ENVIRONMENT ORIGINAL ARTICLE

"Plants in the Classroom": a citizen science experience to improve indoor air quality at the Gobetti-Volta Scientific High School in Bagno a Ripoli (Italy)

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Abstract The "Plants in the Classroom" project, conducted at the Gobetti-Volta Scientific High School in Bagno a Ripoli (Italy), originated from the need to scientifically investigate indoor air quality in school classrooms. With the support of the International Society of Doctors for the Environment (ISDE-Sezione Firenze), the scientific coordination of the National Research Council – Institute of BioEconomy (CNR-IBE) in Florence, and the active involvement of students and teachers, three classes were equipped with plant species selected for their air-purifying properties. Indoor environmental parameters (CO2, PM2.5, relative humidity, and temperature) were continuously monitored using low-cost AirQino stations, previously applied and validated in other environmental contexts, enabling cost-effective measurements in real school settings. Measurements were compared with those collected in a fourth classroom without plants, which served as a control. While acknowledging limitations such as the limited number of plants, structural differences between classrooms, and variable ventilation conditions, the collected data offer a reliable snapshot of everyday classroom management. The results show how plants, through photosynthesis and transpiration, contributed to reducing CO2 and PM2.5 levels and increasing relative humidity. In addition to the environmental benefits, students reported improvements in concentration and perceived well-being. Overall, the project represents a replicable model of active learning and ecological awareness.

Keywords indoor air quality; classroom vegetation; environmental education; active learning; CO2; PM2.5; student well-being; citizen science.

1. INTRODUCTION

In many classrooms, large student populations, stagnant air, and limited ventilation can create a stuffy and uncomfortable indoor environment[1]. However, the resulting discomfort is not limited to basic comfort parameters, such as temperature or humidity: indoor air pollution-defined as the presence of harmful substances in the air beyond its natural composition-can have direct effects on health and well-being, including irritation and fatigue, as well as indirect effects, such as reduced student concentration[2]. In urban settings, where much of the day is spent indoors, the quality of air in school spaces plays a central role not only in preventing physical and respiratory disorders but also in fostering an environment conducive to learning and the safety of all classroom occupants[2,3,4].

Numerous studies support this evidence. In school-aged children, exposure to indoor air pollution is associated with increased incidence of respiratory infections and allergic diseases[5,6,7].

In school environments, the main sources of indoor air pollution include fine particulate matter (PM10 and PM2.5), carbon dioxide (CO2), volatile organic compounds (VOCs), formaldehyde, and benzene. These pollutants originate from multiple factors, including the presence of people in classrooms, inadequate ventilation, the use of cleaning products and building materials, and biological sources such as dust mites, mold, and pollen[8]. Monitoring CO2 is essential, as levels can rise rapidly in crowded classrooms, leading to fatigue, reduced concentration, and, in some cases, an increased risk of pathogen transmission[9]. High carbon dioxide concentrations have also been associated with elevated microbial loads[10].

In this regard, a 2003 study conducted in the United States highlighted the relationship between CO2 concentrations and the transmission of influenza infections[11]. In a classroom of 30 students, one of whom was infected with influenza, the study found that five people became infected at a CO2 concentration of 1000 ppm, twelve at 2000 ppm, and fifteen at 3000 ppm. These results demonstrate that poor air quality can directly increase the risk of infection.

Another example of the impact of indoor air on human health is the so-called "Sick Building Syndrome" (SBS) [12]. This term refers both to buildings that induce discomfort in their occupants and to the symptoms experienced by the individuals themselves. Reported symptoms include irritation of the eyes and mucous membranes, dry skin and airways, difficulty breathing, and mental fatigue.

Unlike outdoor air pollution, which has been studied for decades and is regulated by specific legislation such as the European Directive 2008/50/EC and its Italian implementation (D.Lgs. 155/2010), indoor air pollution has only recently been recognized as a significant issue, especially as scientific evidence mounts about its health effects[13]. Currently, there are no regulations that establish limits for indoor pollutant concentrations, including in school buildings[14]; however, national technical guidelines and monitoring recommendations provide practical guidance for indoor air quality management, including *ISS ISTISAN 20/3* and *DPCM 26 July 2022*[15,16]. In recent years, the adoption of low-cost sensor technologies has enabled schools and local authorities to monitor indoor air quality in a simple and cost-effective manner, even in settings with limited resources[17,18]. Given the lack of binding regulations for indoor air quality, such monitoring initiatives are essential for increasing awareness among students and school staff, supporting evidence-based management, and informing potential future policy development. The situation observed in many Italian schools confirms that elevated CO2 concentrations are a widespread and tangible issue[8]. However, good practices can contribute significantly to mitigating this problem, regardless of the number of occupants or the duration of their stay in the classroom, these practices include improving ventilation strategies and adopting nature-based solutions[19]. Among these practices, the use of plants stands out as a natural and effective tool for improving the indoor microclimate[20].

From 2022 to 2023, a previous trial was conducted at the Saffi Institute in Florence to investigate the impact of plants on classroom air quality. The initiative, carried out in collaboration with Coldiretti Toscana, the Institute of BioEconomy of the CNR, Donne Impresa Coldiretti, AFFI (Associazione Floricoltori Fioristi Italiani), and the Regional School Office, provided preliminary evidence of the potential benefits of plant-based interventions in school environments Specifically, the study reported reductions in CO2 and PM2.5 concentrations in classrooms where selected plant species were introduced, with particularly marked decreases observed during periods of elevated CO2 levels. In some cases, reductions of up to 75% were recorded for CO2 concentrations exceeding 1000 ppm[21].

Building on this background, the "Plants in the Classroom" project was launched as a participatory environmental monitoring initiative with scientific, educational, and pedagogical objectives. At the Gobetti-Volta High School, the project involved three classes in a hands-on Citizen Science experience aimed at raising students' awareness of indoor air quality, promoting data literacy, and supporting the design of sustainable interventions. A fourth class, comparable in terms of the student number but without plants, served as a control.

The primary objective of this study was to evaluate the impact of plants on classroom air quality during the 2024-2025 school year. Low-cost air quality sensors were used as a key component of the research, providing a practical, affordable, and reliable method for monitoring CO2 and particulate matter (PM2.5) in real-world school environments.

As often occurs in real school environments, the project had to account for variables that could not be fully controlled[3]. These included slight differences in classroom volume (e.g. the presence of double-height ceilings), varying sun exposure, and the difficulty of maintaining consistent ventilation conditions due to uncontrolled window and door opening.

Class ID	Educational track	Number of students	Classroom volume	Plants
3BLS	Liceo Scientifico (LS)	15-16	Similar (~150m^3)	Yes
4ALS	Scienze Applicate (SA)	15-16	Similar (~150m^3)	Yes
2DSA	Scienze Applicate (SA)	15-16	Similar (~150m^3)	Yes
2GSA	Scienze Applicate (SA)	15-16	Similar (~150m^3)	No

Table 1 - Main characteristics of the participating classrooms

The number of plants was also constrained by economic and logistical factors, such as budget availability, classroom space, and maintenance requirements. Nevertheless, the data collected provide a reliable and representative snapshot of typical school conditions.

2. MATERIALS AND METHODS

To implement the "Plants in the Classroom" project, selected classes from the Gobetti-Volta High School were involved, including both experimental groups and a control class. The activities took place during the 2024-2025 school year, with the aim of directly evaluating the effectiveness of plants in improving air quality in real school environments experienced daily by students.

The selection of classes was not random; the aim was to achieve a reliable comparison between similar spaces with a comparable number of occupants, in order to obtain meaningful and easily interpretable data.

2.1 Participating Classes

To ensure reliable results and minimize external variables, the experiment involved four classes at Gobetti-Volta High School. These were selected not only for their structural homogeneity (similar classroom volumes) and a comparable number of students per class[15-16].

External variables considered include differences in classroom volume, number of students, and metabolic load, all of which can influence CO2 and particulate matter concentrations in indoor environments. Detailed information on the participating classes is reported in Table 1 [22].

The classes included 3BLS, 4ALS, and 4DSA as the experimental group, and 2GSA (Fig. 1) as the control class without plants. The experiment followed a rotation scheme in which the same plants were moved among the three experimental classrooms, ensuring that potential differences between plant species did not influence the results[23].

