



Beyond leaf traits: context dependent particulate matter accumulation across outdoor, indoor and active green walls

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ABSTRACT

Nature-based Solutions (NbS) have been shown to effectively remove air pollutants, such as particulate matter (PM), from the atmosphere, with this capacity being largely dependent on the plant species-specific morphological traits. However, other factors including chemical interactions and atmospheric and microclimatic parameters can also affect PM removal efficiency. To test this hypothesis, we compared PM accumulation across five plant species with distinct morphological traits (*Chlorophytum comosum*, *Hedera helix*, *Monstera deliciosa*, *Nephrolepis exaltata*, *Tradescantia zebrina*) grown on outdoor (OGW) and indoor (IGW) green walls. Additionally, four of these species were tested in an active green wall (AGW) installed within a closed chamber with forced ventilation, where *M. deliciosa* could not be included because of space constraints. Leaf surfaces were analysed via Scanning Electron Microscopy (SEM) to characterise the micromorphological features associated with PM accumulation. The deposited PM load was quantified using a combination of gravimetric and conductimetric approaches, while the PM chemical composition was assessed by Microwave Plasma Atomic Emission Spectroscopy (MP-AES). Significant statistical differences in PM capture were observed among the species. Furthermore, the species exhibited distinct PM accumulation patterns across the different green wall systems, showing species-specific affinities for certain potentially toxic elements. This demonstrates that PM retention is not driven by leaf morphology alone. Among species, *Chlorophytum comosum* performed best in OGW and IGW. Finally, the presence of the plants in the AGW reduced PM concentration by approximately 50%, while high humidity enhanced wet deposition and increased fine-particle capture, confirming the critical role of microclimatic factors in air purification.

1. Introduction

In the current global context, the improvement of air quality is amongst the most relevant societal challenges [1], being strictly related to human health. Indeed, about 250,000 people die each year in Europe due to diseases caused by air pollution [2].

Particulate matter (PM), a complex airborne mixture of organic and inorganic solid particles and liquid droplets, is recognized as one of the major air pollutants [3]. It can be produced by either anthropogenic or

natural sources [4]. It is classified according to particles' aerodynamic diameter in PM₁, PM_{2.5} and PM₁₀ (i.e., diameters smaller than 1, 2.5 and 10 micron, respectively), with each class having a different penetration capability within human tissues. PM harmfulness is also related to its chemical composition, with anthropogenic PM being particularly risky. Indeed, being produced by processes such as motor combustion, painting, building construction [5], PM may contain Potentially Toxic Elements (PTEs), i.e. heavy metals and metalloids that cause severe impacts on environments, human, plants and animals health [6].

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The challenge of improving air quality in urban contexts is also faced nowadays by the implementation of Nature-based Solutions (NbS), which are ecosystem-based actions used to address biodiversity, climate crises, and other societal issues by providing multiple benefits and Ecosystem Services (ES) [7]. In particular, NbS can promote phytoremediation, improving the quality of contaminated air, soil and water by using plants. Regarding air, it was proved that plants can effectively remove gaseous pollutants and PM from the atmosphere [8,9]. In particular, plant leaves capture atmospheric PM through wet and dry deposition pathways [10] and then transfer PM to soil upon leaf fall or raining events (wash-off).

To better understand PM adsorption mechanisms on leaves, several scientific papers investigated the relation between PM removal capacity and plant characteristics [11–13]. The plant PM removal capability has been demonstrated to be species-dependent, and a few models were developed to predict the PM plant removal efficiency based on macro-morphological (foliage, leaf shape, expansion, margin), micro-morphological (roughness, stomata, trichomes) and physiological parameters [14,15]. Such models assume that PM deposition on leaves is based only on physical interactions. Nevertheless, recent studies suggested the existence of a chemical driver beyond species-specific PM removal [3].

Among NbS, Green Walls (GWs) are particularly interesting due to their applicability in both indoor and outdoor environments [12]. Furthermore, GWs are very useful experimental prototypes to better investigate the relationship between plant species and PM capture efficiency, since they allow monitoring heterogeneous mixes of herbaceous plants within the same microclimatic conditions and pollution exposure.

In this study, we compared the PM accumulation on five plant species located both in an outdoor (OGW) and in an indoor (IGW) green wall, under similar PM exposure. Four of these species were further tested also in an active (AGW) green wall, exposed to synthetic PM reproducing the outdoor contaminants. OGW and IGW are passive systems relying on natural air circulation, while the AGW is an active system that mechanically forces air passage through plants and substrate, thereby maximising air-surface interactions and improving phytoremediation efficiency [16]. Specifically, the comparison across the three systems was designed to test the hypothesis that species-specific PM deposition patterns are strongly modulated not only by leaf morphology but also by environmental exposure conditions (e.g., airflow velocity, relative humidity, and source-specific particle size distributions). We conducted this comparison to evaluate whether plant species ranked as high-performing PM accumulators in outdoor settings maintain their effectiveness in indoor microclimates or under forced ventilation, thereby providing actionable criteria for optimizing green wall design across contrasting environments. In particular, it is worth noting that the comparison between outdoor and indoor conditions is very peculiar and rarely reported, and it was possible in this study because it was conducted in Seville, where the mild Mediterranean climate allows the same species to be grown both indoor and outdoor.

Thanks to this threefold comparison, the main objectives of this work are to:

- (a) clarify whether the species' efficiency in PM removal is mainly driven by the morphological traits or not, by analysing the removed PM load in each size fraction ($PM_{0.2-2.5}$, $PM_{2.5-10}$, PM_{10-100}) across species and walls;
- (b) disclose the role played by the chemical interactions occurring in the phyllosphere between leaves and particles, by studying the species-specific affinities for PTEs contained in PM;
- (c) quantify the effect of the AGW, and related microclimatic conditions, on indoor air quality, by assessing PM concentration dynamics in each size fraction ($PM_{0.2-2.5}$, $PM_{2.5-10}$, PM_{10-100}) with respect to baseline conditions.

Collected data will be useful to better understand the mechanisms

behind PM removal by plants in different GW systems and thus realise new databases and design guidelines for future NbS implementations.

2. Material and methods

2.1. Case studies

Experiments were conducted between September 2024 and February 2025 at the School of Agricultural Engineering of the University of Seville (Spain), where the three GWs were installed. The OGW (Fig. 1a) was in an outer facade of the university building, a few meters from the car park. The IGW (Fig. 1b) was inside the building's hall, a large space exposed to outdoor air flows. The AGW (Fig. 1c) was set up in the Urban Greening laboratory, in a basement with minimal temperature variations.

The three GWs shared the same structural modular system, which were composed of different polyamide layers sewn together forming 0.14 m by 0.14 m pockets where the plant root balls were inserted. Both OGW and IGW have an extra impervious layer, to avoid damping. This layer was missing in the AGW to facilitate air flowing.

The five selected species (*Chlorophytum comosum* (Thunb.) Jacques, *Hedera helix* L., *Monstera deliciosa* Liebm., *Nephrolepis exaltata* (L.) Schott and *Tradescantia zebrina* hort. ex Bosse) were ornamental species that could easily adapt to both outdoor and indoor environments and have been used in previous experiments by the authors [3,17].

