynthetic uptake of CO₂, contributing significantly to the measured decrease.

Exposure to VOCs can result in both acute and chronic effects, with individuals with respiratory pathologies, such as asthmatic patients, being particularly vulnerable to such effects, even at low concentrations. While most indoor VOCs are present in low concentrations and do not significantly impact the health of occupants, high concentrations can lead to symptoms ranging from sensory or behavioral irritation to neurological, hepatological, mutagenic, and even carcinogenic effects [76]. These VOCs originate from various sources, including paints, varnishes, cleaning products, and others. In the context of this research, both classrooms had undergone a uniform cleaning process several hours before the monitoring phase began. Additionally, the building materials and furnishings had aged sufficiently to minimize VOC emissions, with only the shading curtains—installed three months prior to IAQ monitoring—being relatively new. As evidenced in Figure 7b, the initial VOC_T concentration in both classrooms, prior to occupancy, was 9.7 µg/m³,

a value that is significantly low and very close to zero. This observation enables us to attribute subsequent VOCs increases to two primary sources: occupant emissions and materials introduced by the occupants themselves. As noted, the experimental conditions maintained identical classroom configurations, equal occupant numbers, and equivalent initial VOC_T concentrations, with the natural green structure installation serving as the sole variable. With these controlled parameters, the measured reduction in VOC_T can be reliably ascribed to the phytoremediation capacity of the installed natural green structure. This finding aligns with the established literature demonstrating plants' ability to absorb and metabolize airborne volatile organic compounds through both leaf surface adsorption and root microbiome activity. Soil and associated microorganisms can break down VOCs, contributing to a cleaner indoor air environment. The combined effect of plant foliage, soil, and microbial degradation is a well-documented means of VOC reduction [45,77,78].

Our monitoring results also underscore the significance of promoting sufficient natural ventilation to enhance indoor air quality (IAQ). It has been demonstrated that there was a decrease in pollutant values whenever the door to the classroom was opened, a notion that is substantiated by the findings of Wood et al. [18] and Plazas and Tejada [79]. Inadequate ventilation has the potential to culminate in deleterious health consequences for students, manifesting in both immediate and long-term health effects. Previous research has established a correlation between air pollutants and the prevalence of health concerns among young people. Notwithstanding the acknowledgment of these concerns, they persist as a substantial challenge within educational facilities.

However, it is important to note that the CO_2 levels in both classrooms exceeded the protection threshold of 1250 ppm set by Portuguese legislation [67], although the values were lower in the green room, verifying that the plants played a significant role in reducing CO_2 levels, which is a notable contribution. With regard to VOCs, a substantial decrease was observed in the green room, with the values in this classroom being considerably lower than those in the neutral room and below the threshold stipulated by the legislation mentioned above [67], $600 \mu\text{g}/\text{m}^3$.

As previously mentioned, several studies have demonstrated an association between exposure to particles and the development of pathologies, primarily at the level of the respiratory system. However, there are no established limits that would guarantee safe exposure levels, i.e., levels below which exposure to particles would not cause health effects in exposed individuals. The risk of exposure to particles depends on the particles' chemical compositions and size. Particles with a diameter of less than $1 \mu\text{m}$ are of particular concern to human health because they can be inhaled and reach the lungs [80], while larger particles, with diameters greater than $10 \mu\text{m}$, are filtered through the nose. Exposure to particles is associated with several serious health effects, including lung disease, asthma, and other respiratory problems. Fine particles (diameter $\leq 2.5 \mu\text{m}$) have been shown to exacerbate asthma and bronchitis, and short-term exposure can lead to symptoms such as shortness of breath, eye and lung irritation, nausea, dizziness, and allergic reactions. In 2021, the World Health Organization (WHO) [81] published guidelines recommending that annual average concentrations of $\text{PM}_{2.5}$ should not exceed $5 \mu\text{g}/\text{m}^3$ (long-term exposure), while 24 h average exposure should not exceed $15 \mu\text{g}/\text{m}^3$ for more than 3–4 days annually (short-term exposure). It is noteworthy that these values are more restrictive than those established at the national level in Portugal. A comparison of the monitored values for $\text{PM}_{2.5}$ (Figure 9a) with the values recommended by the WHO for $\text{PM}_{2.5}$ in terms of short-term exposure indicates that students are exposed to values that are below the recommended limits.