In each classroom, the plants remained for a minimum of two weeks, a period considered sufficient to capture significant changes in the assessed environmental parameters.

The control class, 2GSA, remained without plants throughout the monitoring period, providing a stable reference for comparison.

It should be noted that this class, together with 4DSA, presented some structural differences compared to the other classrooms, most notably a higher ceiling, which could have marginally affected the distribution of air pollutants, including carbon dioxide and fine particulate matter.

Fig 1 - Top: on the left, class 3BLS; on the right, class 4ALS. Bottom: on the left, class 4DSA; on the right, class 2GSA (control class without plants).

2.2 Selected Plants

The group of plants used in the experiment was always the same and consisted of 16 specimens, chosen for their well-known ability to absorb CO2 and PM2.5[24,25]. The selected species were:

- *Aglaonema Silver Bay*
- *Sansevieria Laurentii*
- *Dracaena Marginata*
- *Ficus Benjamina*
- *Chamaedorea Elegans*

The plants were strategically placed in the classrooms, near windows to maximize the effect of photosynthesis. The monitoring station was always positioned at the center of the plant group, to directly evaluate the effect of the plants on air quality in their immediate surroundings. This placement provides a representative measurement of the plants' impact, while not necessarily reflecting the absolute average conditions of the entire classroom.

2.3 Instrumentation and Measured Parameters

Environmental parameters were monitored using the AirQino Indoor LITE device, provided by CNR-IBE (Fig. 2). This is a compact, low-cost indoor monitoring station, previously validated in other indoor and outdoor environments, allowing affordable and reliable measurements under real-world conditions. The device is equipped with sensors for the following environmental parameters: CO2, PM2.5, air temperature and relative humidity. Measurements were recorded at 2-3-minute intervals, providing high temporal resolution of indoor air quality. Sensor accuracy and resolution are summarized in Table 2. Previous studies have confirmed the reliability of AirQino sensor measurements, showing good agreement with reference instruments[26,27]. The low cost, compact size, and ease of use of the AirQino system have made it particularly suitable for classroom monitoring and citizen science activities.

Two monitoring stations were used:

- SMART 416, which was moved between the three experimental classrooms along with the plants.
- SMART 420, which was installed permanently in the control classroom, 2GSA.

Both stations were powered via a 12V external power supply connected to the mains and transmitted data in real time via Wi-Fi.

2.4 Significant Sampling Days

Specific sampling days were selected to provide a representative comparison of environmental conditions, in the presence and absence of students. The schedule for each classroom is summarized in Table 3.

Fig 2 - AirQino Indoor LITE monitoring station.

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	$\mu g/m^3$	0 ÷ 1000	1,0	±10 %

Table 2 - Technical specifications of the AirQino Indoor LITE monitoring station used for indoor measurements

Class ID	Date	Student Presence	notes	Monitoring period
4DSA	20 Feb 2025	No	Empty classroom	19-Feb-2025 to 2-Apr-2025
4DSA	28 Feb 2025	Yes	Regular school activities	
3BLS	15 Apr 2025	Yes	Regular school activities	9-Apr-2025 to 30-Apr-2025
3BLS	18 Apr 2025	No	Easter holidays	
4ALS	9 May 2025	Yes	Regular school activities	2-May-2025 to 30-May-2025

Table 3 - Dates of sampling for each class, with student presence and notes

The experiment had to account for variables that could not be fully standardizable such as slight differences in classroom volume (some classrooms with double-height ceilings), varying sun exposure, and the difficulty of maintaining consistent ventilation conditions (uncontrolled opening of windows and doors). However, these factors also reflect the real-world conditions in which students live and study daily, adding further value to the project in terms of reliability and applicability of the results to similar contexts.

2.5 Data Processing and Statistical Analysis

Raw data from the AirQino Indoor LITE stations were recorded at regular intervals throughout the entire monitoring period. Prior to analysis, data were screened for completeness and consistency. Measurements affected by sensor malfunctions, power interruptions, or outliers were excluded from the dataset.

For each classroom, hourly average concentrations of CO2 and PM2.5 were calculated, both for the selected days described in Section 2.4 and for the entire monitoring period. Daily trends were analyzed by comparing periods with students present (regular school activities) and periods without students (weekends or holidays).

Subsequently, cumulative daily cycles were calculated over the entire monitoring period (February 19 - May 30, 2025): one cycle for the three classrooms with plants, combining all data into a single cumulative profile, and a separate cycle for the control classroom without plants. Values were analyzed distinguishing holiday and weekday periods, and standard error was calculated to account for variability. Percentage differences between classrooms with plants and the control classroom were calculated using daily mean concentrations of the cumulative data, with standard error calculated for each comparison.

Finally, on a cumulative level over the entire monitoring period, but restricted to weekdays and classroom occupancy hours (6:00-16:00), two separate frequency histograms for CO2 and PM2.5 were generated: one for the control classroom without plants and one cumulative histogram for the three classrooms with plants. The histograms report the number of valid observations and the percentage of each concentration range relative to the total observations.

The analysis was primarily descriptive, aimed at comparing environmental trends between experimental and control classrooms under real-world conditions, rather than in fully controlled laboratory settings. While formal inferential statistical tests were not performed, the cumulative and daily trend analyses consistently show superior indoor air quality in classrooms with plants. Error bars included in the figures help visualize variability and highlight the differences between experimental and control classrooms.

3. RESULTS

For the three classrooms involved in the laboratory activities (4DSA, 3BLS, 4ALS) and the control class 2GSA, the following hourly average values were recorded for the parameters: CO2, PM2.5, air temperature, and relative humidity (RH) (Figs. 3, 4, S1, S2).

In all three comparisons, CO2 concentrations increased with the presence of students in the classrooms, with peaks (>2000 ppm) generally occurring between 10:00 and 12:00.

The control classroom, 2GSA, without plants, consistently showed higher CO2 concentrations than the classrooms with plants, particularly during peak daily periods.

During nighttime hours or on days when the classrooms were empty (and presumably without lighting), CO2 concentrations in the classrooms with plants were similar or slightly higher than those in the control classroom, likely due to plant respiration (Fig. 3).

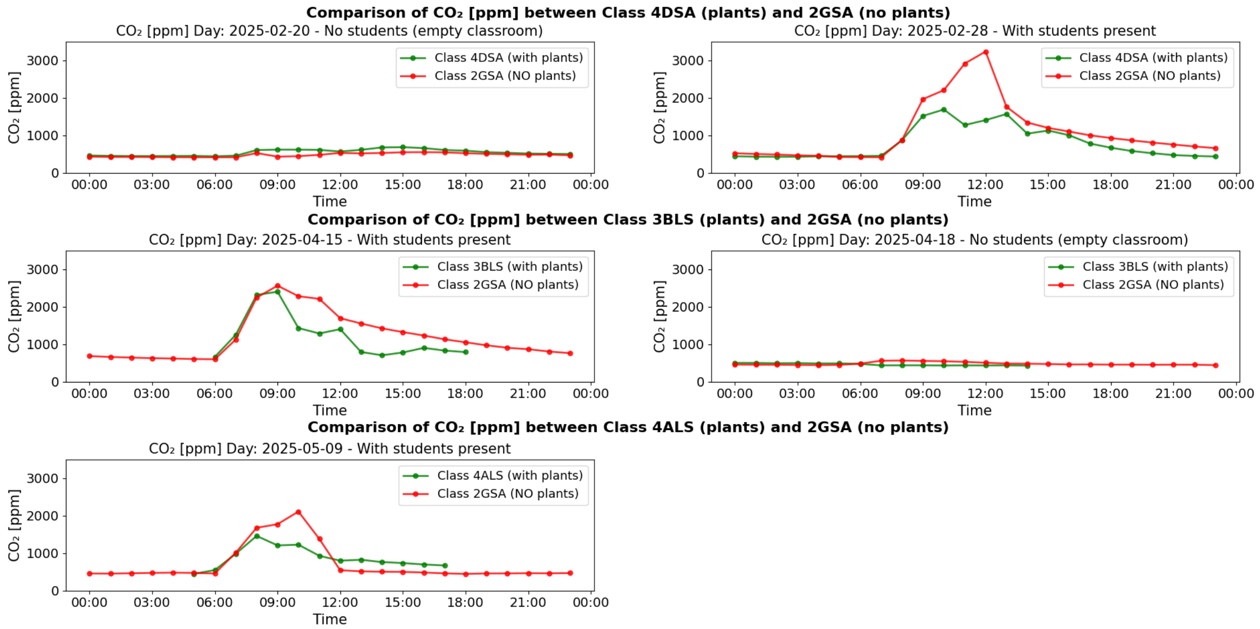

Fig 3 - CO2 concentrations in the three classrooms with plants compared to the control classroom without plants, shown separately for days with and without students. Data for class 3BLS are reported only for days with students.