The plants were purchased from the same nursery, to ensure that they were as similar as possible and brought to the laboratory. Soil was removed from the roots by washing with tap water. Seedlings were then transplanted into the GW pockets, filled with approximately 0.5 litres of expanded clay as a growth medium. For OGW and IGW, an area of approximately 1 m² was considered, and four plants of each species were transplanted. For the AGW, a 1 m² module consisting of 49 pockets was used, and four plants per species were transplanted except *M. deliciosa*, which was too large to grow in such a confined environment. After transplanting, plants were irrigated with water containing a 1:10 diluted nutrient solution prepared according to Rossini Oliva et al., [18]. An acclimatization period of about three weeks was ensured before starting the experiments.

Once assembled, the module containing the AGW was placed inside the experimental chamber, having a volume of 2 m³ (2 m long, 1 m wide and 1 m high; Fig. 2). A water tank for irrigation was placed at the bottom of the AGW. A submersible Eheim Compacton 2100 pump (Eheim, Germany) was used to distribute water by means of a PVC pipe with small holes placed on the top of the AGW. The automatic irrigation system frequency was set at 15 minutes every 2 and 3 hours during day and night, respectively.

Since the laboratory housing the experimental chamber had no natural light, a UT01Forum LED Grow lamp (Lledó, Madrid, Spain) was placed above the chamber, keeping the light on from 8 a.m. to 8 p.m. to simulate the seasonal photoperiod and providing an average illuminance of 4000 lux.

The AGW module was attached to one end of the chamber, upstream of a funnel connected to a forced ventilation system. This system consisted of a fan and a corrugated aluminium duct that linked both ends of the chamber, allowing for the continuous circulation of air through the green wall before reintroducing it at the opposite side. Consequently, this configuration ensured that the airflow passed entirely through the AGW module, encompassing both the plant foliage and the root zone (Fig. 2). The ventilation system was programmed to operate in 10-minute cycles every hour, with an air flow rate of approximately 0.36 m s⁻¹ [3,19]. Two small fans were also installed on the chamber floor to promote particles resuspension. The chamber was cleaned between tests and then closed with a fastening system equipped with screws and gaskets. Upon activating the ventilation system, 2 g of synthetic PM particles were injected through a 2 cm diameter circular opening on the chamber upper face (see Section 2.7 for details).



Fig. 1. (a) Outdoor Green Wall (OGW), (b) Indoor Green Wall (IGW) and (c) Active Green Wall (AGW) located at the School of Technical Agricultural Engineering of the University of Seville.



Fig. 2. Closed glass chamber for experiments with active green wall (AGW).

A control experiment was performed by measuring PM dynamics in the chamber at analogous environmental parameters but substituting the GW with a polyethylene wall featuring irregular holes of different sizes and shapes.

2.2. Air PM monitoring

To investigate the chemical composition of the outdoor atmospheric PM, three PM₁₀ samples were collected before the leaf sampling by using a particle medium volume sampler (COMDE-DERENDA MVS 6.1) equipped with 47 mm Ø quartz microfibre filters (Whatman QM/A™) with a pore diameter of 2.2 µm. These filters do not simply act as a sieve, but capture particles through mechanisms of interception, impact and Brownian diffusion. The air flow dynamics and the filter convoluted surface allow the effective capturing of particles even smaller than the filter pore size [3]. This sampler constitutes the reference system for PM₁₀ and PM_{2.5} (according [20], EN 12341:2023), total suspended

particles, TSP (VDI 246) and Soot (VDI 2465). It was set to draw in an air flow of 2.35 m³h⁻¹, for a daily air volume of 56 m³ day⁻¹. To assess the amount of filtered PM, filters were weighed with a precision balance (with 0.0001 g sensitivity) before and after six-days exposure, upon being dried in an oven at 105°C for two hours and in a desiccator for 30 minutes. The used temperature is higher than standards typically employed and may cause evaporation of VOCs and other volatile components. However, this can be considered negligible, as the study focuses on quantification and characterization of PM related metals and non-volatile inorganic fraction. The average atmospheric PM chemical composition were used as reference for the synthesis of PM employed in the AGW experiment.

The PM concentration and composition within the AGW chamber were similarly obtained. Furthermore, an air quality monitor (IQAir - AirVisual Outdoor, Germany) was placed inside the chamber for the control test and for the AGW test to monitor PM concentration per size fractions (i.e., PM₁, PM_{2.5}, PM₁₀) as well as temperature (°C), relative

humidity (%) and barometric pressure (mbar), in real time via a smartphone app (iQAir Airvisual), and thus calculate the real-time Air Quality Index (AQI) following the guidelines of European Environmental Agency (EEA). According to the manufacturer's technical specifications, the device's tolerance is $\pm 10\%$ of the measured value for the three PM fractions.

2.3. Leaf sampling

Before starting the experiment, all plants were similarly washed with distilled water to establish the same starting conditions. Five washed leaves per species per wall were collected to be used as reference samples of clean leaf surfaces. Residual particles remaining after washing similarly affected all the species and can be considered as background noise that does not invalidate the general observed PM accumulation trends. Plants were then exposed to atmospheric contamination for six days (without rain). After exposure, a total leaf area between 300 and 400 cm² per species, from each green wall was sampled using gloves and placed in clean, white paper envelopes. The surface area of the leaf samples was scanned and then measured using pixel-measurement software. Each sample consisted of a mix of leaves randomly taken from four plants within the same wall. Five leaves per species, per wall, were used for the characterization of the macro and micromorphological traits, while the remaining leaves were used to assess the deposited PM amount and chemical composition.

2.4. Leaf macro and micromorphology

Relevant macromorphological traits, such as the total leaf area and the ratio between leaf perimeter and area, were measured using ImageJ software [21]. Average value per species were obtained from at least three leaves per species and are reported in the Supplementary Materials (SM; Table SM1). Scanning Electron Microscopy (SEM) observations of three washed and three unwashed leaves per species was conducted at the CNR-IRET (Porano, Italy), to characterise the relevant micromorphological traits, such as the presence of stomata, trichomes, grooves and roughness [12,14]. Microscopic analysis was performed using a Phenom PRO-X microscope equipped with a charge-reduction sample holder suitable for the analysis of biological samples. Portions of approximately 1 cm² of both the adaxial (AD) and abaxial (AB) surfaces of each leaf were randomly cut and mounted on carbon stubs (PELCO Tabs, Ted Pella, Inc.). Images were taken with an incident electron energy of 5 keV to limit surface charging. Ten images were then acquired for each leaf sample, each covering an area of approximately 150 × 150 μm² (1024 × 1024 pixels).

2.5. PM load determination on leaf surface

The PM load on leaf surfaces was assessed by gravimetric vacuum filtration methodology [22]. Each leaf sample (7–10 g) was washed with 250 ml of microdistilled water type I, 18.2 MΩ cm⁻¹ (Elga Purelab® Flex 6, from Elga Veolia) and exposed to an ultrasonic bath (120 W, 40 KHz) for 5 minutes to facilitate the PM detachment. The washing solution was first filtered through a metal sieve with a mesh size of 100 μm to remove the coarsest impurities. Then it was filtered (in sequence) through 10 μm (NY10-nylon filter mesh opening 10 μm), 2.5 μm (Whatman 42 filter papers Ashless CAT No. 1442-047, mesh opening 2.5 μm) and 0.2 μm (PRAT DUMAS France REF M0475520, mesh opening 0.20 μm) pore filters, to collect PM₁₀₋₁₀₀ μm, PM_{2.5-10} and PM_{0.2-2.5}. Both before and after the filtration, filters were placed in an oven at 60°C for 30 minutes, in a desiccator for 15 minutes and weighed using a precision balance (with 0.0001 g sensitivity). The difference between post- and pre-filtration weights determined the PM amount captured by the filter. Then, leaf samples were scanned, to measure the washed leaf surface area and thus normalize the removed PM weight, obtaining the PM load (i.e., mass per unit leaf area) per species, per GW. The concentration of

total dissolved solid (TDS) remaining in the washing solution after filtration was further estimated using a multifunctional conductometer [23]. By adding the normalized TDS estimation to the PM load obtained by the washing-filtration procedure, a more accurate measurement of the leaf accumulated PM was obtained. For each species and GW system, four replicates were obtained.

