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Article

Effects of Green Plants on the Indoor Environment-Real-Life Case Studies in Italian Schools and Office Spaces

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Abstract

Students and workers spend much of their day in school and office environments, where poor indoor air quality (IAQ) can negatively affect health and comfort. Indoor vegetation is increasingly proposed as a low-cost Nature Based Solution (NBS) to improve IAQ. This study evaluated the effects of phytoremediation on IAQ and indoor microclimate in schools across different regions and educational levels, as well as in office environments, under real-world conditions. Several C₃ plant species (e.g., *Chamaedorea*, *Schefflera*, *Ficus*, *Epipremnum*, *Yucca* and *Spathiphyllum*) were used, with Crassulacean Acid Metabolism (CAM) plants (*Sansevieria*) included in selected settings. Temperature, relative humidity, CO₂, PM_{2.5}, and PM₁₀ were continuously monitored using intercalibrated low-cost sensors in absence and presence of vegetation. A comparable plant configuration was implemented in offices to assess effects on volatile organic compounds (VOC). Indoor greenery reduced particulate matters, especially PM₁₀ (18-20%), and improved microclimatic condition by lowering air temperature (1-2 °C) and increasing relative humidity (6-15%). However, CO₂ reductions were limited and context-dependent. In office environments, plant introduction was associated with reduced total VOC concentrations (25-50%) without evidence of biogenic VOC emissions. Overall, indoor vegetation represents a robust, low-cost NBS that can complement conventional ventilation systems in educational and occupational settings.

Keywords: indoor air quality (IAQ); potted plants; phytoremediation; microclimate; CO₂; VOC; PM₁₀; PM_{2.5}

1. Introduction

In modern societies, people typically spend approximately 80-90% of their time in indoor environments, including residential buildings, workplaces, schools, public buildings and transportation systems [1,2]. Indoor air pollutant concentrations are often higher than those measured outdoors. This condition occurs when polluted outdoor air enters indoor spaces through natural or mechanical ventilation and combines with pollutants generated by indoor sources, resulting in increased overall exposure levels [3,4].

Long-term exposure to indoor airborne contaminants poses significant health risks and can contribute to the development of various adverse health outcomes [5,6]. At the global scale, the World Health Organization (WHO) estimated that approximately 3.8 million deaths per year are attributable to diseases associated with indoor air pollution, accounting for around 7.7% of total global mortality [7].

Ensuring satisfactory Indoor Air Quality (IAQ) is essential for living in a healthy environment, preventing the occurrence of Sick Building Syndrome (SBS) [8]. A variety of pollutants can contribute to poor IAQ, including Carbon Dioxide (CO₂), Volatile Organic Compounds (VOC), and Particulate Matter (PM), each of which poses various health risks. In indoor environments, the main source of CO₂ is human respiration; therefore, occupant density and ventilation effectiveness are key determinants of indoor CO₂ levels. Although CO₂ is often regarded as non-toxic, commonly used guideline values typically consider concentrations <1000 ppm as indicative of good IAQ and <1500 ppm as acceptable for the general population in settings such as schools and offices [9,10].

VOC are the most abundant and dangerous indoor air pollutants: formaldehyde and BTEX (benzene, toluene, ethylbenzene and xylene) have been identified as the main causes of SBS [11,12], and some of them are classified as carcinogenic [13]. The main sources of indoor VOC are paints, plastic and wood furniture coating and cleaning products [14,15]. Exposure to typical indoor VOC belonging to different chemical classes can have negative effects even at low concentrations, particularly in people with respiratory conditions such as asthma. At high levels, VOC can cause mild symptoms ranging from fatigue, dizziness, eye, nose, and throat irritation, headache, nausea, and even more severe damage to the heart and respiratory system, kidneys and lungs [5,16,17].

Indoor PM can be produced by numerous sources, such as paints, varnishes, solvents, cleaning products, printers, and heaters. Prolonged exposure to these particles can cause respiratory diseases and increase the risk of lung cancer [18,19].

Many countries have implemented regulatory standards and guidelines to ensure that indoor air pollutants concentrations remain below a defined threshold in buildings such as offices, schools, and residences [20,21]. The European Union has revised the European Ambient Air Quality Directive guidelines, updating the air quality standards to be implemented by 2030 [22] while the WHO in 2021 updated the Global Air Quality Guidelines, revising the levels and times of exposure to some of the main indoor air pollutants [23]. In Italy, the UNI 11976:2025 standard, entitled "Indoor Air Quality - Requirements for Monitoring and Evaluation" provides the update technical framework for assessing and managing IAQ, with a specific focus on high-occupancy settings such as schools (UNI 11976:2025) [24].

Beyond their aesthetic value, indoor plants have been associated with improved psychological well-being and IAQ [25–27] as well as positive effects on occupants' health and well-being [28,29] - Plants can also influence indoor microclimatic conditions by increasing relative humidity (RH) and reducing air temperature through evapotranspiration [30–33]. RH is particularly relevant for occupant comfort and health: low RH is associated with mucous dryness, skin and eye irritation, higher susceptibility to respiratory infections, and increased persistence of airborne viruses [34], whereas excessive RH, especially when combined with high indoor temperatures, may cause thermal discomfort, fatigue, and exacerbate respiratory and allergic symptoms [35].

Schools represent one of most important and critical infrastructures in modern societies, as children and adolescents spend most of their time in densely occupied classrooms characterized by multiple indoor pollution sources and higher respiration rates compared to adults [36,37]. Growing youth are particularly sensitive to environmental stressors [38] and more vulnerable to the adverse effects of indoor pollutants due to the ongoing physiological development, including the maturation of lung function [39,40].

To address these concerns, the Italian Society of Environmental Medicine (SIMA) and the UNESCO Chair on Health Education and Sustainable Development have proposed recommendations focused on improving indoor comfort. While passive and active ventilation strategies are essential for pollutant removal and moisture control, they entail high maintenance costs and show limited effectiveness for certain contaminants, such as VOC (e.g., formaldehyde) [41]. Consequently, the integration of nature-based solutions (NBS) has been highlighted as a complementary strategy, offering potential benefits for both physical and mental well-being [42,43]. In this context, indoor green infrastructures have been proposed as effective and low-cost alternative interventions for pollutant removal and co-benefits, as shown by international studies [10,44].

These IAQ considerations are critical determinants of health, comfort, and productivity not only in school but also in other confined indoor spaces, such as offices, where individuals spend a substantial portion of their working day [35].

Overall, potted plants may contribute to improve IAQ through multiple mechanisms, including atmospheric CO₂ sequestration [45,46], VOC absorption [47,48], PM retentions [27,49], as well as temperature reduction and RH enhancement. However, the reported outcomes are not always consistent. While laboratory studies frequently document reductions in CO₂ concentration [50], even with a limited number of plants [51,52], other investigations have not observed significant improvements across multiple IAQ parameters [51,53]. Furthermore, evidence from real-life office environments remains limited [47,54].

The effectiveness of indoor phytoremediation is strongly influenced by a combination of physiological, physical, and biological processes including plant size, leaf micromorphology, stomatal uptake, surface deposition and light availability [55]. Smaller species typically exhibit lower CO₂ sequestration capacity than larger plants [56] while insufficient light may even increase indoor CO₂ concentrations as a result of enhanced plant respiration under low irradiance [57,58].

Within this framework, a previous investigation [59], conducted in classrooms as part of the 'Plants in the Classroom' project, demonstrated that indoor green infrastructure contributed to reducing CO₂ and PM_{2.5} concentrations while increasing relative humidity. Nevertheless, to address inherent limitations and variability, further studies have been recommended to test and extend this green model to different contexts and over longer monitoring periods.

To contribute to the still limited body of experimental evidence assessing the influence of indoor plants on IAQ under real-life conditions, the present study aims to evaluate the effectiveness of commonly used houseplant species through two distinct experimental settings conducted in schools and office environments during regular daily activities.

Relative humidity, CO₂, PM₁₀, and PM_{2.5} were continuously monitored in classrooms using automated acquisition systems designed to operate without interfering with teaching activities or causing student distraction. VOC concentrations were investigated exclusively in office environments, where spatial layout and routine activities allowed for more targeted measurements, as repeated punctual sampling would have interfered with teaching activities if conducted in classrooms.

2. Materials and Methods

2.1. Case Studies: Air Quality in Classrooms

2.1.1. Study Location

Three schools representing different educational stages, primary, middle, and high, were selected as case study in Italy. Primary school "Dante Alighieri" is located in Mirandola (MO, 44°52'51"N, 11°04'35" E), while middle school "Leonardo da Vinci Orazio-Nucola" is situated in Terni (42°33'53"N, 12°38'49"E) (Figure 1). The selected high school "Piero Gobetti", situated in Genova (44°24'37"N, 8°53'54"E) served as representative institution for the final educational stage (Figure 1). For both the primary and high schools, the selection was conducted in collaboration with school managers and teachers, together with the municipality and the local Federation of Coldiretti, the main agricultural organization in Italy and across Europe, representing the majority of Italian agricultural enterprises. In the case of the middle school, the Garden Club cultural association was also involved, providing additional support in coordinating school participation and facilitating local engagement.