The results for PM₁₀ (Figure 9b) indicate a greater prevalence of the highest values in the NR compared to the GR, suggesting that the green structure may contribute to a slight reduction in the concentration of suspended particles with a diameter less than 10 µm. A similar study by Pegas et al. [82] also observed a reduction in PM₁₀ concentrations after installing a green wall. The maximum recorded concentration, both in the NR and GR classrooms, was 13 µg/m³. An increase in concentration was observed at around 2:00 pm in both classrooms, indicating an enhancement in comparison to the initial measurements. In the NR classroom, the initial value was 6 µg/m³, and the subsequent value was 11 µg/m³. A similar trend was observed in the GR, where the initial value was 7 µg/m³ and the subsequent value was 10 µg/m³. It was further noted that the opening of the door did not have a significant impact on the parameters under observation. The values remained well below the recommended limit of 50 µg/m³ as stipulated in Portuguese legislation, specifically Order No. 138-G/2021 [67]. In a similar manner, the World Health Organization (WHO) [81] has stipulated that annual average concentrations of PM₁₀ should not exceed 15 µg/m³ (long-term exposure), while 24 h average exposure should not exceed 45 µg/m³ for a maximum of 3–4 days per year (short-term exposure). The values measured align with the recommended limits for PM₁₀ at short-term exposure levels (see Figure 9b).

It is noteworthy that the substantial improvement in IAQ observed in the GR was only evident after a year of plant growth. At the onset of the study, following the installation of the NGS, the plants exhibited minimal foliage volume. Consequently, the initial phase of IAQ monitoring revealed only marginal improvements in the GR compared to the NR [64]. However, in the subsequent phase of this study, in which a higher foliage volume was employed, indicated a notable improvement in IAQ in the green classroom (GR) with the NGS installed in comparison to the IAQ in the neutral classroom (NR) without the natural green structure (NGS).

4. Conclusions

The present study demonstrates the significant benefits of incorporating biophilic design elements, specifically natural green structures (NGSs), into educational environments to enhance indoor air quality (IAQ). The findings indicate that the presence of plants notably improves thermal conditions and reduces levels of indoor pollutants, including carbon dioxide (CO₂) and volatile organic compounds (VOCs).

As illustrated in Table A2 in Appendix A and by taking the values of the NR as a point of reference, it is evident that significant reductions were observed in almost all the descriptive indicators of the CO₂ and VOC parameters in the GR. With regard to CO₂, a median reduction of up to 19.4% was achieved, which represents the maximum median value recorded in the fifth period. For VOCs, the magnitude of reduction was even more pronounced, exhibiting the maximum reduction in median values, amounting to up to 70.0%, which also occurred in the fifth period.

Although CO₂ levels that surpassed the limits stipulated in Portuguese legislation, Order No 138-G/2021 [67] (1250 ppm), were present in the green room, the levels of VOC_T remained well below the limits set by the same legislation [67] (600 µg/m³). While ventilation remains a key factor in enhancing IAQ, the plants showed measurable benefits during low-ventilation periods when comparing the green and neutral rooms under identical conditions. This study highlights the role of plants in mitigating indoor air pollutants by promoting a conducive learning atmosphere and enhancing students' general well-being. The integration of biophilic design in schools offers a dual opportunity: improving IAQ and promoting sustainability. The Italian Society of Environmental Medicine (SIMA) and UNESCO have both emphasized the pressing need for educational institutions to adopt such strategies, underscoring the vital role schools play in shaping future genera-

tions. Consequently, the prioritization of healthy and sustainable learning environments is imperative.