2.6. PM chemical composition characterization

The filters used to monitor the atmospheric PM and to filter the leaf washing solutions were further processed to assess the chemical composition of the retained PM particles [3]. After being weighed as described in the previous Sections 2.2 and 2.5, filters were placed in 50 mL plastic DigiTUBEs, 8 ml of concentrated HNO₃ Suprapur was added, and the tubes were digested in a DigiPREP® MS heating system (SCP Science, Quebec, Canada) heating gradually to 115°C for 120 min. After waiting about an hour for cooling, the tubes were brought back to a volume of 10 ml with ultrapure water Type 1, 18.2 MΩ·cm (Milli-Q® Direct system from MerckMillipore, Merck KGaA, Darmstadt, Germany) and were filtered through 0.45 μm hydrophilic Teflon® membrane DigiFILTERs in the vacuum DigiManifold. To determine the concentration of PTEs (Al, Ca, Cd, Co, Cu, Cr, Fe, K, Mg, Mn, Na, Ni, Pb and Zn), the obtained solutions were analysed using a microwave induced-plasma optical emission spectroscopy (4200 MP-AES, Agilent Technologies, Santa Clara, USA) equipped with the autosampler Agilent model SPS4. Sample introduction was performed with an inert One-Neb nebulizer with a double-pass glass cyclonic spray chamber, and a quartz torch. The plasma used the online N₂ generator Agilent 4107. Operating conditions were gas flow at 20 L min⁻¹ and auxiliary gas at 1.5 L min⁻¹ and the following operational settings: uptake time of 82 s, stabilization time of 15 s, read time of 3 s (3 measures of intensities), wash time of 72 s. Before measurements, both viewing position and nebulizer flow were optimized for each element using the Agilent Wavecal solution. Automatic background correction was used.

Analytical calibrations were prepared from a 1000 mg L⁻¹ Certipur® multi-element standard solution (Merck KGaA, Darmstadt, Germany). Standard concentrations were prepared from 1.0 μg L⁻¹ to 250 mg L⁻¹ in 3% HNO₃. Samples with concentrations above 250 mg L⁻¹ were analyzed by low-fold dilution (< 1:3). Linear ranges of concentration were selected around the concentrations of the samples depending on the element. Good precision and linearity of the calibration curve, low quantification limits and high sensitivities were obtained [24].

2.7. Synthetic PM preparation and injection

Synthetic PM was prepared to be used within the AGW chamber. Based on the PM concentration and composition measured close to the OGW, the selected chemical elements were Al, Cd, Ca, Cu, Cr, Fe, Mg, Mn, Ni, Pb, K, Na, B, Zn, and P. The specific quantity (%) used of each element is reported in Table 1. Relative concentration amongst PTE mimic what observed outdoor, but to speed up PM deposition, the overall PTE concentration was increased and a total of 9.5 g of PM was synthesised. The mixture of salts of analytical grade consisting of nitrates, sulphates, chlorides, phosphates and carbonates of various metals was prepared handling reagents within a vertical laminar airflow cabinet (Indelab IDL-48V), based on the methodology described by [25] and [26], and improved by the same authors in 2023 [24]. After preparation, the mixture was stored in a plastic tube and kept in a desiccator with relative humidity below 5–10%. At this stage, the mixture was multi-coloured, as the particles of the different reagents retained their original shape, particle size and colour. To dilute the concentration of metals, reproduce the typical PM chemical composition, and make the mixture more similar to atmospheric particles, 3 g of sodium carbonate (Na₂CO₃) and 3 g of silicon dioxide (SiO₂) were added, both with very low density.

The mixture was manually ground in an agate mortar to reduce the particle size, facilitating mixing and colour homogenisation towards

Table 1

Concentrations of potentially toxic elements (%) in the synthetic particles used for the experiments in the active green wall.

Element	%
Al(NO ₃) ₃ •9H ₂ O	5.44
CdSO ₄ •3/8H ₂ O	0.04
CaSO ₄ •2H ₂ O	13.24
Co(NO ₃) ₂ •6H ₂ O	0.13
CuSO ₄	0.15
CrCl ₃ •6H ₂ O	0.04
Fe(NO ₃) ₃ •9H ₂ O	5.92
Mg(NO ₃) ₂ •6H ₂ O	4.03
MnSO ₄ •H ₂ O	0.12
Ni(NO ₃) ₂ •6H ₂ O	0.04
Pb(NO ₃) ₂	0.02
KNO ₃	1.61
NaNO ₃	5.08
Na ₂ B ₄ O ₇ •10H ₂ O	0.24
ZnSO ₄ •7H ₂ O	0.17
Na ₂ HPO ₄ •2H ₂ O	0.19
NaCl	0.38
SiO ₂	31.6
Na ₂ CO ₃	31.6
Total	100

light grey. The mixture was passed through a 20 µm metal sieve, using a fine-tipped brush. The sieved mixture was collected in a glass test tube to avoid any external contamination and further checked by MP-AES and SEM, to verify the obtained chemical composition and the abundance of the different PM fractions (see SM, Fig. SM1).

2.8. Statistical analysis

Statistical analysis was performed by using in STATISTICA Release 7 ©. Statistically significant differences in PM accumulation and composition between species within each GW were assessed by one-way ANOVA; when significant effects were detected, the *post hoc* least significant difference (LSD) test was applied at $p < 0.05$. Shapiro-Wilk tests were used for normality. When data did not meet normal distribution, the non-parametric Kruskal-Wallis test was used, and groups were compared using the Mann-Whitney test. Statistical differences between results of the two treatments within the chamber (with and without AGW) were analysed by using the T-test by groups. Principal component analysis (PCA) was performed to analyse the association between plant species and chemical characteristics of PM. Data from at least three replicates per species were used as input cases, and chemical elements were used as input variables.

Data visualisation and graphing were performed using OriginPro 8.5©.

3. Results and discussion

3.1. Leaf morphological analysis

Representative pictures of the used species and representative SEM images of their abaxial (AB) and adaxial (AD) surfaces before and after the PM exposure are shown in Fig. 3. The micromorphological traits are clearly visible in the SEM images of the clean leaves: sparse PM particles are present, visualized as bright spots, and micromorphological features, such as stomata, grooves and roughness are well distinguished. In particular, *C. comosum* and *M. deliciosa* had substantially smooth surfaces characterised by few grooves, and PM particles were distributed sparsely across all the leaf surfaces. *H. helix* and *N. exaltata* had a rougher surface, characterised by continuous and fairly regular grooves, where PM tended to settle near the stomata, grooves and any other concave surfaces that favoured their trapping. Finally, *T. zebrina* had a micromorphology characterised by a smooth surface interspersed with

continuous and regular grooves, but much more spaced than in *H. helix* and *N. exaltata*, resulting in a more scattered PM deposition pattern. These structural differences are relevant because grooves, roughness, and surface concavities may act as preferential deposition sites, especially under dry deposition conditions, whereas smoother surfaces tend to retain less particles.