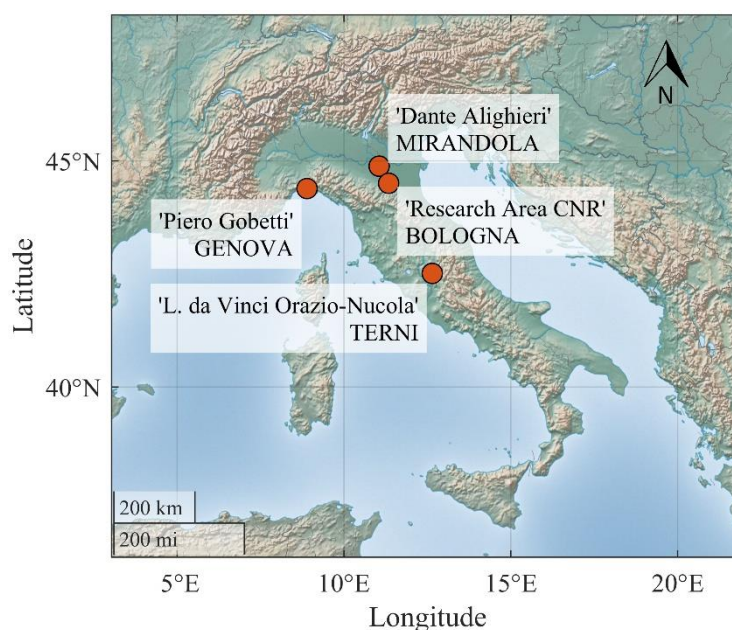


Figure 1. Geographical distribution of the school study sites and offices across Italy. Base map credits: Esri, USGS, NOAA (Color Terrain layer).

This multi-stakeholder approach ensured the selection of schools with different climatic, structural, and socio-organizational characteristics, providing a representative framework for assessing IAQ across diverse educational environments.

In each school, the same experimental protocol was implemented, consisting of a “green” classroom, with plants, and a control classroom without plants. The technical configuration for plant placement was defined according to the architectural features of each room and in compliance with all the relevant safety regulations. The potted plants remained in place throughout the entire monitoring period. Additional details are provided in Table 1.

Table 1. Monitoring period, plant species number, and support structures used for indoor vegetation in each school.

School	Monitoring Period	Monitoring station height	N° Plants & Species	Plant Structure
Primary school “Dante Alighieri” (Mirandola)	06/03/2025 to 06/04/2025	1.70	38 total: 35 <i>Epipremnum aureum</i> , 1 <i>Sansevieria laurentii</i> , 1 <i>Philodendron</i> spp., 1 <i>Schefflera arboricola</i>	Three-level vertical metal shelving units
Middle school “L. da Vinci O.N.” (Terni)	08/02/2026 to 08/03/2026	1.00	71 total: 18 <i>Sansevieria laurentii</i> , 19 <i>Epipremnum aureum</i> , 10 <i>Spathiphyllum</i> spp., 10 <i>Ficus benghalensis</i> , 8 <i>Chamaedorea elegans</i> , 2 <i>Nephrolepis exaltata</i> , 2 <i>Schefflera arboricola</i> , 1 <i>Dracaena</i> spp., 1 <i>Yucca gigantea</i>	Waterproof horizontal wooden shelves

		40 total:		
High school "Piero Gobetti" (Genova)	04/02/2026 to 04/03/2026	1.00	10 <i>Spathiphyllum spp.</i> , 10 <i>Epipremnum aureum</i> , 10 <i>Chamaedorea elegans</i> , 10 <i>Chlorophytum comosum</i>	Two-level vertical metal shelving units

The "green" and control classrooms were carefully selected in each school to ensure maximum comparability in terms of floor area, exposure and orientation, type of heating system, windows distribution and orientation, received solar radiation, and number of pupils. Artificial light consisted of ceiling-mounted fluorescence lamp units. The structural and operational characteristics of each school, along with the typical organization of the educational day, are summarized in Table 2.

Table 2. Classroom technical specifications including surface area, occupancy, orientation, and lesson schedules.

School	Classroom	Surface (m ²)	N° Students	Exposure	Lesson Hours
"Dante (Mirandola)	"Alighieri" Without Plants	42	22	West	8:15 - 13:15
	With Plants	42	22	West	8:15 - 13:15
"L. da Vinci O.N." (Terni)	Without Plants	74	25	West	8:00 - 14:10
	With Plants	74	25	West	8:00 - 14:10
"Piero Gobetti" (Genova)	Without Plants	53	27	South-East	8:00 - 14:00
	With Plants	48	23	South-West	8:00 - 14:00

2.1.2. Green Infrastructure (NBS)

Indoor plant infrastructure was implemented using ornamental potted plants arranged on dedicated plant stands, consisting either of three-level vertical metal shelving units or waterproof horizontal wooden shelves (Table 1). These configurations were selected to adapt to the classroom constraints while ensuring safety, stability, and adequate light exposure.

Plant species were selected based on functional and operational criteria, including non-allergenic suitability for school environments, documented air-purifying capacity, robustness under variable indoor conditions, and the inclusion of both C3 (Calvin cycle) and CAM (crassulacean acid metabolism) species to integrate complementary photosynthetic pathways and pollutant-removal dynamics, particularly relevant for enhancing indoor CO₂ mitigation under suboptimal lighting conditions, with CAM species absorbing CO₂ at night and C3 plants potentially releasing CO₂ under low irradiance—as well as availability from local nurseries.

Whenever possible, plants were positioned in proximity to windows to optimize natural-light exposure and enhance photosynthetic activity. A detailed description of the plant configurations and the number of individuals per species used in each school is provided in Table 1.

2.1.3. Indoor Environmental Measurements

Continuous monitoring of the indoor environmental parameters was performed using the AirQino Indoor LITE air-quality unit (Figure 2), developed by CNR-IBE. The system is built on an Arduino Shield Compatible electronic board, equipped with low-cost and high-resolution sensors (Figure 2). AirQino is equipped with factory-calibrated sensors [60,61], capable of measuring both meteorological variables (air temperature, °C; RH, %), and air quality parameters (CO₂ concentration,

ppm; PM_{2.5} and PM₁₀, $\mu\text{g m}^{-3}$). The device includes a microprocessor that acquires all readings from all sensors. Through the General Packet Radio Service (GPRS) technology, the unit transmits geolocated data to a remote server hosting the visualization platform and web interface, enabling real-time access to observations via a standard web browser.



Figure 2. AirQino Indoor LITE monitoring station.

A summary of sensor accuracy, resolution, and operating ranges is provided in Table 3.

Table 3. Technical specifications of the AirQino Indoor LITE monitoring station used for indoor measurements.

Parameter	Units	Range	Resolution	Accuracy
Air Temperature	°C	-40 ÷ 80	0.3	±5%
Relative Humidity	%	0 ÷ 100	1.0	±5%
CO₂	ppm	0 ÷ 2000	1.0	±10%
PM_{2.5}- PM₁₀*	$\mu\text{g/m}^3$	0 ÷ 1000	1.0	±10%

* PM₁₀ sensor was not available in the monitoring station of the primary school “Dante Alighieri”.

Monitoring stations were positioned 1–2 m above the floor, according to classroom configuration (Table 1), to approximate student breathing height while minimizing potential interference and enabling the evaluation of localized air-quality variations.

2.1.4. Intercalibration of Airqino Monitoring Stations

Prior to deployment, all AirQino units underwent an intercalibration procedure to reduce inter-unit variability typical of low-cost sensors and to ensure measurement consistency across devices. This procedure complemented the factory calibration, was previously validated under various operating conditions [60,61].

Monitoring stations (two per school) were co-located within classrooms for 6 days, simultaneously recording all parameters to allow direct comparison between devices. Hourly averaged datasets were then analysed, and descriptive statistics were computed for the co-location period (Table S1).

A tolerance threshold, consistent with the nominal sensor accuracy (Table 3), was defined to assess the need for corrective actions. According to the adopted approach, no correction was applied when differences between instruments remained within the sensor resolution limits, in order to avoid amplification of instrumental noise and preserve data reliability. This criterion was applied to all monitored parameters, including particulate matter (PM₁₀ and PM_{2.5}). When deviations exceeded this

threshold, a linear regression model ($y = ax + b$) was applied, using one station as reference, to derive calibration coefficients and harmonize the datasets. Given that all units were identical in design and performance, the reference station was selected arbitrarily, as no a priori differences were expected. This procedure aimed at defining a common baseline across devices. Detailed statistical metrics, including r^2 values, are reported in the Supplementary Material (Table S1).

2.2. Case Studies: VOC Measurements in Office Environment

2.2.1. Study Location

The study was conducted in two offices located within the Research Area of CNR in Bologna, Italy (44°31'25" N, 11°20'21" E) (Figure 1): an empty (October 2023) and an occupied office (April-May 2024, Table 4). The two experiments were carried out in two different settings: in October, a small unoccupied office (one room without occupants, approximately 13 m²), kept isolated throughout the experimental period (9 days) and during spring a shared space, of approximately 30 m², occupied daily by 4 to 5 people, with the door kept open throughout the experimental period (26 days). No cleaning was carried out in the unoccupied office after experimental set up, while the normal cleaning routine was followed in the occupied office.

2.2.2. Green Infrastructure (NBS)

A total of 18 potted plants (three individuals per each species) were used in this study, belonging to the same species or at least to the same genus of those used in the classroom experiments (Table 4). All plants were regularly watered through the experimental period.

Table 4. Technical specifications of the monitored offices.