The findings of this study could encourage the development of green infrastructure in schools via policies, with the ultimate aim of contributing to healthier communities. This is particularly pertinent considering recent data indicating elevated stress levels and symptoms of depression in a significant proportion of higher-education students in Portugal. The positive outcomes of this study provide a compelling case for the adoption of natural solutions in educational design, with the potential to transform classrooms into vibrant, supportive environments that foster learning and improved well-being.

The health and well-being of individuals and the planet are of paramount importance in relation to the 17 Sustainable Development Goals (SDGs). In this study, we aimed to promote the health and well-being of the student population (SDG 3) and improve indoor air quality (SDGs 11) through biophilic solutions.

Author Contributions: Project conceptualization, the development of the methodology adopted, and research activities were carried out as a set of work tasks conducted by M.I.G., A.M.B. and A.R. Data processing and analysis were performed by M.I.G., A.M.B., A.R. and I.P. All team members contributed to the preparation, writing, review, and editing of this paper. The project received funding from several entities. M.I.G. coordinated a project funded by IPL on indoor air quality (IAQ), and A.R. led a project funded by ISEL on biophilic solutions in classrooms. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of Instituto Superior de Engenharia de Lisboa (protocol code “Parecer Projeto HealthyIES” and date of approval 10 January 2025).

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

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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

Appendix A

Table A1. Shapiro–Wilk tests results.

	1st Period (<i>n</i> = 30)		2nd Period (<i>n</i> = 35)		3rd Period (<i>n</i> = 25)		4th Period (<i>n</i> = 10)		5th Period (<i>n</i> = 70)	
	GR	NR	GR	NR	GR	NR	GR	NR	GR	NR
T (°C)	<i>p</i> < 0.001	<i>p</i> < 0.001	<i>p</i> < 0.001	<i>p</i> < 0.001	<i>p</i> = 0.026	<i>p</i> = 0.064	<i>p</i> = 0.115	<i>p</i> = 0.298	<i>p</i> < 0.001	<i>p</i> < 0.001
HR (%)	<i>p</i> < 0.001	<i>p</i> < 0.001	<i>p</i> < 0.001	<i>p</i> = 0.058	<i>p</i> = 0.041	<i>p</i> = 0.013	<i>p</i> = 0.076	<i>p</i> = 0.325	<i>p</i> < 0.001	<i>p</i> < 0.001
CO ₂ (ppm)	<i>p</i> < 0.001	<i>p</i> < 0.001	<i>p</i> = 0.143	<i>p</i> = 0.196	<i>p</i> = 0.062	<i>p</i> = 0.055	<i>p</i> = 0.096	<i>p</i> = 0.652	<i>p</i> = 0.001	<i>p</i> < 0.001
VOC _T (µg/m ³)	<i>p</i> < 0.001	<i>p</i> < 0.001	<i>p</i> = 0.607	<i>p</i> = 0.386	<i>p</i> < 0.001	<i>p</i> = 0.098	<i>p</i> = 0.113	<i>p</i> = 0.468	<i>p</i> = 0.002	<i>p</i> = 0.001
PM ₁₀ (µg/m ³)	<i>p</i> < 0.001	<i>p</i> = 0.048	<i>p</i> = 0.002	<i>p</i> = 0.012	<i>p</i> = 0.002	<i>p</i> = 0.024	<i>p</i> = 0.111	<i>p</i> = 0.410	<i>p</i> < 0.001	<i>p</i> = 0.005
PM _{2.5} (µg/m ³)	<i>p</i> < 0.001	<i>p</i> = 0.020	<i>p</i> < 0.001	<i>p</i> = 0.003	<i>p</i> = 0.041	<i>p</i> = 0.013	<i>p</i> = 0.191	<i>p</i> = 0.015	<i>p</i> < 0.001	<i>p</i> < 0.001

Legend: *p*: Shapiro–Wilk test *p*-value.

Table A2. Descriptive statistics for different monitoring periods in the green room (GR) and neutral room (NR).