Qualitative analysis of the images revealed a greater accumulation of particles on the leaf adaxial surfaces than on the abaxial, confirming results of other studies [27,28], because particles carried by air flows tended to mainly settle on the more exposed side [15]. Another difference was observed between PM deposition dynamics in the different GWs. In OGW and IGW, particle removal occurred mainly through dry deposition/resuspension cycles, driven by mechanical processes such as gravity, diffusion, interception and turbulence [13]. In contrast, in AGW, the higher humidity level favoured the accumulation of particles on leaves through wet deposition, penetrating deeper into the micromorphological structures than when dry deposition occurs. Despite the lack of quantitative evidence, these observations support the idea that microclimatic factors strongly affect PM-leaf interaction.

3.2. PM accumulation differences across species

The species-specific PM loads in the three GWs are shown in Fig. 4 (numerical data are in SM; Table SM2). In OGW (Fig. 4a), significant differences ($p < 0.05$) were observed in PM accumulation between species for all size fractions except for PM_{0.2-2.5}. In IGW (Fig. 4b), significant differences were observed for all fractions except PM_{2.5-10}. In AGW (Fig. 4c), significant differences were assessed only for PM₁₀₋₁₀₀.

In OGW, *C. comosum*, *H. helix* and *N. exaltata* accumulated the same load of PM₁₀₋₁₀₀, while the lowest value was obtained by *M. deliciosa*. Regarding PM_{2.5-10}, the high value observed in *C. comosum* was statistically similar to *M. deliciosa*, while *N. exaltata* showed the lowest capacity to trap coarse PM. *H. helix*, *M. deliciosa* and *T. zebrina* trapped a similar amount of total PM, and the highest value ($14.83 \pm 3.66 \mu\text{g}/\text{cm}^2$) was found in *C. comosum*. A similar behaviour of this species in total PM trapping was reported by Rossini-Oliva et al., [3], when comparing it with others in an AGW.

In IGW, similar PM₁₀₋₁₀₀ trap capacity was observed between all species except for *M. deliciosa* (statistically lower than the others). *Hedera helix*, *N. exaltata* and *T. zebrina* had similar capacity to trap PM_{0.2-2.5} and *C. comosum*, together with *H. helix*, showed the highest fine PM accumulation, with $3.3 \pm 1.37 \mu\text{g}/\text{cm}^2$ and $1.5 \pm 0.47 \mu\text{g}/\text{cm}^2$, respectively. For the total PM, no statistical differences between species were found, except for *C. comosum*, whose high value ($15.25 \pm 2.37 \mu\text{g}/\text{cm}^2$) was similar only to that of *H. helix* ($12.81 \pm 3.36 \mu\text{g}/\text{cm}^2$).

Finally, in AGW all the species trapped PM_{0.2-2.5} and PM_{2.5-10} in similar loads. *Chlorophytum comosum* and *N. exaltata* showed the significant highest values of PM₁₀₋₁₀₀, whereas *H. helix* and *T. zebrina* had similar trapping capacity.

Results indicate that the same species behaved differently depending on location and contamination conditions (load and distance from the contamination sources) and that *C. comosum* is a good candidate to trap fine PM in indoor environments. *Nephrolepis exaltata* showed different trapping behaviour depending on the location. For example, it was very effective for trapping large PM in AGW but showed the lowest capacity for coarse PM under outdoor conditions. In line with this, a recent study conducted in a closed chamber with air recirculation [29] observed that *N. exaltata* was a very efficient species in removing PM. Its high phytoremediation potential may be due to its micromorphological characteristics, especially narrow and deep grooves, and to its numerous small, evenly distributed leaves, which maximise particles interception through impact mechanisms.

Several studies suggest that polycultures of plants may be more effective than monocultures in removing PM over the long term [30,31]. Previous studies conducted on IGW have observed that *C. comosum* is very effective in PM accumulation [17,31], confirming our results. Tang

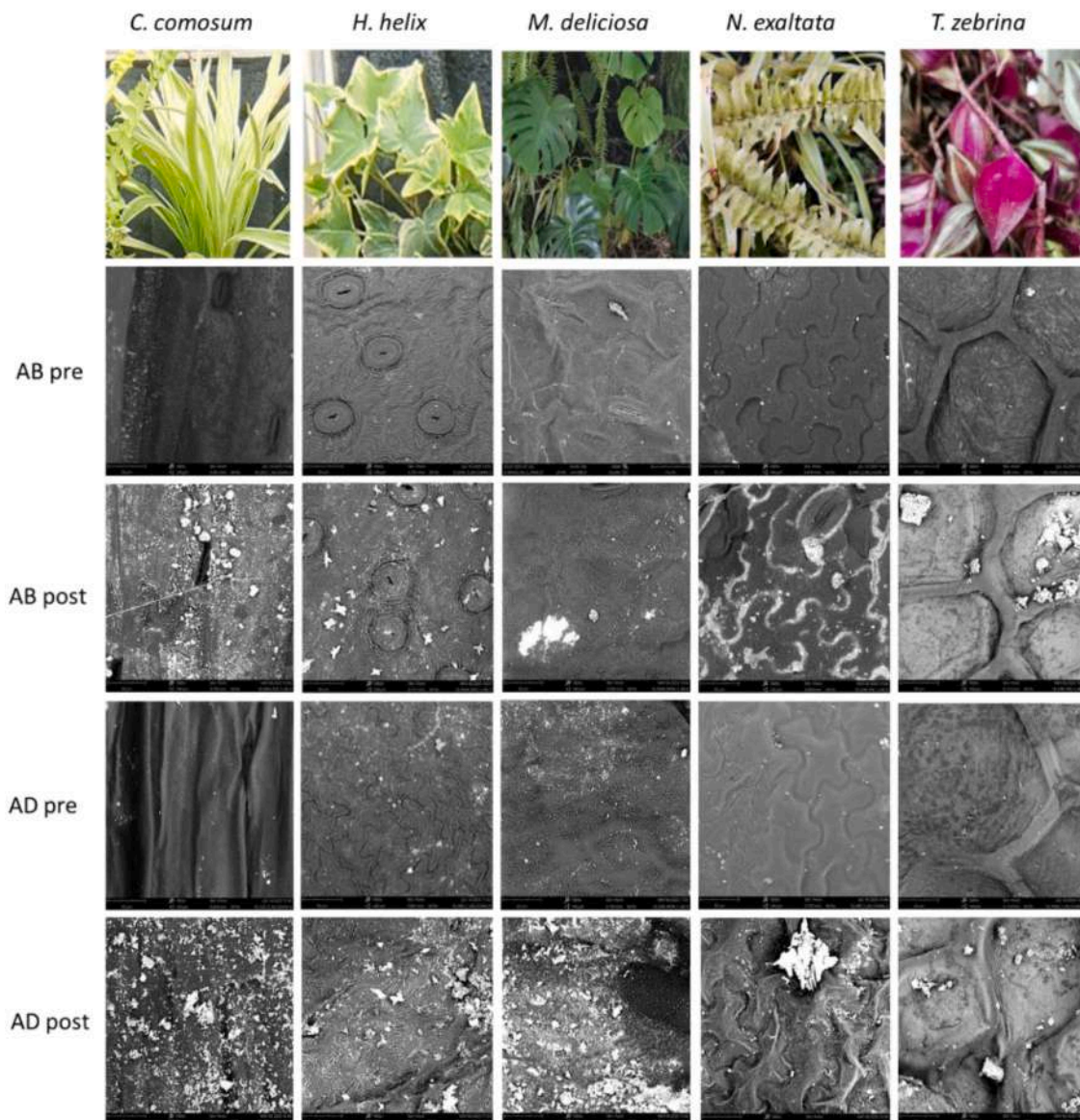


Fig. 3. Pictures of the five studied plant species (first row), and images acquired using a scanning electron microscope (SEM) from both the abaxial (AB; second and third rows) and the adaxial (AD; fourth and fifth rows) surfaces of leaves from each species, collected before the experiment (pre; second and fourth rows) and after (post; third and fifth rows) the contamination exposure.