Office	Surface (m ²)	N° occupants	N° Plants & Species
Unoccupied	13	-	18 total (3 for species): <i>Schefflera actinophylla</i> , <i>Spathiphyllum wallisii</i> , <i>Epipremnum aureum</i> , <i>Ficus Benjamin</i> , <i>Chamaedorea elegans</i> , <i>Yucca elephantipes</i>
Occupied	30	4-5	18 total (3 for species): <i>Schefflera actinophylla</i> , <i>Spathiphyllum wallisii</i> , <i>Epipremnum aureum</i> , <i>Ficus Benjamin</i> , <i>Chamaedorea elegans</i> , <i>Yucca elephantipes</i>

2.2.3. Voc Sampling and Analytical Procedure

VOC measurements were carried out in both experimental conditions before (*ex ante*) and after (*ex post*) the introduction and acclimatation of the potted plants using advanced analytical instrumentation for collection and chemical characterization of both anthropogenic and biogenic VOC. The total and individual concentrations of VOC were determined through offline chemical characterization performed *ex ante* and *ex post*. In each sampling session, 1-h air collections were carried out: air was drawn through adsorption cartridges using portable pumps (Pocket389Pump, SKC Inc., Washington County, PA, USA), that provided a constant flow of air of 200 mL min⁻¹, yielding sampling volumes of 12 l. Traps consisted of inert metal tubes (8 cm × 0.3 cm i.d.) filled with Tenax TA and Carbograph 1TD (350 mg; 35/60 and 40/60 mesh, respectively), provided by Markes International, Ltd. (Llantrisant, UK). Measurements were carried out on different days but at the same time of day (11:00 a.m.) to minimize diurnal variability in indoor emissions and ventilation patterns, 1 measurement *ex ante* and 3 measurements *ex post*. During each sampling event, temperature, RH, CO₂ and PM_{2.5} concentrations were also recorded with low-cost sensors to provide contextual environmental information relevant to VOC dynamics, together with photosynthetically active radiation (PAR). Chemical analysis of total VOC was performed by thermal desorption coupled with gas chromatography-mass-spectrometry (TD-GC-MS) (TD: unity series 2, Markes International,

Sacramento, CA, USA; GC–MS: Agilent Technologies, Wilmington, DE, USA). VOC identification was based on the combined evaluation of retention times and mass spectra, which were matched against the NIST 11 reference library using Agilent Mass Hunter Qualitative Analysis software. Following compound identification, quantification was carried out using an external standard calibration approach [62]. All measurements were carried out in triplicate.

2.3. Leaf Micromorphology

For micromorphological analyses, fully developed and healthy leaves were collected and immediately transported to the laboratory for environmental scanning electron microscopy (ESEM) observations [63]. For each leaf, a 1 cm² section was excised from the central lamina between the main vein and the margin. A total of 18 leaf portions (adaxial and abaxial sides) per species were mounted on stubs using double stick tape. Both surfaces were examined using an ESEM Zeiss, EVO LS 10 (Oberkochen, Germany). Micromorphological traits of the adaxial and abaxial surfaces were systematically observed and described. Stomatal density was quantified using an image analysis software (Leica Application Suite), by acquiring five images per leaf at 200x magnification. Stomata features were characterized according to the position of guard cells (prominent or sunken relative to the epidermis; stomatal rim orientation with respect to the veins; presence and extent of epicuticular waxes and possible occlusion of stomatal rims) [64]. Epicuticular waxes were assessed in terms of abundance, morphological typology (granules, rodlets and platelets), and surface distribution [65]. Cuticular ornamentation was also evaluated, distinguishing among deep ridges, micro ridges and surface with nearly absent ridges. None of the investigated species displayed trichomes.

3. Data Processing and Statistical Analysis

Raw data from the AirQino stations were recorded at regular intervals (every ~5 minutes) for the entire monitoring period. Before analysis, a checklist was applied to identify measurements affected by sensor malfunctions, power outages, or identified as outliers, which were subsequently removed from the dataset.

Hourly average concentrations of CO₂, PM_{2.5}, and PM₁₀, along with air temperature (Air Temp.) and RH, were calculated for each classroom during the selected monitoring periods (see Section 2.1). The analysis focused on weekdays with regular teaching activities to assess indoor environmental conditions under representative occupancy scenarios. A time window between 7:00 and 15:00 (or 14:00 for the “Dante Alighieri” primary school) was selected to capture both peak occupancy and the subsequent transition period after a classroom was vacated.

Diurnal profiles were obtained by aggregating measurements by time of day (00:00–23:00) for the entire monitoring period for both the experimental classroom (with plants) and the control classroom (without plants). For each time window, mean values and the standard error of the mean (SE) were calculated ($SE_h = \sigma_h / \sqrt{n_h}$, where σ_h is the standard deviation and n_h is the number of valid observations).

The effect of plants was assessed through a comparative analysis of hourly mean concentrations within the selected time window. Descriptive statistics (minimum, maximum, and mean values, with the corresponding standard error of the mean) were used to characterize the environmental conditions in the two classrooms. The relative difference ($\Delta\%$) between the experimental and control classrooms was calculated for each hour as: $\Delta\% = ((\mu_{\text{plants}} - \mu_{\text{control}}) / \mu_{\text{control}}) \times 100$; where μ_{plants} and μ_{control} indicate the hourly mean concentrations measured in the vegetated classroom and the control classroom (without plants), respectively. The variability of $\Delta\%$ was quantified as the SE of the hourly relative differences, derived from the standard deviation (SD) of inter-class differences, providing an estimate of the temporal consistency of the plant effect.

For the office monitoring campaigns (Empty and Occupied Office), VOC concentrations were measured using a dedicated analytical system distinct from the AirQino stations (see Section 2.2). A statistical analysis was performed to compare conditions before (EXANTE) and after (EXPOST) plant installation. Compounds were identified and classified according to their chemical class and name,

and only valid observations were included in the analysis. Summary statistics (minimum, maximum, and mean \pm SE) were computed for each compound under both conditions. Changes in VOC concentrations were expressed as: $\Delta\%(\text{VOC}) = ((\mu_{\text{EXPOST}} - \mu_{\text{EXANTE}}) / \mu_{\text{EXANTE}}) \times 100$; where μ_{EXANTE} and μ_{EXPOST} represent mean concentrations before and after plants introduction, respectively. The associated uncertainty was estimated via error propagation: $\text{SE}(\Delta\%) = |\Delta\%| \times \sqrt{[(\text{SE}_{\text{EXPOST}} / \mu_{\text{EXPOST}})^2 + (\text{SE}_{\text{EXANTE}} / \mu_{\text{EXANTE}})^2]}$.

Statistical significance of differences was assessed using two-tailed t-tests. For the classroom's dataset, paired-sample t-tests were applied to hourly mean values to account for the matched temporal structure of the measurements between experimental and control conditions.

For the office VOC dataset, paired-sample t-tests were used when EXANTE and EXPOST datasets had equal sample sizes, while independent two-sample t-tests were applied when sample sizes differed, reflecting the structure of the sampling campaigns described in Section 2.2.3 (i.e., one pre-intervention campaign and multiple post-intervention measurements).

Significance levels in both analyses (schools and office) were defined as (*) $p < 0.05$, (**) $p < 0.01$, and (***) $p < 0.001$.

4. Results

4.1. Air Quality in Classroom

4.1.1. Primary School "Dante Alighieri"

Over the four weeks monitoring period, hourly mean CO₂ concentration increased during classroom occupancy, reaching a maximum around midday (~1800 ppm). Concentration decreased during the afternoon and stabilized at baseline levels during nighttime hours (Figure 3; Table 5). This diurnal pattern was consistent under both experimental conditions, with or without plants but CO₂ concentration was not statistically different in the classroom with or without vegetation (Table 5). During nighttime, when students are absent, CO₂ concentrations were comparable between classrooms irrespective of plant presence.

Table 5. Comparative analysis of indoor air quality parameters in classrooms with and without plants during the 07:00–14:00 time window, selected to encompass lesson hours (typically starting at 08:00 and ending between 12:30 and 13:00) from Monday to Friday for the period 06/03/2025 - 06/04/2025 at the primary school "Dante Alighieri".

Parameter	Unit	Classroom without Plants			Classroom with Plants			Δ (%)
		min \pm SE	max \pm SE	mean \pm SE	min \pm SE	max \pm SE	mean \pm SE	
CO ₂	ppm	436.1 \pm 6.7	1856.1 \pm 129.1	1089.4 \pm 71.8	444.0 \pm 10.3	1811.7 \pm 150.2	1127.5 \pm 74.8	4.5 \pm 6.4
PM _{2.5}	$\mu\text{g m}^{-3}$	2.6 \pm 0.5	8.8 \pm 1.0	6.4 \pm 0.9	3.5 \pm 0.8	7.8 \pm 1.1	5.8 \pm 1.1	-2.9 \pm 7.6
RH	%	34.7 \pm 0.7	38.0 \pm 0.6	36.2 \pm 0.6	36.1 \pm 1.1	40.3 \pm 0.8	38.5 \pm 0.9	6.4 \pm 1.2 ***
Air Temp.	$^{\circ}\text{C}$	27.2 \pm 0.3	29.9 \pm 0.3	28.6 \pm 0.3	25.8 \pm 0.6	29.1 \pm 0.4	27.6 \pm 0.4	-3.3 \pm 0.5 ***

Note: All values are reported as minimum, maximum, and mean \pm standard error (SE), where SE indicates the standard error of the mean. Delta (Δ) values represent the absolute and percentage differences (Δ (%)) calculated as (Classroom with plants – Classroom without plants). P-values were obtained using a paired t-test on synchronized data points. Statistical significance is denoted by $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***).

PM_{2.5} concentrations exhibited greater temporal variability than CO₂, with peak values observed around midday (7.8–8.8 $\mu\text{g m}^{-3}$). During lesson hours, PM_{2.5} concentrations were on average slightly lower in the classroom with plants (-3%) compared to the control; however, the difference was not statistically significant, and concentrations never exceeded 10 $\mu\text{g m}^{-3}$.