		1st (<i>n</i> = 30)		2nd (<i>n</i> = 35)		3rd (<i>n</i> = 25)		4th (<i>n</i> = 10)		5th (<i>n</i> = 70)	
		GR	NR	GR	NR	GR	NR	GR	NR	GR	NR
T (°C)	Min	15.7	15.2	16.3	15.8	18.7	18.0	18.6	18.0	17.7	17.2
	Q1	15.8	15.2	16.6	16.1	18.9	18.3	18.7	18.2	17.7	17.3
	Median	15.8	15.3	16.8	16.3	19.1	18.4	18.9	18.4	17.8	17.3
	Q3	16.1	15.6	17.8	17.1	19.5	18.5	19.3	18.6	18.0	17.5
	Max	16.3	15.8	19.2	18.2	20.1	19.0	19.4	18.7	19.2	18.4
	IQR	0.3	0.4	1.3	1.0	0.5	0.3	0.6	0.4	0.3	0.2
	Skewness	0.81	0.84	1.10	0.96	0.92	0.83	0.17	−0.02	2.01	2.25
	Kurtosis	−1.00	−0.96	−0.39	−0.50	0.00	0.28	−1.93	−1.77	3.74	5.02
HR (%)	Min	65.3	64.8	65.9	69.1	63.2	67.0	65.3	69.4	65.4	69.3
	Q1	65.4	65.1	68.4	69.8	64.2	68.3	66.3	70.1	68.6	71.9
	Median	65.5	65.2	68.9	70.4	65.2	69.6	66.9	70.6	70.6	73.9
	Q3	67.1	67.6	69.4	71.5	65.8	70.1	67.2	71.0	71.9	75.0
	Max	68.4	68.9	69.7	72.4	66.3	70.4	67.3	71.1	72.8	75.8
	IQR	1.6	2.5	0.9	1.6	1.6	1.8	0.9	0.9	3.3	3.1
	Skewness	1.09	0.68	−1.48	0.40	−0.46	−0.74	−1.40	−0.76	−0.76	−0.67
	Kurtosis	−0.34	−1.18	1.18	−1.01	−1.151	−0.76	2.00	−0.52	−0.52	−0.73
CO ₂ (ppm)	Min	435.0	451.0	837.0	885.0	1538.0	1961.0	1904.0	2392.0	1755.0	2146.0
	Q1	436.0	452.0	1091.0	1149.0	1832.5	2034.5	1997.5	2413.3	1978.8	2420.3
	Median	436.5	470.0	1325.0	1402.0	1920.0	2141.0	2032.5	2446.5	2316.0	2872.0
	Q3	689.0	751.3	1582.0	1684.0	2068.5	2312.0	2180.8	2484.5	2662.5	3263.8
	Max	830.0	955.0	1771.0	1922.0	2153.0	2422.0	2193.0	2503.0	2941.0	3499.0
	IQR	253.0	299.3	491.0	535.0	236.0	277.5	183.3	71.3	683.8	843.5
	Skewness	0.93	0.91	−0.06	−0.07	0.92	0.83	0.00	0.02	−0.20	−0.10
	Kurtosis	−0.85	−0.65	−1.22	−1.14	0.00	0.28	−1.50	−1.30	−1.34	−1.40
VOC _T (µg/m ³)	Min	6.5	3.2	145.3	316.5	358.4	878.3	361.7	920.3	251.9	752.4
	Q1	9.7	12.1	216.3	510.2	435.9	933.2	381.8	959.9	293.8	935.6
	Median	14.5	42.0	280.9	623.2	442.4	962.3	394.0	1018.8	331.0	1101.1
	Q3	96.9	201.0	348.7	723.3	455.3	1043.0	456.9	1074.5	400.4	1293.3
	Max	148.5	332.6	426.2	878.3	465.0	936.4	465.0	1097.9	442.4	1401.4
	IQR	87.2	188.9	132.4	213.1	19.4	109.8	75.1	114.6	106.6	357.6
	Skewness	0.89	0.84	0.09	0.267	−2.17	0.17	0.43	−0.40	0.19	−0.08
	Kurtosis	−0.86	−0.80	−0.93	−0.64	5–17	−1.15	−1.63	−1.12	−1.24	−1.27
PM ₁₀ (µg/m ³)	Min	6.0	5.0	7.0	8.0	7.0	7.0	8.0	7.0	6.0	7.0
	Q1	7.0	6.0	9.0	9.0	8.0	8.0	8.0	8.0	8.0	9.0
	Median	7.5	7.0	9.0	10.0	9.0	9.0	9.5	9.0	9.0	10.0
	Q3	10.0	9.3	10.0	11.0	9.0	10.0	10.0	10.3	9.0	11.0
	Max	11.0	12.0	13.0	13.0	10.0	11.0	11.0	11.0	13.0	13.0
	IQR	3.0	3.3	1.0	2.0	1.0	2.0	2.0	2.3	1.0	2.0
	Skewness	0.38	0.46	0.83	0.14	−0.56	0.32	−0.04	0.10	0.70	0.11
	Kurtosis	−1.30	−0.71	2.32	−0.48	0.11	−0.90	−1.24	−1.17	2.09	−0.57
PM _{2.5} (µg/m ³)	Min	6.0	5.0	7.0	7.0	7.0	6.0	7.0	7.0	6.0	7.0
	Q1	7.0	6.0	8.0	8.0	8.0	7.0	7.0	7.0	8.0	8.0
	Median	7.0	7.0	8.0	9.0	8.0	7.0	8.0	8.0	8.0	8.0
	Q3	9.0	8.3	9.0	9.0	9.0	8.0	9.0	8.0	9.0	9.0
	Max	10.0	10.0	11.0	11.0	10.0	10.0	10.0	9.0	10.0	11.0
	IQR	2.0	2.3	1.0	1.0	1.0	1.0	2.0	1.0	1.0	1.0
	Skewness	0.61	0.32	0.72	0.29	0.10	1.164	0.27	0.43	−0.31	0.60
	Kurtosis	−0.94	−1.02	0.50	0.31	−0.274	1.603	−0.90	−0.28	−0.05	−0.37