[31] reported a good performance for PM accumulation in *H. helix* in outdoor contexts and reported that its accumulation potential can vary considerably depending on the season and was negatively correlated with leaf surface contact angle.

Monstera deliciosa often showed a PM trapping capacity similar to the other studied species, and its capacity to trap $PM_{2.5-10}$ in OGW was high and similar to *C. comosum*, even though their leaf characteristics are very different. In this case, macromorphology appears to have a greater influence than micromorphology. *Chlorophytum comosum* has long, narrow leaves, whereas *M. deliciosa* has very large lobed leaves. Many studies found that smaller leaves can be more effective in PM removal than large leaves [15,32], but leaf architecture also appears to be an important character. Regarding shape, some studies agree that lanceolate leaves can be more effective than linear, elliptical or needle-like leaves [33]. From this point of view, we found clear differences in PM accumulation patterns in plants with lanceolate leaves (*N. exaltata* and *T. zebrina*) compared with the others. At the same time, it was difficult to make an accurate comparison with the same species analysed in other studies, because atmospheric and microclimatic factors may have a greater

influence on accumulation dynamics than micromorphological and macromorphological characteristics.

It should be noted that the macromorphological analysis performed in this study was limited to leaf area and perimeter-to-area ratio. Other traits known to influence PM capture, such as leaf inclination angle, leaf density, canopy architecture and leaf area index, were not assessed and therefore their contribution cannot be excluded.

Concerning micromorphological traits, many authors focused on their impact on PM particle capture, in the last years [3,9,14]. However, the obtained results showed some discrepancies that still deserve to be investigated. In this study, leaves with wrinkled surfaces, grooves and ridges (such as *N. exaltata* and *H. helix*) were more effective in PM accumulation than leaves with smooth or weakly structured surfaces (such as *T. zebrina* and *M. deliciosa*), as previously observed [15], although differences were also affected by the GW context. Trichomes contribution to PM particle capture is still under debate. Several studies reported that trichomes may physically trap larger PM particles, preventing their resuspension into the atmosphere [33,34], but the low amount of trichomes in the species selected in this study did not allow to

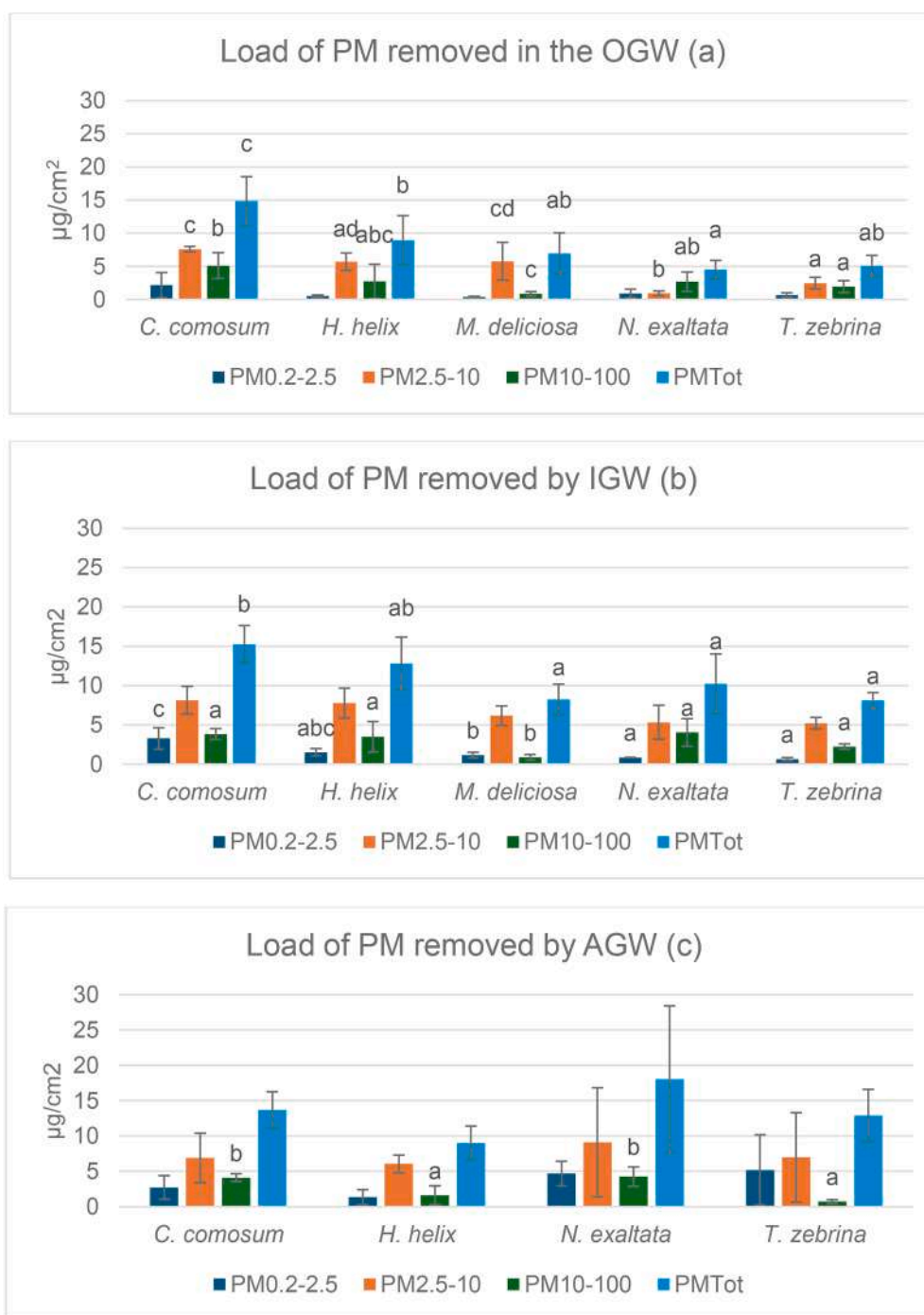


Fig. 4. PM accumulation load (mean value, $\mu\text{g}/\text{cm}^2$) of the same plant species in (a) an outdoor green wall (OGW); (b) an indoor green wall (IGW); and (c) an active green wall (AGW), per size fraction. Statistical differences are defined as $p < 0.05$. Different letters indicate statistical differences between species. Error bars represent standard deviations. Data are also reported in Table SM3 of Supplementary Materials.

speculate about their role in PM accumulation. The role of stomata in PM capturing is still controversial: some studies consider them useful for increasing the micromorphological complexity of the leaf ([35]; Del Carmen [36]), while others claim no evident impact of their presence on PM deposition [12]. Finally, another element to consider is cuticular waxes, which can influence PM capture by increasing the adhesive power of the leaf surface [28,34], but also on this aspect our data cannot support any hypothesis.