Hourly mean air temperature increased during daytime classroom occupancy, reaching approximately 29–30 °C at midday before decreasing to about 28 °C in the afternoon. On average, temperatures in the classroom with plants were significantly lower (−3%) than in the control classroom, with differences also observed under unoccupied conditions. In contrast, RH was significantly higher in the presence of plants by approximately 6%, and this increase persisted during periods without students.

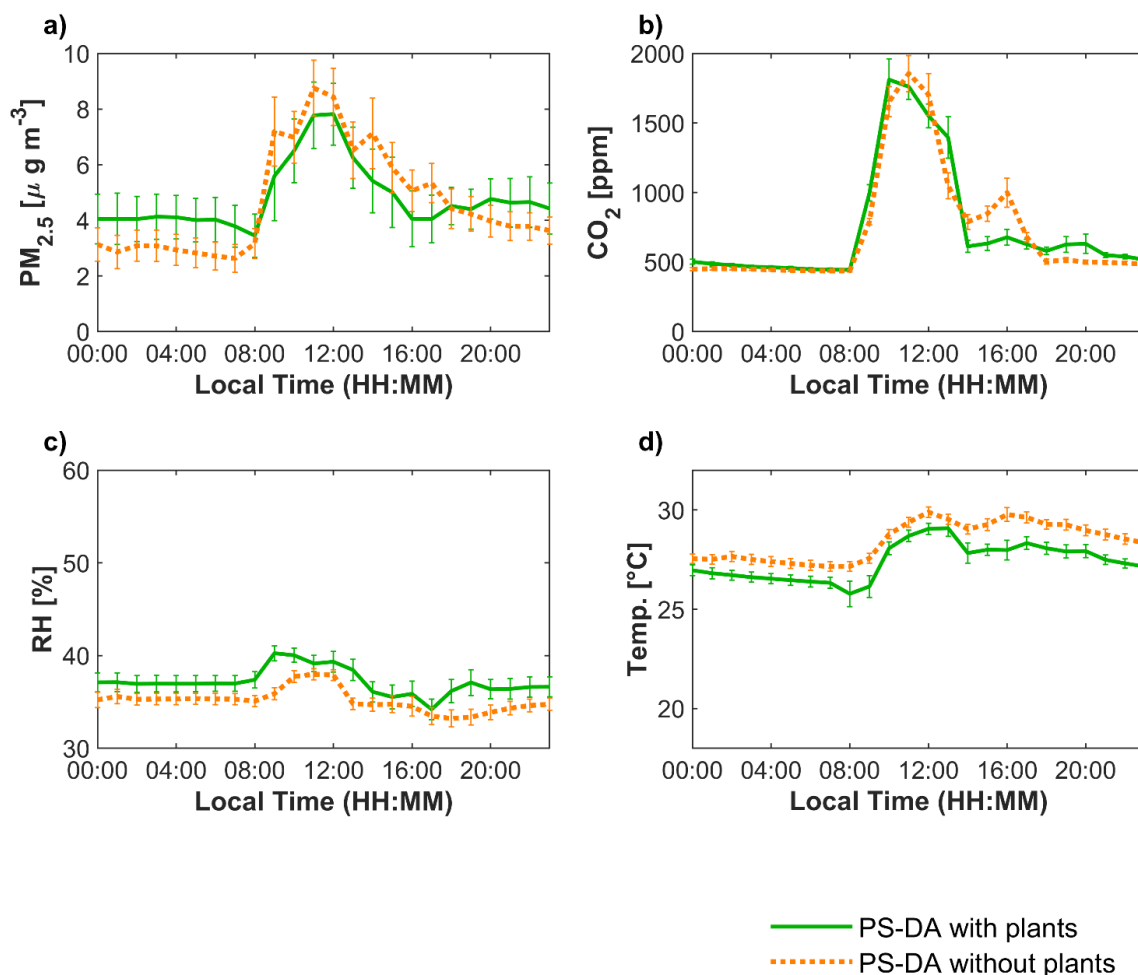


Figure 3. Daily hourly averages of a) PM_{2.5}, b) CO₂, c) RH and d) temperature in classroom with and without plants from Monday to Friday for 06/03/2025 to 06/04/2025 at the primary school “Dante Alighieri” (PS-DA).

4.1.2. Middle School “Leonardo Da Vinci Orazio-Nucola”

Over the four-week monitoring period, hourly mean CO₂ concentrations increased during periods of student occupancy, reaching maximum values around midday (1357–1517 ppm) (Figure 4; Table 6). Concentrations subsequently decreased and gradually returned to a stable nighttime baseline. This diurnal pattern was observed under both experimental conditions; however, CO₂ concentrations were significantly lower (−9.6%) in the classroom with vegetation. During nighttime, when classrooms were unoccupied, CO₂ concentrations were comparable between the two conditions (366–423 ppm) (Table 6).

PM_{2.5} concentrations exhibited higher temporal variability than CO₂, with peak values typically occurring around midday (4.5–5.0 $\mu\text{g m}^{-3}$) (Figure 4; Table 6). PM_{2.5} levels were consistently lower in the presence of plants (−11.2%), and this difference persisted during nighttime hours. A secondary increase in PM_{2.5} concentrations was observed after 16:00, despite the absence of students, likely associated with cleaning activities, followed by a decrease approximately five hours later. PM_{2.5} concentrations remained below 7 $\mu\text{g m}^{-3}$ throughout the entire monitoring period.

Similarly, PM₁₀ concentrations increased during classroom occupancy, reaching maximum values around midday (18.5–23.6 $\mu\text{g m}^{-3}$), with an additional smaller increase in the late afternoon, likely related to cleaning activities. Across all periods, the presence of vegetation was associated with significantly lower PM₁₀ concentrations, resulting in an average reduction of approximately 21%.

Hourly mean indoor air temperature increased during periods of classroom occupancy, reaching approximately 26 °C at midday in the control classroom, whereas temperatures remained lower in the classroom with vegetation, averaging around 23.7 °C (Figure 4; Table 6). Temperatures subsequently declined to approximately 20 °C under both conditions. Overall, the vegetated classroom showed significantly lower temperatures (–8%) compared to the control. During unoccupied periods, temperature differences between classrooms decreased and were not statistically significant. In contrast, RH was consistently and significantly higher in the classroom with plants (+15%), irrespective of student presence.

Table 6. Comparative analysis of indoor air quality parameters in classroom with and without plants during the 07:00–15:00 time window, selected to encompass lesson hours (typically starting at 08:00 and ending between 13:00 and 14:00) from Monday to Friday for the period 08/02/2026–08/03/2026 at the middle school “Leonardo da Vinci Orazio-Nucola”.

Parameter	Unit	Classroom without Plants			Classroom with Plants			Δ (%)
		Min \pm SE	Max \pm SE	Mean \pm SE	Min \pm SE	Max \pm SE	Mean \pm SE	Mean \pm SE
CO ₂	ppm	423.0 \pm 4.2	1517.0 \pm 123.3	1073.8 \pm 64.9	366.0 \pm 37.6	1357.4 \pm 145.4	971.0 \pm 105.4	-10.1 \pm 1.7
								**
PM _{2.5}	$\mu\text{g m}^{-3}$	3.0 \pm 0.6	5.0 \pm 0.7	4.1 \pm 0.6	2.6 \pm 0.8	4.5 \pm 0.8	3.6 \pm 0.7	-11.2 \pm 1.3

PM ₁₀	$\mu\text{g m}^{-3}$	7.3 \pm 0.8	23.6 \pm 2.9	17.6 \pm 1.6	6.0 \pm 0.9	18.5 \pm 2.5	13.9 \pm 1.8	-19.6 \pm 4.0
								**
RH	%	42.6 \pm 1.0	48.6 \pm 0.9	45.4 \pm 1.0	49.8 \pm 0.9	54.5 \pm 0.8	52.1 \pm 0.9	14.8 \pm 1.6

Air Temp.	°C	20.5 \pm 0.3	26.2 \pm 0.8	24.1 \pm 0.4	20.0 \pm 0.3	23.7 \pm 0.2	22.2 \pm 0.2	-7.6 \pm 1.3

Note: All values are reported as minimum, maximum, and mean \pm standard error (SE), where SE indicates the standard error of the mean. Delta (Δ) values represent the absolute and percentage differences (Δ (%)) calculated as (Classroom with plants – Classroom without plants). P-values were obtained using a paired t-test on synchronized data points. Statistical significance is denoted by $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***).