Legend: Q1: 1st quartile; Q3: 3rd quartile; IQR: interquartile range.

Table A3. Independent-samples Kolmogorov–Smirnov test.

	1st Period	2nd Period	3rd Period	4th Period	5th Period
T (°C)	$p < 0.001$	$p = 0.001$	$p < 0.001$	$p = 0.003$	$p < 0.001$
HR (%)	$p = 0.01$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
CO ₂ (ppm)	$p < 0.001$	$p = 0.683$	$p = 0.001$	$p < 0.001$	$p < 0.001$
VOC _T (µg/m ³)	$p = 0.071$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
PM ₁₀ (µg/m ³)	$p = 0.586$	$p = 0.033$	$p = 0.699$	$p = 1.000$	$p < 0.001$
PM _{2.5} (µg/m ³)	$p = 0.134$	$p = 0.683$	$p = 0.006$	$p = 0.759$	$p = 0.179$

Legend: p : Independent-samples Kolmogorov–Smirnov test p -value.

Table A4. Related-samples Wilcoxon signed-rank test p -value.

	1st Period	2nd Period	3rd Period	4th Period	5th Period
T (°C)	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.005$	$p < 0.001$
HR (%)	$p = 0.229$	$p < 0.001$	$p < 0.001$	$p = 0.005$	$p < 0.001$
CO ₂ (ppm)	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.005$	$p < 0.001$
VOC _T (µg/m ³)	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.005$	$p < 0.001$
PM ₁₀ (µg/m ³)	$p = 0.286$	$p = 0.007$	$p = 0.623$	$p = 0.722$	$p < 0.001$
PM _{2.5} (µg/m ³)	$p = 0.016$	$p = 0.306$	$p = 0.001$	$p = 0.194$	$p = 0.008$

Legend: p : related-samples Wilcoxon signed-rank test p -value.

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