Finally, it is worth noting that, although efforts were made to characterize ambient PM and reproduce comparable pollution conditions in the AGW experiment, the three GW systems were inherently exposed to

different atmospheric environments. The OGW, IGW and AGW differed not only in microclimatic conditions, but also potentially in PM concentration, source profile and particle size distribution. Consequently, part of the observed variability in species performance may reflect differences in pollutant exposure in addition to intrinsic species characteristics. Nevertheless, the purpose of this study was to evaluate PM accumulation under three realistic GW contexts rather than under identical exposure conditions. Therefore, species rankings should be interpreted as context-dependent responses to different environmental settings rather than as universal indicators of PM capture efficiency.

Overall, results highlight that species-specific PM accumulation is

strongly context-dependent, with shifts in relative performance between GWs indicating that deposition mechanisms interact differently with plant traits under outdoor, indoor, and in forced-ventilation conditions. The contrasted behavior across PM size fractions also suggests that leaf traits alone cannot consistently predict trapping performance, especially when environmental and microclimatic factors modify the dominant deposition pathways. Deposition dynamics depend not only on macro- and micromorphological characteristics, but are also strongly affected by environmental conditions, meteorological variables and microclimate. It has been observed that the air PM concentration is correlated with temperature and relative humidity levels [33], while it is usually

negatively correlated with wind speed and precipitation abundance, which tend to bring PM to the ground and temporarily improve air quality [37]. High humidity conditions, for example, can alter the size of PM particles, as they can adsorb water molecules dispersed in the atmosphere due to their hygroscopic power. As a result, changes in particle size and weight can affect PM deposition mechanisms and increase accumulation on leaf surfaces [38], as can be seen in the results we found in the experiment inside the chamber with the AGW.

More insights can be obtained by comparing the relative weight percentages of PM size fractions ($PM_{0.2-2.5}$, $PM_{2.5-10}$ and PM_{10-100}) in the three GWs, shown in Fig. 5. The most represented PM fraction was the



Fig. 5. PM accumulation percentage on plant species in outdoor green wall (OGW), indoor green wall (IGW) and active green wall (AGW), per size fraction.

coarse one (PM_{2.5-10}), followed by the large fraction in all three systems, except in AGW for *T. zebrina*. This agrees with Terzaghi et al., [39], but contrasts with results from Miralles-Pérez et al., [40], who reported that the most representative weight PM trapped on leaf surface in outdoor conditions was the largest fraction. Submicron (<1 µm) and fine particles (1–2.5 µm) are the PM fractions mostly deposited on the abaxial surface [41] and fine particles may also enter via stomata [42].

In AGW system, the PM_{0.2-2.5} fraction in *T. zebrina* was much more abundant (40%) than PM₁₀₋₁₀₀ (5.6%). As discussed above, PM dispersion dynamic in the AGW differs from the other systems. Also, the high concentration of fine PM in the synthetic PM may also explain this result. Nevertheless, the high accumulation rate of fine and medium PM observed in the three GW systems is a positive outcome in relation to human health, as particles smaller than 10 µm can be inhaled into the upper airways and reach the thoracic region and respiratory organs, such as the trachea, pharynx and lungs [43].

Finally, data on PM trapped on filters upon washing-filtration can be complemented by the quantification of the TDS in the washing solutions, which estimates the ionic fraction of the leaf adsorbed PM [23]. The sum of TDS per unit leaf area and the total PM load (PM_{Tot}, obtained by summing PM_{0.2-2.5}, PM_{2.5-10} and PM₁₀₋₁₀₀) represent a more comprehensive estimation of the total adsorbed PM (Table SM3) by leaves. It is worth noting that, while the ranges of total PM load per species are similar in the three walls, TDS shows a different behaviour, being much higher in the OGW and much lower in the IGW, with the AGW showing intermediate values. In particular, the ratio between TDS and PM_{Tot} (Table SM3) revealed both that the ionic fraction of leaf adsorbed PM is context dependent and that the species have (again) different ionic fraction trapping capacity. In IGW, all the species show a comparable TDS/PM_{Tot} ratio of about 0.7–1.0, except *C. comosum* that has a TDS/PM_{Tot} ratio of 2.0 ± 0.6 . In contrast, in the OGW, the TDS/PM_{Tot} ratio is highly variable across species but still *C. comosum* shows the highest value (7.7 ± 3.2). In the AGW, the TDS/PM_{Tot} ratio is always above 1, but lower than in OGW, with *C. comosum* and *H. helix* showing the highest values (4.0 ± 1.4 and 4.9 ± 3.0 , respectively). A possible explanation for the context dependency could reside in the higher exposition of OGW to natural sources (e.g., marine aerosol) and, thus, the high ratio observed in AGW may depend on the fact that the artificial PM composition has been modelled upon the outdoor ambient PM. Considering the species specificity, again *C. comosum* and *H. helix* are confirmed as the most efficient species in PM trapping [17,31].

Taken together, these findings indicate that leaf morphology alone cannot explain PM accumulation patterns across species. Although some micromorphological traits, such as grooves, roughness and surface complexity, were associated with enhanced PM retention. Species rankings varied considerably among the three GW systems and among PM size fractions. This shift in performance under different environmental conditions suggests that PM capture is driven by the interaction between plant traits and external factors, including humidity, air circulation, and particle characteristics.

3.3. PM chemical composition characterization

The PTE concentrations in leaf deposited PM, per GW system, are reported in SM (Table SM4). The most frequent elements appearing in PM were Al, Ca, Fe, K, Mg, and Na, while the least represented were Cd, Co, Cu, Cr, Mn, Ni, and Zn. Lead (Pb) was only found in the fine fraction of the IGW. It is worth noting that species accumulated chemical elements in a species-specific manner, as evidenced by the significant differences among species. The greatest statistical differences were found for the fine fraction (PM_{0.2-2.5}), while the smallest differences were found for the large PM fraction (PM₁₀₋₁₀₀).

In the OGW, Cd was not detected in the fine and coarse PM deposited on *H. helix* and *N. exaltata* and it was not detected in the large PM fraction, for any species. In the OGW, *H. helix* showed the highest Ni amounts in the fine PM fraction, while *N. exaltata* accumulated the

highest amounts of Cu in the fine fraction, whereas retained the highest Ni concentration in the coarse fraction.

In the IGW, *T. zebrina* and *N. exaltata* accumulated the highest amount of Cr in the fine PM fraction, and *N. exaltata* was more efficient in accumulating Co in the coarse PM fraction.

Finally, in the AGW, *C. comosum* was the species that accumulated the highest concentrations of Cd and Cu in the fine PM fraction compared with the other species. Mean, while *H. helix* showed the significantly higher values of Ni and Zn in the fine fraction, whereas *C. comosum* accumulated more Co in the coarse PM fraction than the other species.

The set of the most abundant elements (Al, Ca, Fe, K, Mg, Na) was linked to the high presence of coarse particles. These elements are also known as “crustal components”, i.e., mineral dust aerosols derived from the disintegration of soil and crustal rocks [44]. The prevalence of crustal elements is consistent with the suburban location of the University campus, about 9 kilometer far from the city centre, and surrounded by rural areas. Conversely, the least represented elements — Cd, Co, Cu, Cr, Mn, Ni and Zn, mainly associated with the fine fraction — are likely related to vehicular sources [45].