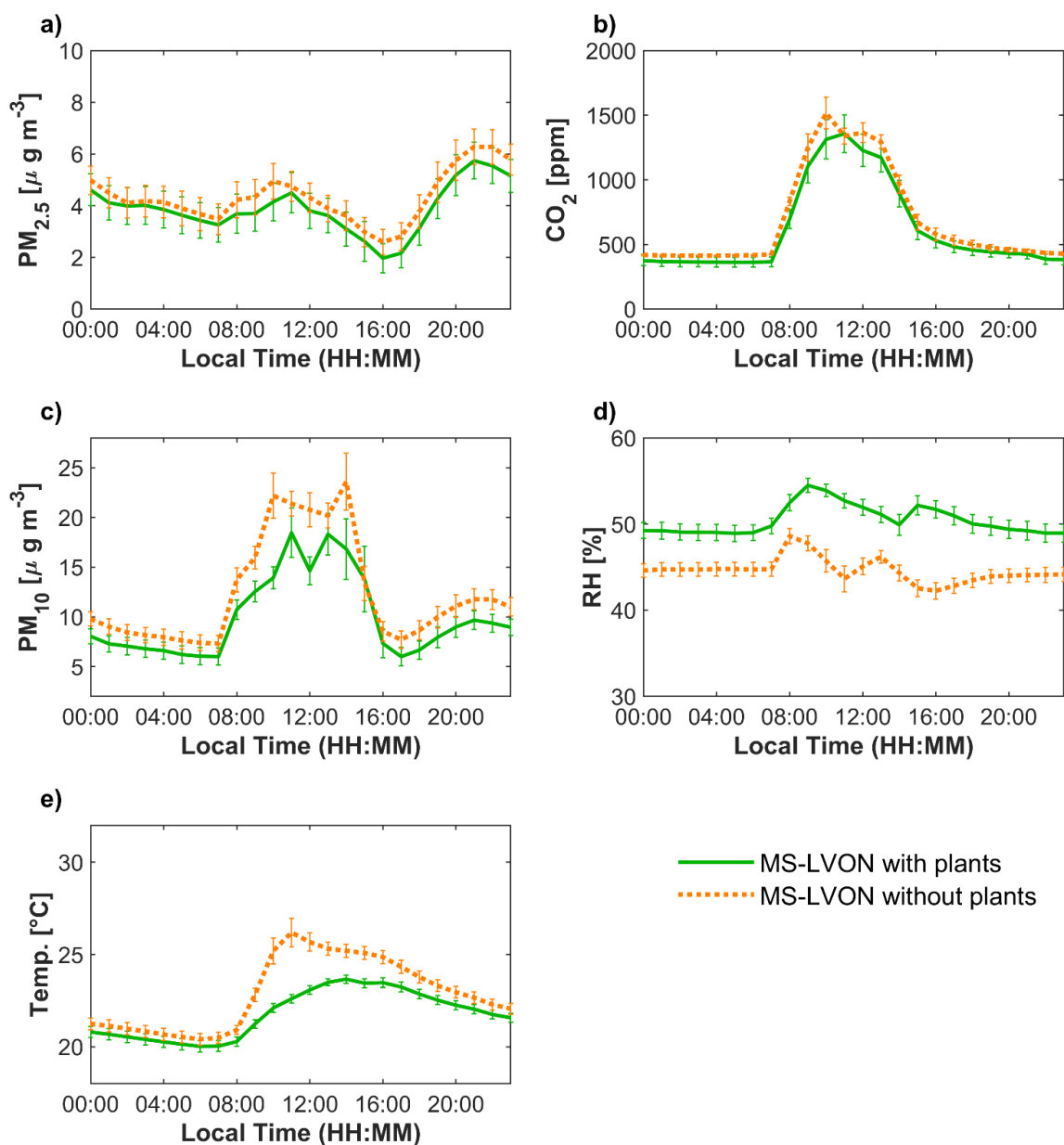


Figure 4. Daily hourly averages of a) PM_{2.5}, b) CO₂, c) PM₁₀, d) RH and e) temperature in classroom with and without plants (Monday to Friday) for the period 08/02/2026 - 08/03/2026 at the middle school "Leonardo da Vinci Orazio-Nucola" (MS-LVON).

4.1.3. High School "Piero Gobetti"

After four weeks of observations, hourly mean CO₂ concentrations increased during periods of student occupancy, reaching maximum values around midday (1500–1600 ppm) (Figure 5; Table 7). Concentrations subsequently decreased and gradually returned to a stable nighttime baseline. This diurnal pattern was consistently observed under both experimental conditions, with and without plants; however, no statistically significant differences in CO₂ concentrations were detected between classrooms.

PM_{2.5} concentrations exhibited greater temporal variability than CO₂, with peak values occurring around midday (1.9–2.6 $\mu\text{g m}^{-3}$) and an additional increase in the late afternoon (Figure 5; Table 7). PM_{2.5} levels were consistently lower in the classroom with plants (–23%), and this reduction persisted during nighttime hours. Throughout the monitoring period, PM_{2.5} concentrations remained below 3 $\mu\text{g m}^{-3}$.

Similarly, PM_{10} concentrations increased during classroom occupancy, reaching maximum values around midday (8.2–11.7 $\mu\text{g m}^{-3}$). The presence of vegetation was associated with significantly lower PM_{10} concentrations, with an average reduction of approximately 21% compared to the control classroom.

Hourly mean indoor air temperature increased during periods of classroom occupancy, peaking at approximately 24 °C around midday in both classrooms, before declining to about 21 °C under both conditions. On average, temperatures in the classroom with plants were significantly lower (–1%) than in the control. During unoccupied periods, particularly at night, temperature differences between classrooms were reduced and comparable. In contrast, RH consistently remained higher in the classroom with plants, with an average increase of approximately 7%, regardless of student presence.

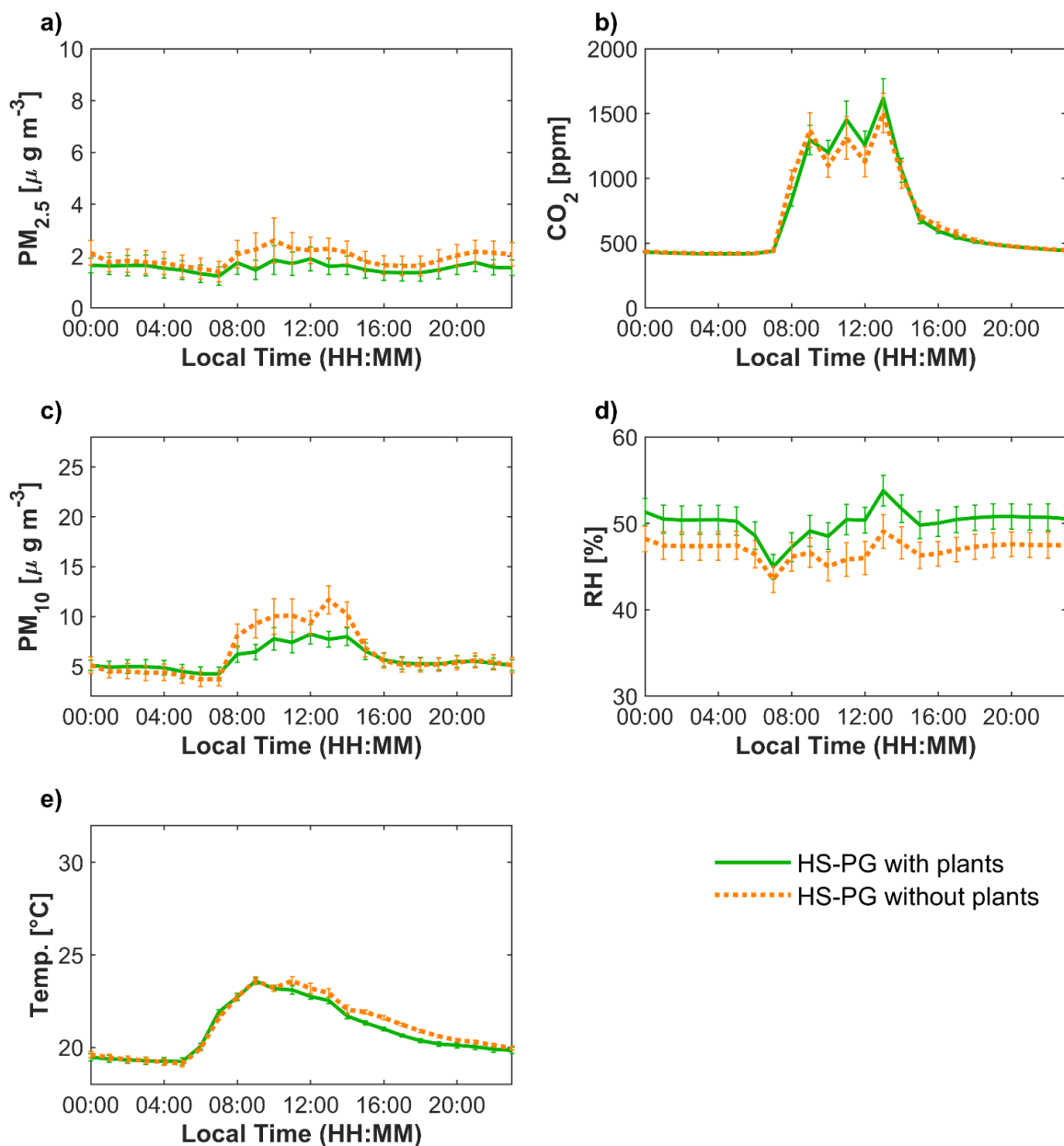


Figure 5. Daily hourly averages of a) $PM_{2.5}$, b) CO_2 , c) PM_{10} , d) RH and e) temperature in classroom with and without plants (Monday to Friday) for the period 04/02/2026 - 04/03/2026 at the high school “Piero Gobetti” (HS-PG).

Table 7. Comparative analysis of indoor air quality parameters in classroom with and without plants during the 07:00–15:00 time window, selected to encompass lesson hours (typically starting at 08:00 and ending between at 14:00 from Monday to Friday for the period 04/02/2026 - 04/03/2026 at the high school “Piero Gobetti”.