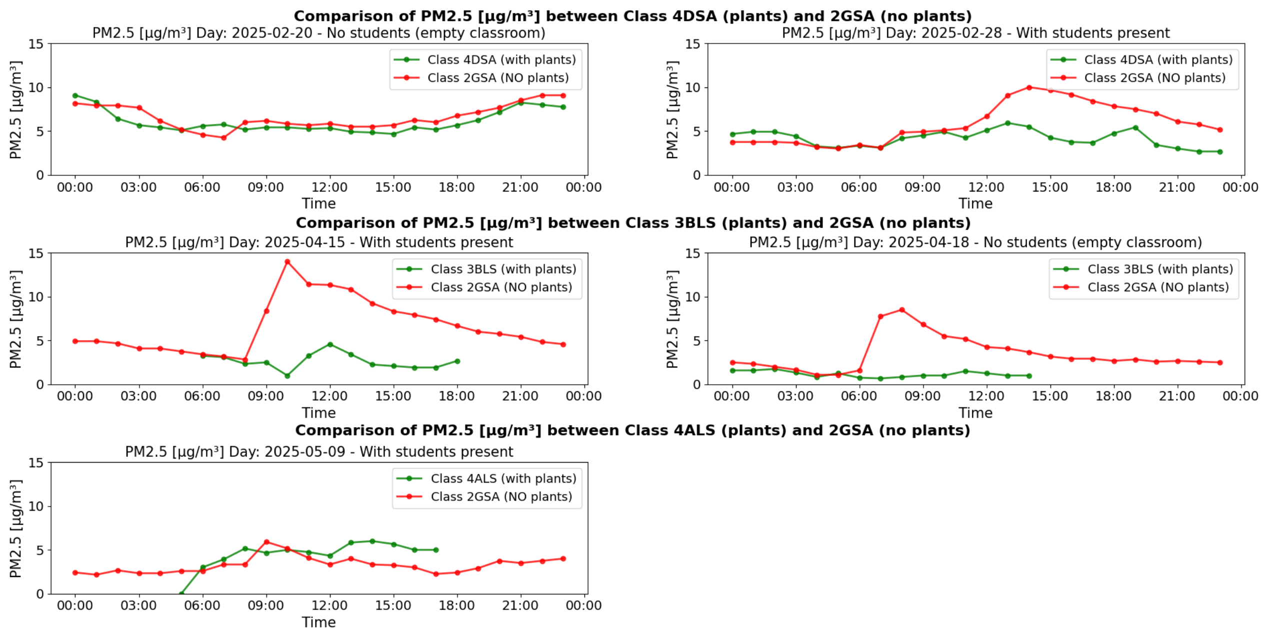

Fig 4 - PM2.5 concentrations in the three classrooms with plants compared to the control classroom without plants, shown separately for days with and without students. Data for class 3BLS are reported only for days with students, as in Fig. 3.

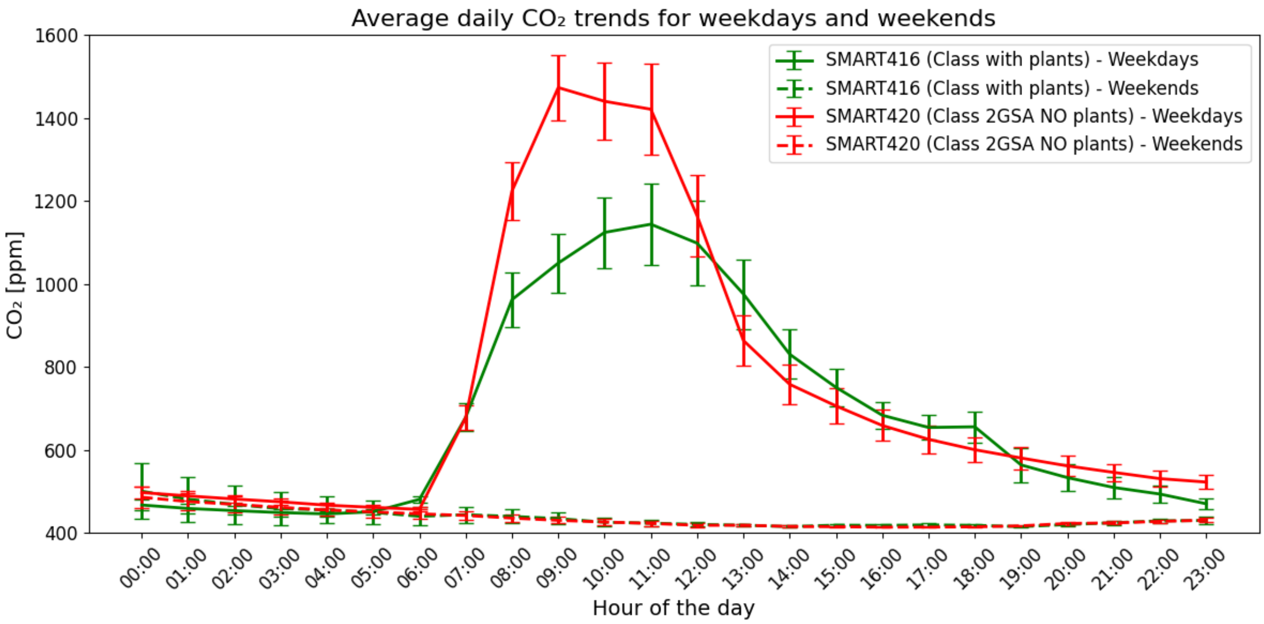

Fig 5 - Daily hourly averages of CO2 concentrations in classrooms with plants compared to the control classroom without plants, shown separately for weekdays (Monday–Saturday, schools open) and holidays (Sunday and other closure days).

Analysis of PM2.5 concentrations revealed less pronounced differences than those observed for carbon dioxide. Nevertheless, measured concentrations remained below 15 µg/m^3, even during peak periods. Overall, classrooms with plants, whether occupied or not, showed lower mean PM2.5 levels than classrooms without plants. The exception was classroom 4ALS, where differences were minimal, with concentrations slightly above 5 µg/m^3 (Fig. 4).

Analysis of hourly mean temperature showed an increase associated with the advance of the warmer season. Differences between classrooms appeared to be influenced by internal microclimatic factors, such as sun exposure and classroom management practices. Steady temperature increases were observed in response to heating activation and, on May 9, also because of direct solar radiation (Fig. S1).

Finally, relative humidity (RH) values, limited to the selected days, showed no significant differences between the classroom with plants and the one without plants. Note that no measurements were available for classroom 3BLS (with plants) on April 14, 2025 (Fig. S2).

Despite differences in classroom characteristics, cumulative analysis were performed as described in Section 2.5, aggregating data collected throughout the entire monitoring period. This approach included a total of 89 "uncontrolled days" (weekends, holidays, and periods without specific experimental interventions) thereby providing a realistic overview of environmental parameters trends under everyday school conditions.

Daily hourly averages of CO2 during weekdays (Monday-Saturday, schools open) indicate that classrooms with plants exhibited higher concentrations only in the early morning (up to 06:00, before school opening) and in the early afternoon (from 13:00 onwards), periods when the rooms were generally unoccupied. During school hours, however, classrooms with plants consistently showed lower CO2 levels than the control classroom without plants, remaining below 1200 ppm and peaking at 1143 ppm at 11:00. By contrast, the control classroom reached approximately 1473 ppm at 09:00, with average values consistently above 1400 ppm during the central morning hours.

On holidays (Sunday and other holidays), both classrooms with plants and the control classroom displayed minimal variations in CO2 throughout the day, with concentrations remaining below 500 ppm. Slightly lower values were observed only in the early hours (00:00-02:00) in the control classroom, by about 20-30 ppm (Fig. 5).