The presence of these elements may be associated with the car park in front of the university building, where vehicles may generate various types of contaminant emissions. Some authors classify particles of vehicular origin, arguing that they derive mainly from vehicle exhaust emissions, brake wear and tyre wear [46,47]. According to this classification, a proportion of Fe, already present within earthy agglomerates, may originate from exhaust gases and brake wear [15,48]. In addition to Fe, the high presence of Cu may also be linked to abrasion processes resulting from brake wear [47]. Conversely, Zn may be a marker linked to emissions from tyre wear [49]. The other elements detected in PM, such as Cr, Mn, Ni and Zn, may be linked to vehicle emissions, as reported by other authors [15,50]. Furthermore, elements of saline origin, such as Na, may be attributable to water used for irrigation the university garden and the proximity of an artificial lake. Finally, traces of residual elements can be classified as mixed agglomerates, formed as a result of PM resuspension processes driven by atmospheric factors, such as wind.

To investigate the relationships between plant species and PM chemical composition deposited on plant leaves, a PCA was performed. In this analysis, the plant species were the cases, while the concentration of chemical elements, expressed in mg/kg, served as the input variables. Fig. 6 shows the PCA plots respectively for OGW (a-c; PM_{0.2-2.5}, PM_{2.5-10}, PM₁₀₋₁₀₀), IGW (d-f; PM_{0.2-2.5}, PM_{2.5-10}, PM₁₀₋₁₀₀) and AGW (g-i; PM_{0.2-2.5}, PM_{2.5-10}, PM₁₀₋₁₀₀). Each plot shows the factor scores of the cases (plant species) and the factor coordinates of the variables as a function of PC1 and PC2 (i.e. the projection of the two most discriminating components on the input variables). In the three OGW graphs, the PC1 and PC2 components represented 48.5% and 24.2% (72.7%) of the total variance for PM_{0.2-2.5}, 64.4% and 11.5% (75.9%) for PM_{2.5-10}, and 35.2% and 22.9% (58.1%) for PM₁₀₋₁₀₀. In IGW, PC1 and PC2 were 64.0% and 12.3% (76.3%) for PM_{0.2-2.5}, 47.4% and 16.3% (63.7%) for PM_{2.5-10}, and 36.1% and 28.6% (64.75%) for PM₁₀₋₁₀₀. In AGW, PC1 and PC2 represented 63.1% and 21.3% (84.4%) for PM_{0.2-2.5}, 59.2% and 16.7% (75.9%) for PM_{2.5-10}, and 52.0% and 21.3% (73.3%) for PM₁₀₋₁₀₀.

Additionally, Table SM5 shows the level of clustering between replicates of the same species (letter c) in each plot, and the positive associations between species and chemical elements for each GW. Clustering was determined based on the presence of the same species replicates within the same PCA quadrant. A good clustering level was observed, suggesting a species-specific behaviour in the retention of particles with analogous chemical pattern. All species except *M. deliciosa* showed good clustering. In particular, *C. comosum*, *H. helix*, *N. exaltata* and *T. zebrina* were well clustered in six out of nine cases, while *M. deliciosa* only in one out of six cases.

The PCA results revealed clear associations when all replicates of a species were associated with the same elements. In other cases,

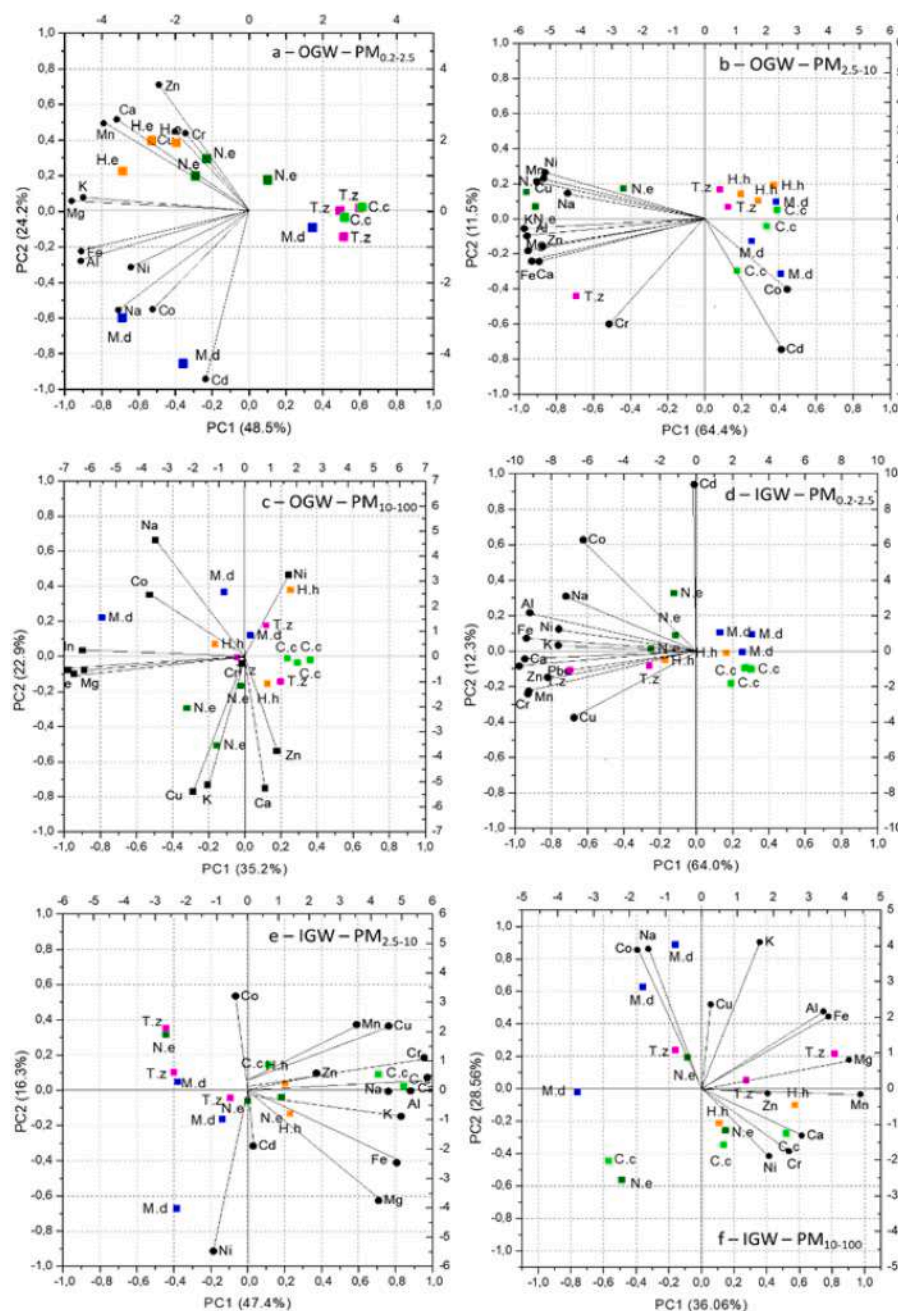


Fig. 6. Factor coordinates of variables and factor scores of the cases related to three replicates per species plotted in the bi-dimensional plane defined by PC1 and PC2, for Outdoor Green Wall (a-c; OGW, PM_{0.2-2.5}, PM_{2.5-10}, PM₁₀₋₁₀₀), Indoor Green Wall (d-f; IGW, PM_{0.2-2.5}, PM_{2.5-10}, PM₁₀₋₁₀₀) and Active Green Wall (g-i; AGW, PM_{0.2-2.5}, PM_{2.5-10}, PM₁₀₋₁₀₀).

clustering involved only two out of three replicates, with preferential accumulation towards certain elements. *Chlorophytum comosum* proved to be a good bioindicator for the accumulation of heavy metals such as Cu, Mn, Cd, Co and macroelements such as Ca, K, Na [51]. A similar assessment can be made for *H. helix*, which reported an elemental composition characterised in particular by Mg, Mn, Zn, Fe, similar to that reported by Tang [31].