Parameter	Unit	Classroom without Plants			Classroom with Plants			Δ (%) mean \pm SE
		Min \pm SE	Max \pm SE	Mean \pm SE	Min \pm SE	Max \pm SE	Mean \pm SE	
CO ₂	ppm	439.1 \pm 4.6	1504.6 \pm 151.2	1065.7 \pm 96.1	438.7 \pm 3.9	1618.2 \pm 150.1	1093.2 \pm 86.5	1.8 \pm 3.1
PM _{2.5}	$\mu\text{g m}^{-3}$	1.4 \pm 0.4	2.6 \pm 0.9	2.1 \pm 0.5	1.2 \pm 0.4	1.9 \pm 0.5	1.6 \pm 0.4	-22.6 \pm 2.6 ***
PM ₁₀	$\mu\text{g m}^{-3}$	3.7 \pm 0.7	11.7 \pm 1.4	8.8 \pm 1.3	4.2 \pm 0.7	8.2 \pm 1.0	6.9 \pm 0.9	-17.9 \pm 4.9 **
RH	%	43.5 \pm 1.5	49.1 \pm 2.0	46.3 \pm 1.8	45.0 \pm 1.4	53.8 \pm 1.8	49.6 \pm 1.6	7.1 \pm 0.9 ***
Air Temp.	$^{\circ}\text{C}$	21.6 \pm 0.1	23.6 \pm 0.2	22.8 \pm 0.2	21.3 \pm 0.1	23.6 \pm 0.2	22.5 \pm 0.2	-1.0 \pm 0.4

Note: All values are reported as minimum, maximum, and mean \pm standard error (SE), where SE indicates the standard error of the mean. Delta (Δ) values represent the absolute and percentage differences (Δ (%)) calculated as (Classroom with plants – Classroom without plants). P-values were obtained using a paired t-test on synchronized data points. Statistical significance is denoted by $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***)

4.2. Voc Measurements in Office Environment

In the *ex ante* conditions, a total of 200 VOC belonging to 14 chemical classes were identified in the unoccupied sealed office, whereas 102 VOC belonging to 10 chemical classes were detected in the *ex ante* occupied open office (Table 8). The number of compounds per chemical class did not directly reflect their contribution to total concentrations. Alkanes were the most represented class in terms of number of compounds in both offices; however, alcohols accounted for the highest concentrations, followed by alkanes, acids, ketones, and esters in the unoccupied office, and by ketones, esters, alkanes, and arenes in the occupied office (Table 8).

Following plant installation, total VOC concentrations decreased significantly in both offices, whereas the overall VOC composition remained qualitatively similar. In the unoccupied office, total VOC concentrations decreased from 8.48 to 4.11 $\mu\text{g m}^{-3}$, corresponding to a reduction of 52%. In the occupied office, total VOC concentrations decreased by 24%, from 9.22 to 6.99 $\mu\text{g m}^{-3}$ (Table 8).

The VOC classes most affected by plant introduction were those showing higher *ex ante* concentrations. Alcohol concentrations decreased by 74% in the unoccupied office and by 31% in the occupied office, alkanes were reduced by 29% and 41%, respectively, while ketones decreased by 40% in the unoccupied and 46% in the occupied office. Monoterpenes and monoterpenoids showed marked reductions in both offices (-77% in the unoccupied and -46% in the occupied office), whereas arenes significantly decreased only in the occupied office (-28%). Ester concentrations significantly declined in the unoccupied office (-51%) but increased in the occupied office (+35%).

Regarding the single VOC, several alcohols showed significant reductions after plant introduction. In the unoccupied office, ethanol, 2-butoxy-(-89%) and benzyl alcohol (-89%), 2-Propanol 1 (2methoxypropoxy)- (-76%) significantly decreased, whereas isopropyl alcohol was significantly reduced in the occupied office (-69%). Ethanol concentration decreased significantly in both offices (-59% in the unoccupied and -37% in the occupied office).

In the occupied office, acetone (ketone; 0.891 $\mu\text{g m}^{-3}$) and isoprene (hemiterpene; 0.109 $\mu\text{g m}^{-3}$) concentrations were higher than those measured in the unoccupied office (0.309 $\mu\text{g m}^{-3}$ and 0.034 $\mu\text{g m}^{-3}$, respectively). Both compounds significantly decreased following plant introduction in the two offices (acetone: -50% in the unoccupied and -56% in the occupied office; isoprene: -76% and -50%, respectively).

Monoterpenes and monoterpenoids were detected at relatively low concentrations in both offices. The most abundant compounds included limonene, p-cymene, and α - and β -pinene, all of which showed significant reductions after plant introduction (limonene: -89% unoccupied, -44% occupied; p-cymene: -78% unoccupied, -29% occupied; α -pinene: -44% unoccupied, -39% occupied; β -pinene: -76% unoccupied, -77% occupied) (Table S2).

Punctual measurements of environmental parameters indicated that, in the unoccupied office, plant introduction was associated with a reduction in air temperature (-3%) and an increase in relative humidity (+13%), while no relevant changes in CO₂ concentrations were observed. In the occupied office, plant presence was associated with decreases in air temperature (-6%) and CO₂ concentrations (-6%), along with an increase in RH (+12%) (data not shown).

Table 8. VOC in unoccupied and occupied offices: chemical classes, number of compounds for each chemical class, concentrations *ex ante* and *ex post* (mean \pm SE), Delta (Δ) values (%) between *ex-ante* and *ex-post*. Statistical significance is denoted by $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ ***). N.d. = Not detected.

Chemical Class	Compo unds (n)	Empty			Δ (%) mean \pm SE	Occupied		Δ (%) mean \pm SE
		Concentr ation <i>ex ante</i> ($\mu\text{g m}^{-3}$)	Concentr ation <i>ex post</i> ($\mu\text{g m}^{-3}$)	Compo unds (n)		Concentr ation <i>ex ante</i> ($\mu\text{g m}^{-3}$)	Concentr ation <i>ex post</i> ($\mu\text{g m}^{-3}$)	
Acid	7	0.550 \pm 0.200	0.845 \pm 0.237	53.6 \pm 24.6%	n.d.	-	-	-
Alcohol	25	5.307 \pm 0.171	1.372 \pm 0.106	-74.1 \pm 6.2% ***	16	4.373 \pm 0.210	3.027 \pm 0.187	-30.8 \pm 2.4% ***
Aldehyde	12	0.190 \pm 0.004	0.293 \pm 0.029	53.8 \pm 5.4%	11	0.386 \pm 0.024	0.417 \pm 0.022	8.2 \pm 0.7%
Alkane	78	0.644 \pm 0.013	0.454 \pm 0.041	-29.4 \pm 2.7% *	24	0.924 \pm 0.050	0.545 \pm 0.020	-41.0 \pm 2.7% ***
Alkene	12	0.028 \pm 0.001	0.050 \pm 0.008	77.7 \pm 12.8%	3	0.049 \pm 0.003	0.041 \pm 0.002	-16.4 \pm 1.3% *
Arene	18	0.332 \pm 0.004	0.385 \pm 0.041	16.2 \pm 1.7%	11	0.717 \pm 0.047	0.518 \pm 0.023	-27.8 \pm 2.2% ***
Chlorinate d compound	5	0.370 \pm 0.016	0.165 \pm 0.033	-55.4 \pm 11.3% **	3	0.208 \pm 0.005	0.193 \pm 0.004	-7.5 \pm 0.2% *
Cycloalka ne	8	0.009 \pm 0.000	0.021 \pm 0.002	142.9 \pm 13.3% **	n.d.	-	-	-
Hemiterpe ne	1	0.034 \pm 0.003	0.008 \pm 0.001	-75.8 \pm 8.6% ***	1	0.109 \pm 0.018	0.054 \pm 0.004	-50.3 \pm 9.0% ***
Ester	13	0.414 \pm 0.039	0.203 \pm 0.024	-50.8 \pm 7.7% **	16	1.078 \pm 0.082	1.451 \pm 0.082	34.6 \pm 3.3% **
Furan	2	0.000 \pm 0.000	0.001 \pm 0.000	Inf \pm 0.0%	n.d.	-	-	-
Ketone	9	0.454 \pm 0.011	0.272 \pm 0.018	-40.0 \pm 2.9% ***	7	1.186 \pm 0.084	0.645 \pm 0.020	-45.6 \pm 3.5% ***

Monoterpe								
nes/		0.123 ±	0.029 ±	-76.7 ±		0.184 ±	0.099 ±	-46.3 ±
monoterpe	8	0.003	0.003	7.4% ***	10	0.023	0.014	8.7% **
noids								
Phenol	2	0.027 ±	0.012 ±	-56.5 ±	n.d.	-	-	-
		0.004	0.003	17.5% *				
Total	200	8.481 ±	4.111 ±	-51.5 ±	102	9.215 ±	6.991 ±	-24.1 ±
		0.086	0.400	5.0% ***		0.437	0.211	1.4% ***

4.3. Leaf Micromorphology

In all analysed species, stomata were exclusively located on the abaxial surface, except for *S. wallisi* and *Y. elephantipes* which also exhibited sparse stomata on the adaxial surface. No morphological differences were observed between stomata occurring on the adaxial or abaxial leaf surfaces. *F. Benjamina* and *S. actinophylla* showed the highest total stomata density (between 150 and 140 stomata mm⁻²), whereas all other species were characterized by markedly lower stomatal densities, ranging from 29 to 63 stomata mm⁻² (Table 9; Figure 6). Trichomes were not observed in any of the examined species.

Epicuticular waxes were abundant and homogeneously distributed on both leaf surfaces in *E. aureum*, *F. benjamina* and *Y. elephantipes*. In *S. actinophylla*, waxes were homogeneously distributed on both surfaces but less abundant on the abaxial side. In *C. elegans*, waxes were abundant and homogeneously distributed only on the adaxial surface, while in *S. wallisi* they were abundant but unevenly distributed on the adaxial surface. Waxes occurred in different morphotypes among species: they appeared as granules in *S. actinophylla*, often surrounding the stomata, and as platelets in *S. wallisi* and in *Y. elephantipes*. In *C. elegans*, *E. aureum*, *F. benjamina* waxes were mainly present as flakes. In addition, in *F. benjamina* and *Y. elephantipes* the stomata rims were variably covered by nearly uniform waxes layers, consistent with previous reports [65]. In agreement with previous observations, stomata in *F. benjamina* were also surrounded by a characteristic cuticular thickening forming a distinct rim and were deeply sunken [66].