Percentage differences were calculated using the cumulative hourly mean concentrations of the classrooms with plants to the control classroom, as described in Section 2.5. The analysis revealed reductions reaching up to 30% during the central morning hours (around 9:00 a.m.) (Fig. 6). Between 07:00 and 14:00, when classrooms are generally occupied and CO2 levels are higher (>1000 ppm), the average reduction observed was approximately 10%.

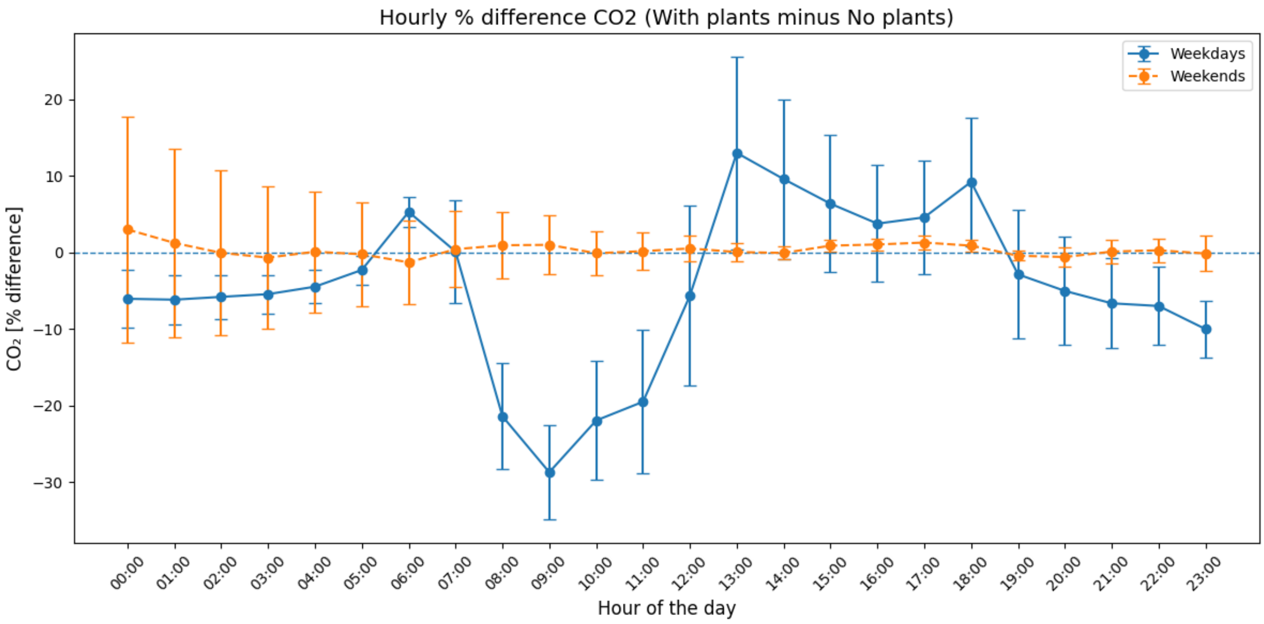

Fig 6 - Percentage differences in daily hourly CO2 concentrations between classrooms with plants and the control classroom without plants, shown separately for weekdays (Monday–Saturday, schools open) and holidays (Sunday and other closure days).

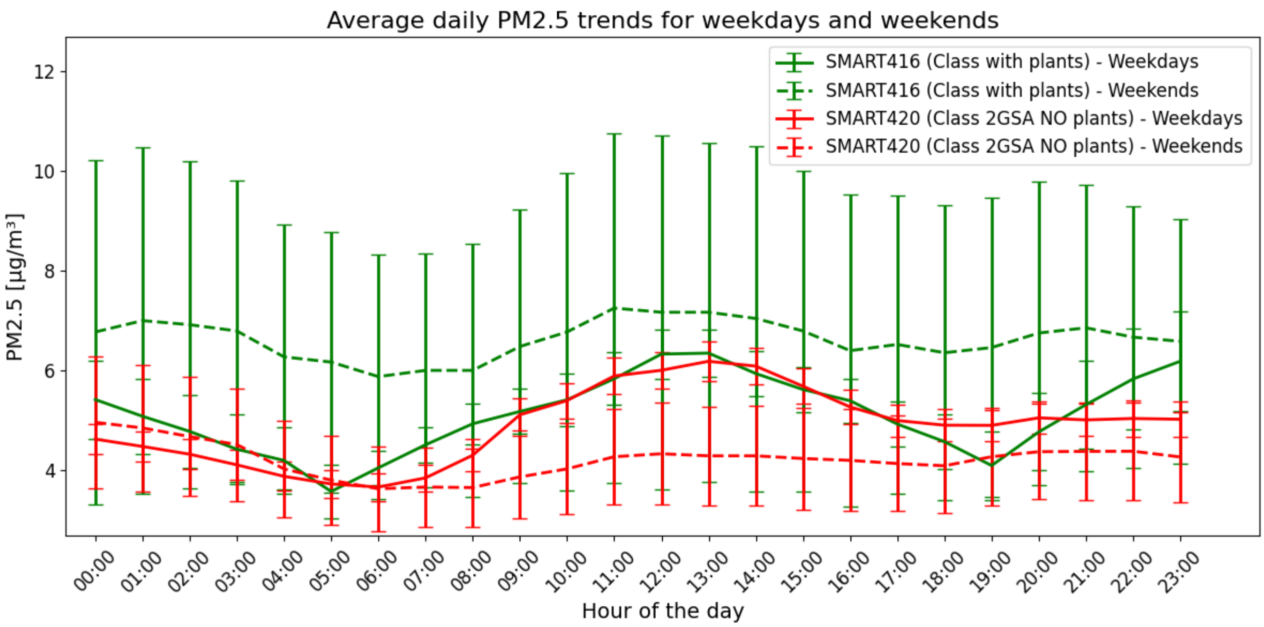

Fig 7 - Daily hourly averages of PM2.5 concentrations in classrooms with plants compared to the control classroom without plants, shown separately for weekdays (Monday–Saturday, schools open) and holidays (Sunday and other closure days).

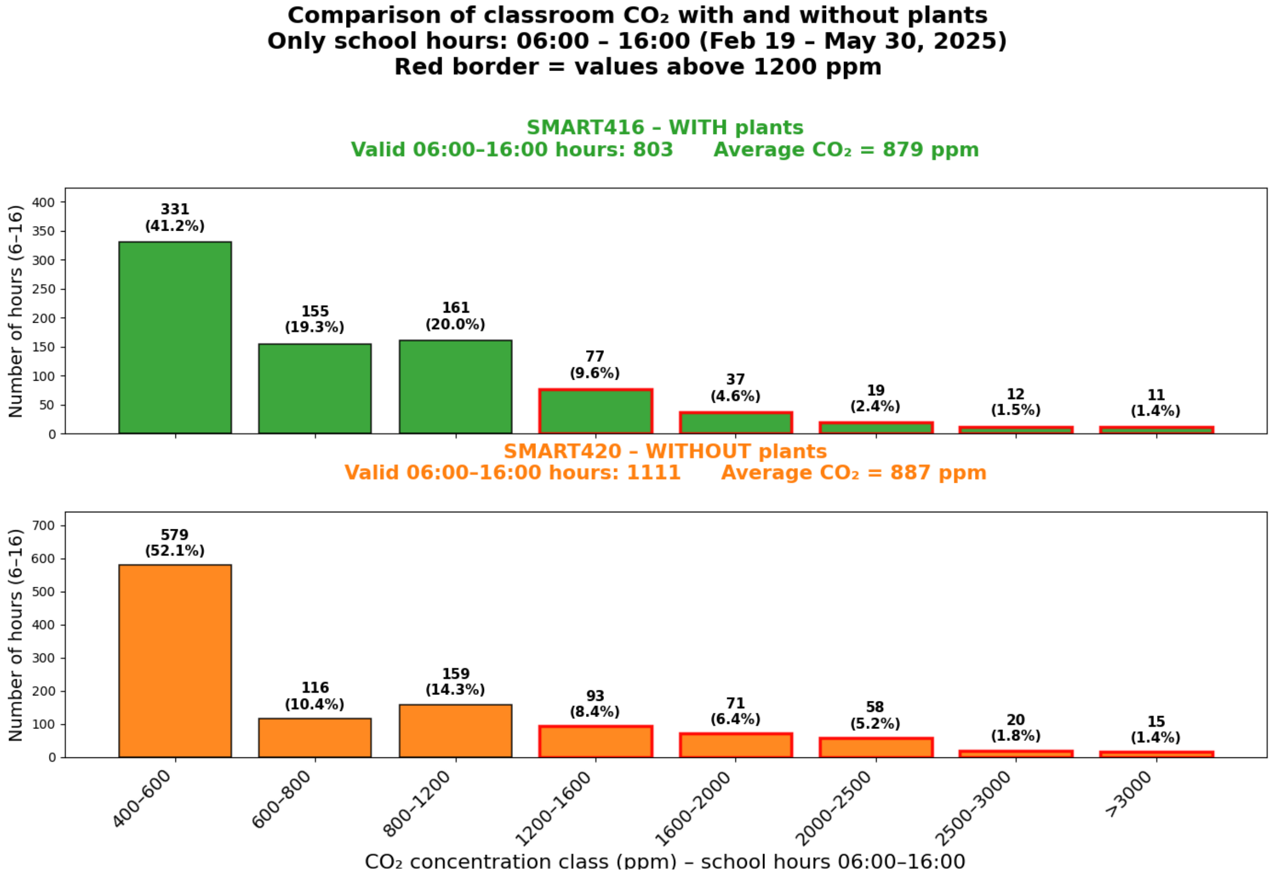

Fig 8 - Frequency histograms of CO2 concentrations [ppm] in classrooms with plants (top) and in the control classroom without plants (bottom) during the monitoring period.

The second parameter monitored to assess indoor air quality was PM2.5. Daily hourly means of PM2.5 did not reveal significant differences between classrooms with plants and the control classroom without plants. Overall, concentrations remained low (<8 µg/m^3), with a slight increase observed around midday (approximately 12:00 PM) on weekdays. The standard error associated with the means was comparable to the concentration values themselves, reflecting a high degree of variability in the data (Fig. 7). Daily hourly averages of relative humidity (RH) throughout the monitoring period revealed distinct trends between classrooms with plants and the control classroom without plants. Overall, classrooms with plants tended to exhibit slightly higher RH values than the control classroom. The standard error associated with the means was comparable to the measured values, reflecting a moderate degree of variability in the data (Fig. S3).

Frequency distribution analysis of CO2 concentrations, organized by classroom and highlighted in the histograms with red borders for levels above 1200 ppm (a threshold above which numerous international standards and guidelines consider indoor air quality suboptimal[28]), revealed notable effects in classrooms with plants. In particular, the relative frequency in the 1600-2000 ppm range decreased from 6.4% to 4.6% (-28%), while in the 2000-2500 ppm range it dropped from 5.2% to 2.4% (-54%). For concentrations above 2500 ppm, reductions were less pronounced. It should be noted that the total number of hours recorded in both conditions for these higher ranges was limited, which may make comparisons between the two classrooms less representative (Fig. 8).

Frequency distribution analysis of PM2.5 concentrations (Fig. 9), organized by classroom and highlighted with red borders for levels above 9 µg/m^3 (the daily mean threshold associated with excellent/good air quality according to the EPA and WHO[29]), showed no substantial differences between classrooms with plants and the control classroom. Interestingly, frequencies of concentrations above 9 µg/m^3 were slightly higher in the classroom without plants. Overall, PM2.5 levels remained very low across all classrooms and well below the limits set by WHO outdoor air guidelines. While these thresholds are cited for indoor environments as a precautionary measure, they do not constitute binding regulatory limits.

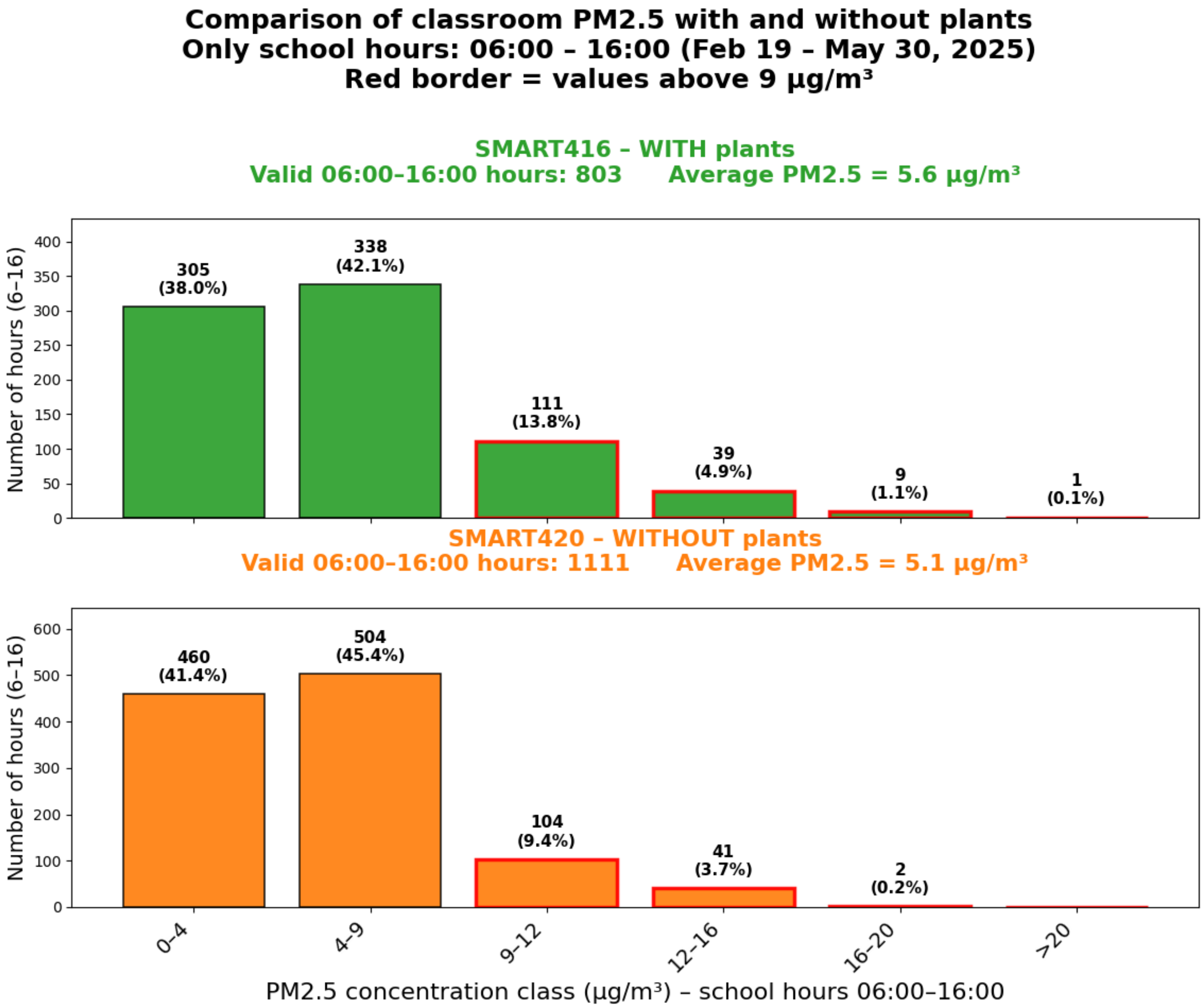

Fig 9 - Frequency histograms of PM2.5 concentrations in classrooms with plants (top) and in the control classroom without plants (bottom) during the monitoring period.

4. DISCUSSION

The results confirm that introducing plants into school environments can be an effective and cost-effective strategy for improving indoor air quality. The reduction of pollutants, particularly CO2, highlights the active role of vegetation in the processes that contribute to air purification: photosynthesis absorbs carbon dioxide and produces oxygen, transpiration increases relative humidity and promotes air microcirculation, and mechanical leaf filtration captures fine dust and suspended particulate matter[30, 25, 31].

Together, these mechanisms improve the quality of the indoor environment, making classrooms healthier and more comfortable[2, 32, 33]. Beyond the physical effects, the presence of greenery introduces an important aesthetic and sensorial component. Numerous studies demonstrate that visual contact with plants promotes concentration, reduces stress, and improves perceived well-being[34].