All the studied species exhibited cuticle ornamentation, characterized by different types of ridges on both the adaxial and the abaxial leaf surfaces. In *S. actinophylla*, ridges were present on both surfaces, while on the abaxial surface micro ridges were arranged in repeated patterns surrounding the stomata. Both leaf surfaces of *S. wallisi* were characterized by ridges oriented parallel to the stomata and by micro ridges arranged in repeated patterns, particularly around the stomata. In *E. aureum*, ridges were arranged parallel to both stomata and leaf veins; additionally, epidermal cells were projected on the leaf surface, with clearly defined cell borders. In *F. benjamina*, the abaxial surface displayed prominently projected veins and ridges arranged in in repeated patterns around the stomata, while the adaxial surface was characterized by projected veins and epidermis cells. In *C. elegans* macro ridges were aligned parallel to both the stomata and epidermal cells, elongated and projected, and exhibited well defined borders. *Y. elephantipes* showed macro ridges parallel to the stomata and the epidermal cells, elongated and projected on the leaf surface; around the protruding stomata, which were also present on the adaxial surface, papillae were arranged in distinct patterns.

Table 9. Leaf macro and micromorphology and stomata density (stomata mm⁻²) on the leaf surfaces of the studied species. Both adaxial and abaxial surfaces are described; stomata density is referred to the abaxial surface. Values are means ± SE (n = 3). a = absent.

Species	Leaf description	Stomata density	Stomata characters	Epicuticular waxes	Trichomes	Cuticular ornamentations
<i>Schefflera actinophylla</i>	Large, dark green, glossy, palmately compound leaves, typically featuring 5 to 8 elliptic-to-ovate leaflets that radiate from a central point	139.7 ± 12.4	Stomata surrounded by guard cells, in the form of regular polygons, raised above the leaf surface; random orientation; length 14-17µm	Smooth layer completely covering the adaxial surface, film covering the abaxial surface; waxes in form of granules	a	Ridges on both surfaces; micro ridges surrounding stomata
<i>Spathiphyllum wallisii</i>	Broadly lanceolate, dark green, glossy, leaves with prominent, deeply impressed veins and acuminate tips.	33.7 ± 0.9	Stomata parallel along the veins, length 35-37 µm	Smooth layer completely covering the adaxial surface; waxes in platelets; no waxes on abaxial surface	a	Ridges and micro ridges on both surfaces; micro ridges also surrounding stomata
<i>Epipremnum aureum</i>	Glossy, heart-shaped, waxy leaves, bright green or irregularly marbled with yellow or cream, varying in size from 10 cm long in young plants to larger	38.1 ± 2.8	Stomata parallel along the veins, length 24-26 µm	Smooth layer completely covering both surfaces; waxes in form of flakes	a	Ridges; epidermis cells projected on the leaf surface

	dimensions in mature plants.					
<i>Ficus benjamina</i>	Small, glossy, deep-green alternate leaves, elliptic with acute to round base, with a distinctly pointed, acuminate tip and slightly undulate margins, 4-13 cm long and 2-6 cm wide.	149.4 ± 7.7	Stomata surrounded by guard cells, raised above the leaf surface; random orientation; length 10-11µm	Fissured layer completely covering both surfaces; waxes in form of flakes	a	Veins and ridges; epidermis cells projected on the adaxial surface
<i>Chamaedorea elegans</i>	Pinnate, with 11–20 pairs of narrow linear to lanceolate, dark green leaflets (15–30 cm long, 1–3 cm wide), with long-acuminate tips, arranged along a central rachis	63.3 ± 2.7	Stomata parallel along the veins and microveins; length 16-18 µm	Fissured layer completely covering the adaxial surface; waxes in form of flakes; no waxes on abaxial surface	a	Macro ridges, epidermis cells projected on the leaf surface
<i>Yucca elephantipes</i>	Long, linear-lanceolate, glossy green, leathery, with entire margins, and a terminal spine at the apex; 60–120 cm long and 5–7.5 cm wide, arranged in spiraled, arching rosettes	28.5 ± 5.7	Stomata surrounded by guard cells, in the form of regular polygons, raised above the leaf surface; random orientation; length 15-17µm	Crust completely covering both surfaces; waxes in form of platelets	a	Ridges; epidermis cells projected on the leaf surface, papillae around stomata

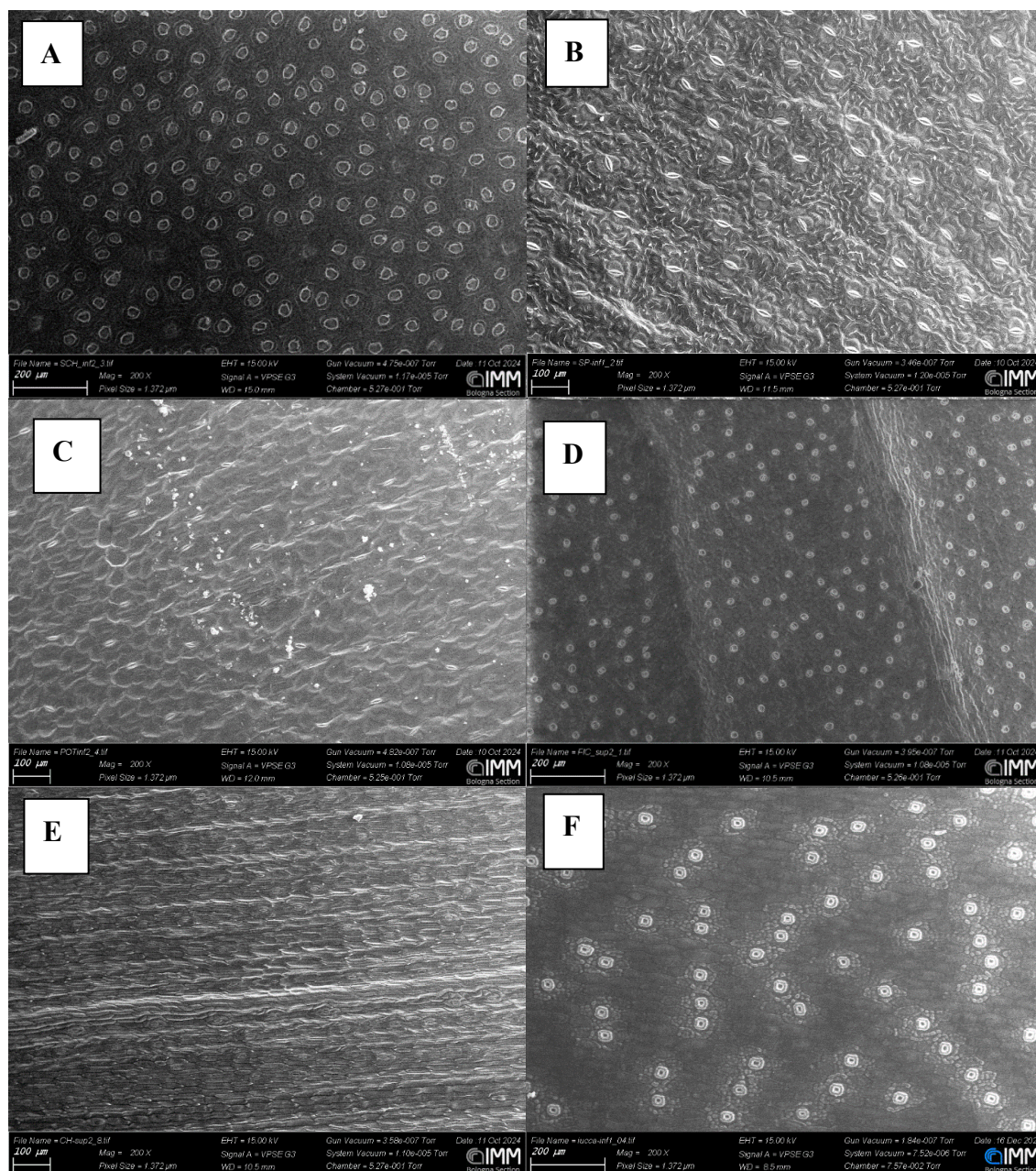


Figure 6. Environmental scanning electron micrograph of leaf abaxial surface with stomata (200 x magnification). A) *Schefflera actinophylla*, B) *Spathiphyllum wallisii*, C) *Epipremnum aureum*, D) *Ficus Benjamina* E) *Chamaedorea elegans*, F) *Yucca elephantipes*.

5. Discussion

Phytoremediation is increasingly recognised as a potentially effective and sustainable strategy for improving indoor air quality; however, its performance strongly depends on both plant density and species composition [30,67–71].

Most commonly used indoor plants follow the C3 photosynthetic pathway and, during daytime, contribute positively to human well-being by absorbing CO₂ and producing oxygen. Nevertheless, under low-light conditions or during nighttime, C3 plants may release CO₂, potentially limiting their effectiveness in continuously occupied indoor settings. In the present study, a nature-based solution was implemented through the integration of many C3 plant species, selected and distributed according to the structural and functional characteristics of the monitored rooms. In addition, CAM plants such as *Sansevieria laurentii* were introduced in substantial numbers in a specific setting (middle school) to complement the diurnal CO₂ uptake of C3 species. As CAM plants primarily

assimilate CO₂ nocturnally through crassulacean acid metabolism, they may contribute to a more balanced gas-exchange cycle over a 24-h period [30]. Similar combined C3–CAM strategies have been proposed in recent indoor air quality studies to mitigate nocturnal CO₂ accumulation in poorly ventilated environment [67].

Under the conditions investigated in the present study, the contribution of indoor vegetation to CO₂ mitigation was detectable but limited. Reductions in CO₂ concentrations were observed only during specific hours of the day and exclusively in the middle school, where the highest plant biodiversity and the most favourable plant-to-occupant ratio were implemented. In this context, the overall indoor CO₂ balance was strongly influenced by human respiration associated with student occupancy, which likely constrained the detectability of plant related CO₂ uptake. This dominance of human respiratory emissions does not imply that plant assimilation is ineffective; rather, it suggests that the magnitude and temporal variability of occupant related CO₂ sources may mask the comparatively smaller contribution of plants under real life conditions.

These findings are consistent with previous results reported by Sharma et al. 2022 [67], who demonstrated that effective CO₂ reduction through indoor plants depends strongly on plant density, species composition, and interaction with ventilation regimes. Likewise, the comprehensive review by Bandehali et al. 2021 [10] highlighted that, under real-life indoor conditions, plant based CO₂ mitigation is generally secondary to ventilation effects unless very high plant densities or engineered botanical biofilters are employed.

In contrast, particulate matter removal was more consistent and pronounced across all monitored school environment. This pattern is consistent with previous studies, which reported higher removal rates for PM_{2.5} and PM₁₀ compared with CO₂ and VOC in vegetated indoor environments, particularly under low-ventilation conditions [10,67]. The preferential removal of PM has been mainly attributed to physical processes such as gravitational settling, impaction, interception, and electrostatic deposition on leaf surfaces, as well as to vegetation-induced changes in airflow patterns and surface roughness that enhance particle deposition [10,67]. In this study, absolute PM concentrations during the monitoring period were generally low; consequently, the observed percentage reductions, ranging from approximately 3% to 23% for PM_{2.5} and of about 18–20% for PM₁₀ across all monitored schools corresponded to modest absolute reductions. The variability observed for PM_{2.5}, compared with the more consistent response of PM₁₀, likely reflects differences in building characteristics, occupancy patterns, and indoor airflow dynamics, all of which can influence particle transport, deposition, and resuspension processes. Nevertheless, even such limited reductions may be environmentally and health-relevant, as they contribute to reducing the cumulative exposure of students to particulate matter in indoor school environments.

Beyond pollutant removal, indoor vegetation also exerted a clear influence on indoor microclimatic conditions, particularly temperature and relative humidity. Across the monitored schools, the implementation of NBS contributed to significantly lower indoor temperatures during periods of daytime student occupancy, with reductions ranging from approximately 1 °C to 2 °C. This cooling effect is largely attributable to evapotranspiration processes, which dissipate sensible heat and reduce thermal fluctuations. Similar temperature moderation effects associated with indoor plants have been reported in densely occupied educational settings [10]. A residual cooling effect was also observed during nighttime periods, suggesting incomplete stomatal closure and sustained, albeit reduced, transpiration under indoor conditions [71,72].

Simultaneously, leaf transpiration led to measurable increases in indoor RH, ranging from approximately 6% to 15%. This finding is consistent with earlier studies demonstrating the role of indoor vegetation in stabilising humidity levels and counteracting excessively dry indoor air, particularly during heating periods or in mechanically ventilated buildings [10,67,72,73]. This is an additional aspect worth discussing that concerns the indirect implications of plant induced humidity regulation for indoor health conditions. In fact, the increase of relative humidity may shift indoor environments toward physiologically more favourable ranges and potentially reduce the stability and transmission of airborne viruses under moderate-to-high humidity conditions [74–76]. In this

context, the ability of indoor plants to contribute to humidity regulation above critically low thresholds (>30%) [77] may represent a complementary, non-invasive strategy for improving indoor environmental conditions [30]. Such effects are particularly relevant in school settings, where thermal comfort and humidity are closely linked to occupants' wellbeing and cognitive performance.

Indoor air pollution comprises multiple components, including also total volatile organic compounds. Numerous studies have demonstrated that potted plants can contribute to the reduction of indoor air contaminants under a range of environmental conditions [30,67–71,78–80] through absorption via leaf stomata and epidermis then further metabolism.

In our studies on office environments, total VOC concentration but not composition varied before and after potted plants positioning. When no plants were present, the office presented higher total VOC concentrations than after plants introduction. This was the case at both experimental scenarios: the reduction was higher in the case of the unoccupied sealed office, where less variables were at play, but was however significant also in the occupied office.

We thus suggest that the presence of VOC in general, and terpenes in particular, cannot be attributed to emissions caused by the physiological activities of the potted plants, although, to our knowledge, only *S. wallisii*, *E. aureum* and *F. benjamina*, can emit biogenic VOC, including terpenoid compounds [81,82]. Conversely, potted plants seemed to contribute to VOC reduction, mainly regarding alcohols, the classes with the highest concentrations, but also alkane, ketone such as acetone, terpenic compounds such as isoprene, and the monoterpenes limonene and α - and β -pinene. VOC are released from different sources: alkanes, alcohols, arenes and terpenes are among the main constituents of waxes and cleaning products; ethanol, 2-butoxy-, isopropyl alcohol and benzyl alcohol are all found in cleaning products [83,84] and when present were significantly reduced after plants introduction; acetone is emitted through human breath and is a product of sugar metabolism [85]; limonene, p cymene, α - and β -pinene are typical fragrances of cleaning products [86,87] and isoprene can be emitted both by plants and through human breath [88,89]. Unlike all other VOC chemical classes, in the unoccupied office, in presence of plants ester concentration significantly decreased while it increased in the occupied office. This phenomenon may be related to the occupants, as these VOC are among the components of many perfumes, personal care products and cosmetics [90]. Arenes, which includes the so-called BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), compounds hazardous to human health, were present at concentrations relatable to external ones.

The species used in office environment, were already studied for their abilities to ameliorate IAQ. In particular, *S. wallisii* was studied for its ability to remove indoor pollutants such as NO₂ and several VOC including formaldehyde, benzene, toluene and 2-ethylhexanol [91–93]; *F. benjamina*, *C. elegans* and *E. aureum* removed formaldehyde, mainly in the root zone [30,91,94]; *E. aureum* removed formaldehyde, xylene, and toluene [91] and PM as well [26] and *S. actinophylla* removed gaseous toluene and benzene in the root zone [91] and formaldehyde [27,30]. The primary effects of the potential of the indoor plants on air quality are formaldehyde, benzene, and toluene removal; thus, using a combination of plant species can further improve air quality [77,93].

As dust-retention potential increases with the number of stomata [95], the relative higher total stomata density in *F. benjamina* and *S. actinophylla* suggested that these species have the potential to efficiently absorb particulate. As the potential of epicuticular wax in trapping particles is species-specific [96] and waxy leaves collected the highest amount of particles from the atmosphere [96,97], our results highlighted that species with more waxy leaves such as *Yucca elephantipes*, *F. benjamina* and *E. aureum* could be more effective in capturing PM. Since leaves with rough surfaces and densely arranged grooves and ridges showed more PM accumulation than those with smooth surfaces [98], the leaf surface complexity and roughness of all of the species under study were considered suitable for capturing dust. Furthermore, in the species *E. aureum*, *F. benjamina*, *C. elegans* and *Y. elephantipes* the epidermis cells projected on the leaf surface contributed to the surface complexity and thus to its coarseness.

Taken together, the combined evidence supports the suitability of all the studied species for indoor applications.

6. Conclusions

Given that people spend up to 90% of their time indoor, ensuring good IAQ is essential to limit human exposure to air pollutants. In this context, indoor vegetation is increasingly recognized as a complementary strategy to improve indoor environmental quality.

Schools are a particularly sensitive setting, as children and adolescents, who are more vulnerable to air pollution, spend a substantial amount of time there.

This study investigated the effects of indoor plants in schools and offices under real world conditions; to the best of our knowledge, it represents one of the first investigations to integrate continuous, real-time monitoring of phytoremediation effects on IAQ across multiple educational levels with the assessment of VOC concentrations in office environments.

The results indicate that the presence of multiple potted plants species is associated with measurable reductions in PM and VOC concentrations, along with improvements in indoor microclimate conditions, including lower air temperatures and higher RH. Despite variability among environments, these findings support indoor plants as an effective and sustainable nature-based solution for enhancing IAQ in indoor workplaces.

While much of the current evidence on indoor phytoremediation is derived from controlled laboratory studies, this work provides in situ data demonstrating its relevance in real, occupied indoor environments. Despite the impossibility of fully controlling variables such as occupancy patterns and window or door opening, these conditions reflect typical school and workplace settings and therefore offer a realistic framework for assessing plant-based interventions. Even modest but consistent improvements across multiple indoor environmental parameters may thus be environmentally and health-relevant.

In conclusion, the integration of indoor plants in schools and other workplaces emerges as a promising complementary strategy to improve indoor environmental quality and promote healthier and more comfortable indoor spaces, particularly for children and adolescents who are more vulnerable to air pollution.

Future research should broaden plant-based experimental approaches and integrate them with systematic, long-term IAQ monitoring to further clarify the phytoremediation potential of indoor vegetation under real-life conditions. In addition, forthcoming initiatives will address the effects of indoor nature-based solutions on student cognitive performance and socio-psychological wellbeing, providing a more comprehensive assessment of their benefits for indoor environments.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Table S1: Intercalibration results of AirQino monitoring stations based on co-location analysis and linear regression. Table S2: Alcohols, monoterpenes and monoterpeneoids, hemiterpenes and acetone in unoccupied and occupied offices: name, chemical classes, concentrations ex ante and ex post (mean \pm SE), Delta (Δ) values (%) between ex-ante and ex-post. Statistical significance is denoted by $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***). N.d. = Not detected.

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