Qualitative observations from this experiment support these findings: students reported greater calm, attention, and satisfaction while learning in plant-rich classrooms, suggesting that vegetation positively influences both environmental parameters and the cognitive-emotional aspects of the learning experience.

Some methodological limitations must be considered. One of these concerns the actual number of occupants: although the classrooms were selected with similar numbers of students (approximately 15-16), daily variations in attendance, inevitable in a school setting, may have influenced CO_2 production and the measured values.

Human metabolic activity is a major source of indoor CO_2, and even small differences in occupancy (for example, variations of 1-2 students in classrooms of 15-16 occupants) can significantly influence indoor CO_2 concentrations, as changes in occupancy affect CO_2 generation rates and air exchange requirements in enclosed spaces[35, 36].

According to EN 16798#1:2019, CO_2 generation rates are determined by occupant metabolic activity and room volume. For example, in a 150m^3 classroom, an increase of only two occupants corresponds to ~40L/h of CO_2, which, in the absence of ventilation, would raise indoor CO_2 concentrations by roughly 267ppm per hour[37].

The architectural features of the classrooms also played a role. Control room 2GSA and room 3BLS have higher ceilings, resulting in larger air volumes. This may have led to thermal stratification and uneven distribution of pollutants, particularly PM2.5, which disperses based on temperature gradients and airflow dynamics[38]. In larger spaces, pollutant dilution is greater, but air mixing is less efficient, increasing measurement variability[39].

Another variable that was not fully controllable was natural ventilation. Despite efforts to maintain comparable conditions, airflow through windows and doors depends on factors such as weather conditions, time of day, teacher behaviour, and occupant comfort, potentially causing variations in CO_2 and PM2.5 levels not directly attributable to plants.

The number of plants introduced also represents a limitation. For logistical and economic reasons, 16 specimens were placed in each classroom; a larger number of plants would likely have produced more pronounced effects on air quality.

While definitive guidelines on plant density are lacking, recent studies suggest that the effectiveness of plants for both CO_2 mitigation and PM2.5 capture is closely related to total leaf surface area and species-specific traits[40, 41].

Nevertheless, the results maintain scientific validity and practical relevance, as they reflect real-world conditions in schools. This experiment provides concrete indications for best practices that can be replicated in educational settings.

Simple, low-cost interventions like this can improve the microclimate of school spaces and promote ecological awareness and responsibility among students regarding shared environments.

In addition to the environmental benefits, the project had a clear educational component. Students were actively involved in the management and care of the plants, which enhanced their understanding of indoor air quality, promoted ecological responsibility, and supported hands-on learning in a citizen-science framework. This participatory approach strengthened students' engagement and awareness of sustainable practices.

In summary, the results demonstrate an overall positive effect of vegetation on both environmental quality and perceived well-being, providing a basis for applied recommendations and future research.

5. CONCLUSIONS

The "Plants in the Classroom" project showed that introducing vegetation into school environments can be a simple, low-cost, and easily replicable strategy to improve indoor air quality and support students' well-being.

In addition to the environmental benefits, the experience highlighted a positive influence on the classroom's psychological and relational climate. The presence of plants was associated with improved concentration, reduced stress, and the development of greater care and responsibility toward shared spaces.

In this way, the project successfully integrated scientific inquiry, environmental education, and sustainability, turning the school environment into an active and participatory learning space.

To further strengthen the results and broaden their practical relevance, future initiatives could focus on:

- replicating the project in different schools and educational contexts, with longer monitoring periods.
- adopting a more structured monitoring protocol, including detailed records of classroom occupancy, ventilation practices, plant conditions, and exposure to natural light.
- exploring the effects of a greater number and diversity of plant species, in relation to space availability and economic feasibility.

Looking ahead, "Plants in the Classroom" represents a concrete example of how environmental and scientific education can start from a local, everyday experience and foster broader awareness.

By combining data collection, observation, and shared responsibility, the project promotes a vision of schooling that is more sustainable, healthier, and increasingly focused on well-being.

SUPPLEMENTARY MATERIAL

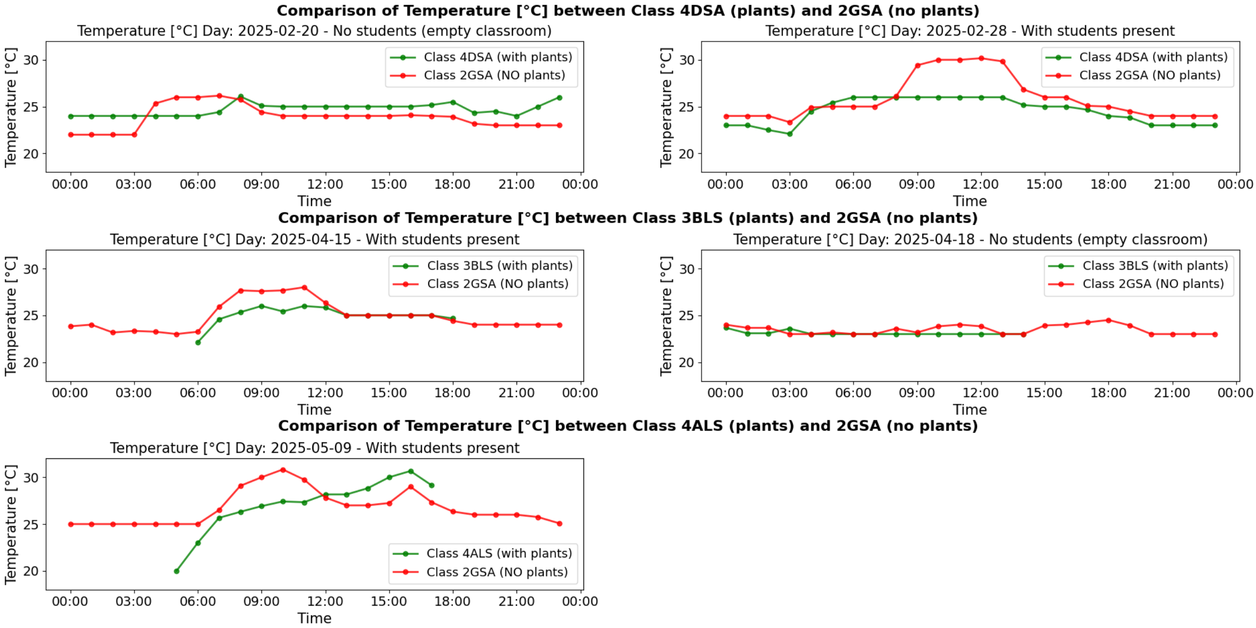

Fig S1 - Air temperature in the three classrooms with plants compared to the control classroom without plants, shown separately for days with and without students. Data for class 3BLS are reported only for days with students.

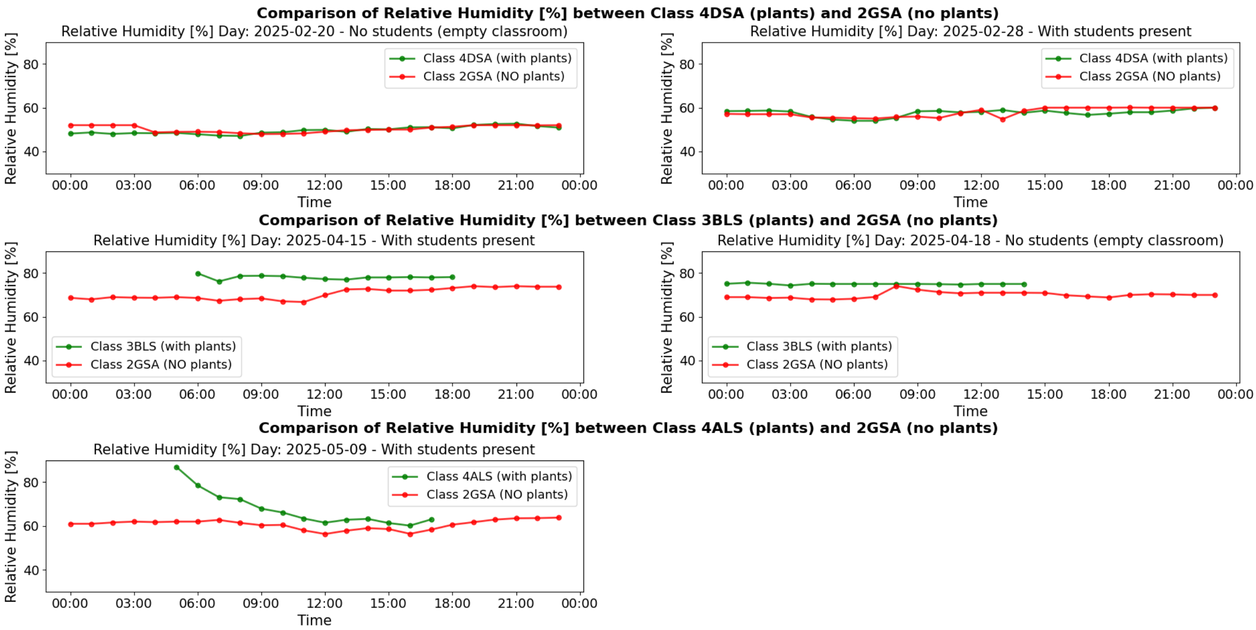

Fig S2 - Relative humidity in the three classrooms with plants compared to the control classroom without plants, shown separately for days with and without students. Data for class 3BLS are reported only for days with students, as in Fig. S1.

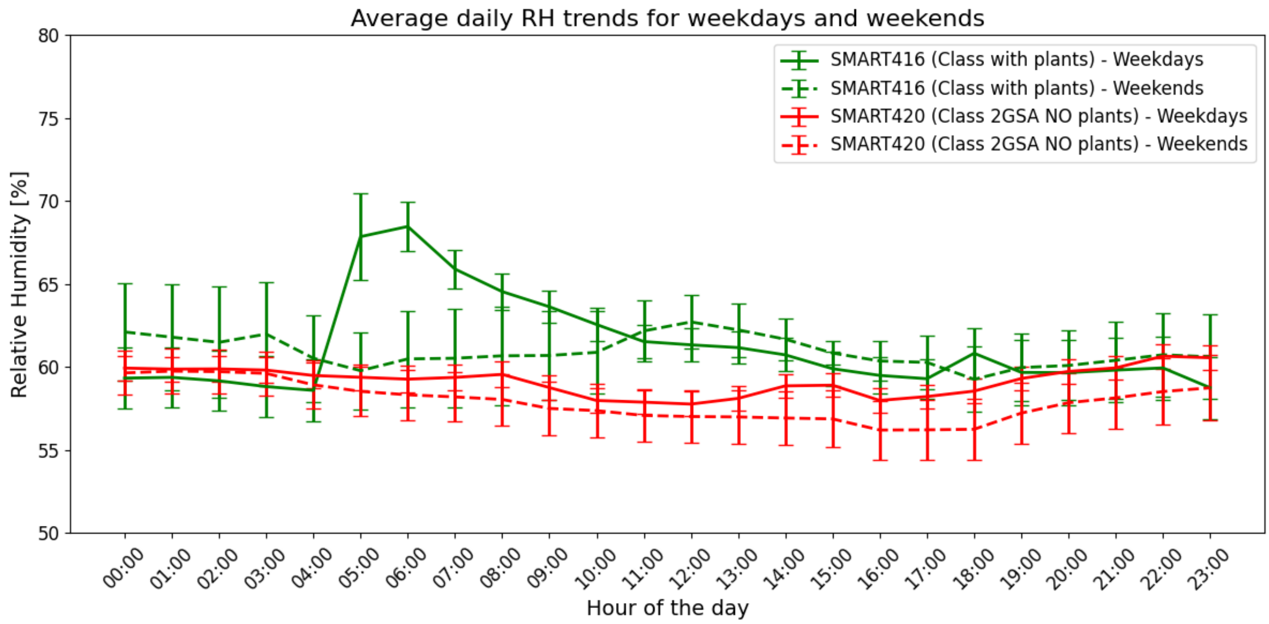

Fig S3 - Daily hourly averages of relative humidity (RH) in classrooms with plants compared to the control classroom without plants, shown separately for weekdays (Monday–Saturday, schools open) and holidays (Sunday and other closed days).

References

1) European Collaborative Action. Guidelines for ventilation requirements in buildings. Report no. 11. EUR 14449 EN. Brussels: European Commission; 1992 [cited 2025 Dec 30]. Available from: https://www.enea.it/it/per-la-scuola/novita-e-segnalazioni/novita-e-segnalazioni-2020/scuola-in-classe-a-istruzioni-per-luso.html

2) World Health Organization. Measures to reduce risks for children's health from combined exposure to multiple chemicals in indoor air in public settings for children with a focus on schools, kindergartens and daycare centres [Internet]. Copenhagen: WHO Regional Office for Europe; 2022 [cited 2026 Jan 8]. Available from: https://www.who.int/europe/publications/i/item/9789289057974

3) Honan D, Gallagher J, Garvey J, Littlewood J. Indoor air quality in naturally ventilated primary schools: a systematic review of the assessment & impacts of CO2 levels. Buildings. 2024;14(12):4003. DOI: 10.3390/buildings14124003.

4) Settimo G, Indinnimeo L, Inglessis M, De Felice M, Morlino R, di Coste A, et al. CO2 levels in classrooms: what actions to take to improve the quality of environments and spaces. Sustainability. 2024;16(19):8619. DOI: 10.3390/su16198619.

5) Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile. #Scuola in Classe A - Istruzioni per l'uso [Internet]. Marchetti A, Aversa P, editors. Roma: ENEA, Dipartimento Unità per l'Efficienza Energetica; 2020 [cited 2026 Jan 8]. Available from: https://www.enea.it/it/per-la-scuola/novita-e-segnalazioni/novita-esegnalazioni-2020/scuola-in-classe-a-istruzioni-per-luso.html

6) Ministero della Salute. Impatto dell'inquinamento indoor sulla salute della popolazione. Roma: Ministero della Salute; 2023 [cited 2025 Dec 30]. Available from: https://www.salute.gov.it/new/it/tema/qualita-dellaria/impattodellinquinamento-indoor-sulla-salute-della-popolazione/

7) Esposito S, Fainardi V, Titolo A, Lazzara A, Menzella M, Campana B, et al. How air pollution fuels respiratory infections in children: current insights. Front Public Health. 2025;13:1567206. DOI: 10.3389/fpubh.2025.1567206

8) Campiotti A, Ricciardi E, Spano G, Dominici L, Comino E, Riggio R, et al. Indoor green walls for improving air quality and human well-being: a case study from a primary school in Turin (Italy). Nat-Based Solut. 2025;8:100280. DOI: 10.1016/j.nbsj.2025.100280.

9) Cao X, Li P, Zhang J, Pang L. Associations of human cognitive abilities with elevated carbon dioxide concentrations in an enclosed chamber. Atmosphere. 2022;13(6):891. DOI: 10.3390/atmos13060891.

10) Andualem Z, Gizaw Z, Bogale L, Dagne H. Indoor bacterial load and its correlation to physical indoor air quality parameters in public primary schools. Multidiscip Respir Med. 2019 Jan 22;14:2. DOI: 10.1186/s40248-018-0167-y. PMID: 30680192; PMCID: PMC6343310.

11) Rudnick SN, Milton DK. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. Indoor Air. 2003;13(3):237-45. DOI: 10.1034/j.1600-0668.2003.00189.x.

12) Ministero della Salute. Sindrome dell'edificio malato - Sick building syndrome [Internet]. Roma: Ministero della Salute; 2015 [cited 2025 Dec 22]. Available from: https://www.salute.gov.it/new/it/tema/qualita-dellaria/sindromedelledificio-malato-sick-building-syndrome/

13) World Health Organization. Air pollution: health impacts [Internet]. Geneva: WHO; 2024 [cited 2026 Jan 8]. Available from: https://www.who.int/teams/environment-climate-change-and-health/air-quality-energy-and-health/health-impacts

14) Morawska L, Huang W. WHO health guidelines for indoor air quality and national recommendations/standards. In: Zhang Y,

Hopke PK, Mandin C, editors. Handbook of indoor air quality. Singapore: Springer; 2022. DOI: 10.1007/978-981-10-5155-5_49-1

15) Settimo G, Bonadonna L, Gucci PM, Gherardi M, Cecinato A, Brini S, et al. Qualità dell'aria indoor negli ambienti scolastici: strategie di monitoraggio degli inquinanti chimici e biologici [Internet]. Roma: Istituto Superiore di Sanità; 2020 [cited 2026 Feb 10]. (Rapporti ISTISAN 20/3). Available from: https://www.iss.it/rapporti-istisan/-/asset_publisher/Ga8fOpve0fNN/content/rapporti-istisan-20-3-qualit%C3%A0-dellaria-indoor-negli-ambienti-scolastici-strategie-di-monitoraggio-degliinquinanti-chimici-e-biologici.-gaetano-settimo-lucia-bonadonnapaola-m.b.-gucci-monica-gherardi-angelo-cecinato-silvia-brinifrancesca-de-maio-a

16) Decreto del Presidente del Consiglio dei Ministri 26 luglio 2022. Linee guida sulle specifiche tecniche in merito all'adozione di dispositivi mobili di purificazione e impianti fissi di aerazione e agli standard minimi di qualità dell'aria negli ambienti scolastici e in quelli confinati degli stessi edifici [Internet]. Gazzetta Ufficiale della Repubblica Italiana n. 180, 03-08-2022. [cited 2026 Feb 10]. Available from: https://www.gazzettaufficiale.it/eli/id/2022/08/03/22A04476/sg

17) Apostolopoulos ID, Dovrou E, Androulakis S, Seitanidi K, Georgopoulou MP, Matrali A, et al. Monitoring of indoor air quality in a classroom combining a low-cost sensor system and machine learning. Chemosensors. 2025;13(4):148. DOI: 10.3390/chemosensors13040148

18) Chojer H, Branco PTBS, Martins FG, Alvim-Ferraz MCM, Sousa SIV. Development of low-cost indoor air quality monitoring devices: Recent advancements. Sci Total Environ. 2020 Jul 20;727:138385. DOI: 10.1016/j.scitotenv.2020.138385.

19) Abhijith KV, Rawat N, Mendes Emygdio AP, Le Den C, Collins K, Cartwright P, et al. Demonstrating multi-benefits of green infrastructure to schools through collaborative approach. Sci Total Environ. 2025;958:177959. DOI: 10.1016/j.scitotenv.2024.177959.

20) Cardinali M, Balderrama A, Arztmann A, Pottgiesser U. Green walls and health: an umbrella review. Nat-Based Solut. 2023;3:100070. DOI: 10.1016/j.nbsj.2023.100070.

21) Consiglio Nazionale delle Ricerche - Istituto per la BioEconomia (CNR-IBE). Cosa respiriamo? Introduzione al monitoraggio della qualità dell'aria per istituti scolastici. Bologna: CNR-IBE; 2023. Available from: https://www.2fmultimedia.it/wp-content/uploads/2023/05/AIRQINO-CATALOGO-_compressed.pdf

22) Toyinbo O. Indoor environmental quality, pupils' health, and academic performance: a literature review. Buildings. 2023;13(9):2172. DOI: 10.3390/buildings13092172

23) Jiang J, Irga P, Coe R, Gibbons P. Effects of indoor plants on CO2 concentration, indoor air temperature and relative humidity in office buildings. PLoS One. 2024 Jul 17;19(7):e0305956. DOI: 10.1371/journal.pone.0305956.

24) Han KT, Ruan LW. Effects of indoor plants on air quality: a systematic review. Environ Sci Pollut Res. 2020;27(14):16019-51. DOI: 10.1007/s11356-020-08174-9 .

25) Weerasinghe NH, Silva PK, Jayasinghe RR, Abeyrathna WP, Perera John WP, Halwatura RU. Reducing CO2 level in the indoor urban built environment: Analysing indoor plants under different light levels. Clean Eng Technol. 2023;14:100645. DOI: 10.1016/j.clet.2023.100645.

26) Cavaliere A, Di Gennaro F, Di Lonardo S, Gioli B, Gualtieri G, Martelli F, et al. Development of low-cost air quality stations for next generation monitoring networks: validation of PM2.5 and PM10 sensors. Sensors. 2018;18(9):2843. DOI: 10.3390/s18092843.

27) Gualtieri G, Carotenuto F, Finardi S, Tartaglia M, Toscano P, Gioli B. Forecasting PM10 hourly concentrations in Northern Italy: insights on models performance and PM10 drivers through self-organizing maps. Atmos Pollut Res. 2018;9(6):1204-13. DOI: 10.1016/j.apr.2018.05.006.

28) Settimo G, Bertinato L, Martuzzi M, Inglessis M, D'Ancona F, Soggiu ME, et al. Nota tecnica ad interim. Monitoraggio della CO2 per prevenzione e gestione negli ambienti indoor in relazione alla trasmissione dell'infezione da virus SARS-CoV-2 [Internet]. Roma: Istituto Superiore di Sanità; 2022 [cited 2025 Dec 22]. Available from: https://www.iss.it/documents/20126/6703853/NT_co2_DEF.pdf

29) World Health Organization. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: WHO; 2021 [cited 2026 Jan 8]. Available from: https://www.who.int/publications/i/item/9789240034228

30) Chang YS, Ho M, Wu CW, Chang YJ. Indoor plant removal of atmospheric CO2: effects on indoor air quality improvement and carbon sequestration. Process Saf Environ Prot. 2025;200:107419. DOI: 10.1016/j.psep.2025.107419.

31)Liu F, Yan L, Meng X, Zhang C. A review on indoor green plants employed to improve indoor environment. J Build Eng. 2022;53:104542. DOI: 10.1016/j.jobe.2022.104542.

32) Sadrizadeh S, Yao R, Yuan F, Awbi H, Bahnfleth W, Bi Y, et al. Indoor air quality and health in schools: a critical review for developing the roadmap for the future school environment. J Build Eng. 2022;57:104908. DOI: 10.1016/j.jobe.2022.104908.

33) Aydogan A, Cerone R. Review of the effects of plants on indoor environments. Indoor Built Environ. 2021;30(4):442-60. DOI: 10.1177/1420326X19900213

34) Kumar R, Verma V, Thakur M, et al. A systematic review on mitigation of common indoor air pollutants using plant-based methods: a phytoremediation approach. Air Qual Atmos Health. 2023;16(8):1501-27. DOI: 10.1007/s11869-023-01326-z

35) Oke O, Persily A. Sensitivity analysis of CO2 concentrations as ventilation metrics. In: Proceedings of the 43rd AIVC Conference; 2023 Oct 4-5; Copenhagen, Denmark. Gaithersburg: NIST; 2023 [cited 2026 Jan 8]. Available from: https://www.nist.gov/publications/indoor-carbon-dioxide-concentrations-ventilation-and-indoor-air-quality-standards

36) Persily A, de Jonge L. Carbon dioxide generation rates for building occupants. Indoor Air. 2017;27(5):868-79. PubMed PMID: 28321932. DOI: 10.1111/ina.12383.

37) European Committee for Standardization. EN 16798-1:2019. Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics [Internet]. Brussels: CEN; 2019 [cited 2026 Feb 19]. Available from: https://store.uni.com/uni-en-16798-1-2019

38) Liu F, Qian H, Luo Z, Wang S, Zheng X. A laboratory study of the expiratory airflow and particle dispersion in the stratified indoor environment. Build Environ. 2020;180:106988. DOI: 10.1016/j.buildenv.2020.106988.

39) Branco PT, Sousa SI, Dudzinska MR, Ruzgar DG, Mutlu M, Panaras G, et al. A review of relevant parameters for assessing indoor air

quality in educational facilities. Environ Res. 2024;261:119713. DOI: 10.1016/j.envres.2024.119713

40) Brilli F, Fares S, Ghirardo A, de Visser P, Calatayud V, Muñoz A, et al. Plants for sustainable improvement of indoor air quality. Trends Plant Sci. 2018;23(6):507-12. DOI: 10.1016/j.tplants.2018.03.004.

41) Pettit T, Irga PJ, Torpy FR. Towards practical indoor air phytoremediation: a review. Chemosphere. 2018;208:960-74. DOI: 10.1016/j.chemosphere.2018.06.048.