Some PCA graphs show all factor scores as negative with respect to PC1, and the absence of discrimination with respect to species and elements may demonstrate that PM had similar chemical characteristics across the three GWs. In such cases, the main discrimination was related to the amount of PM accumulated and not to its chemical composition. In these situations, the variability is better described by PC2, reflecting

specific species–element affinities or preferences for particular PM size fractions.

Furthermore, the results show some differences in the cumulative variance explained by the first two principal components among the different GWs. In all cases, the plots for AGW showed a cumulative variance exceeding 70% (an empirical benchmark for evaluating PCA). Conversely, in some plots, such as OGW–PM₁₀₋₁₀₀, IGW–PM_{2.5-10}, and IGW–PM₁₀₋₁₀₀, the cumulative variance explained by PC1 and PC2 was below 70%. This result indicates that, in these datasets, a larger proportion of the overall variability is also distributed across subsequent principal components, suggesting a more complex multivariate structure. Given the presence of numerous chemical elements, the distribution of elements associated with PM deposited on leaf surfaces may

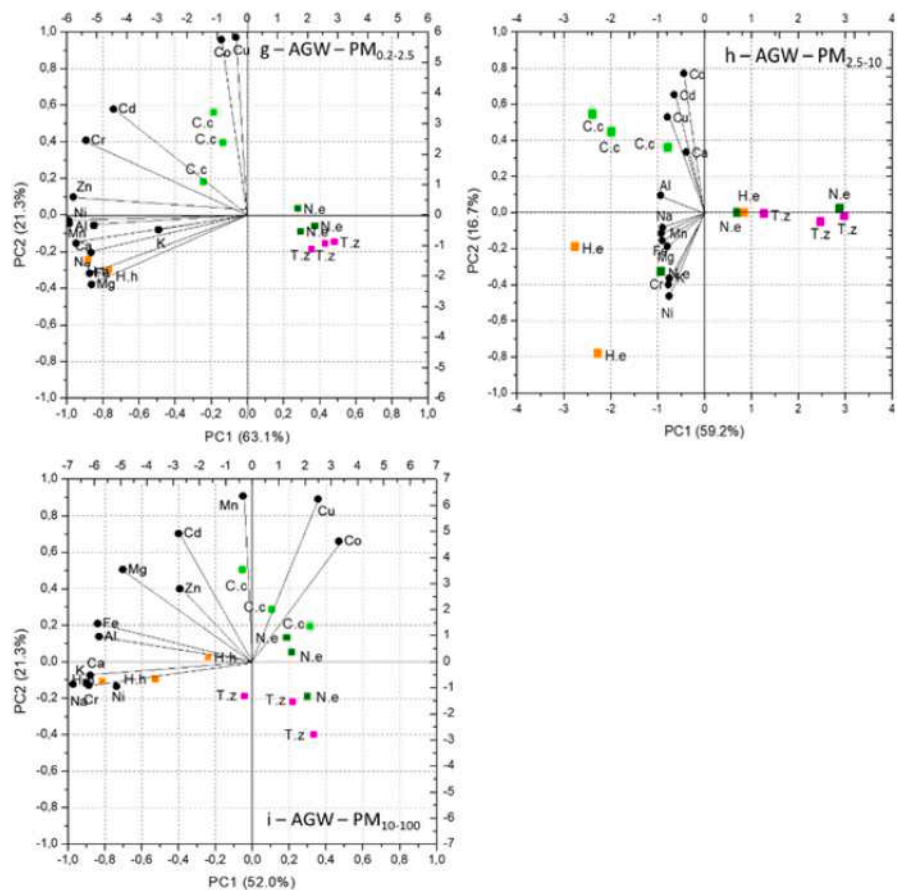


Fig. 6. (continued).

therefore be driven by multiple gradients of variation rather than by a single dominant gradient.

The highest level of clustering for all species was found in AGW, where *C. comosum* and *T. zebrina* showed similar behaviour for all size fractions, while *H. helix* and *N. exaltata* did so mostly for PM_{0.2-2.5}. Regarding chemical-physical interaction between species and chemical elements, *C. comosum* showed positive associations with chemical elements in five out of nine cases, showing a strong affinity with Co and Cu in AGW. *Monstera deliciosa* also showed many associations (four out of six), especially with Co and Na in both OGW and IGW. *Nephrolepis exaltata* showed a strong affinity with Cu. *H. helix* showed affinity with Mg in AGW and *T. zebrina* showed no affinity with specific elements. This may be related to differences in leaf-surface chemistry and pH among species, although these parameters were not measured in the present study.

The leaf surface and phyllosphere represent a chemically active environment in which deposited particles may undergo physico-chemical interactions, potentially influencing PM accumulation patterns and the retention of specific chemical elements [52]. However, leaf-surface pH was not measured in the present study, and therefore its potential contribution to the observed accumulation patterns cannot therefore be quantitatively assessed. Consequently, this consideration should be regarded as an additional parameter that would be valuable to quantify in future studies.

Chemical interactions between species and elements might play a role in accumulation dynamics, but only partial evidence was obtained in this study. In fact, species-element relationships were observed only in relation to different GWs, but the same relationship was never repeated in the three GWs. Therefore, the morphology and PM chemical composition alone were not enough to explain the PM retention capacity of each species. This depends on a combination of factors that includes,

in addition to morphology and chemical interaction, environmental and microclimatic conditions, driven in particular by the level of humidity, as observed in the experiment conducted inside the chamber. Overall, species–element associations were context-dependent and did not reveal universal patterns across GWs, confirming that chemical affinity cannot be considered a stable species trait, but an emergent property affected by environmental conditions.

The observed species–element associations suggest that PM retention is not governed exclusively by physical interception mechanisms. Although the present study cannot identify the exact mechanisms involved, species-specific affinities for individual elements point towards physicochemical interactions occurring at the leaf surface. Differences in cuticular composition, surface pH, electrostatic properties, wettability and hygroscopic behaviour might affect the adhesion, retention and possible dissolution of PM particles and associated elements. The fact that several species showed preferential associations with specific PTEs supports the hypothesis that chemical interactions within the phyllosphere contribute to PM accumulation in addition to leaf morphology alone.

3.4. Air quality improvement by GW under controlled environmental conditions (AGW)

To explore the role of AGW in improving air quality, 2 g of synthetic PM was injected into the chamber and PM size fraction concentrations and the AQI were monitored in both situations (with and without GW) over 6 days (Fig. 7a). Environmental parameters such as temperature and relative humidity were also recorded (EasyLog data logger, EL-USB-2).

In both experiments, temperature remained almost constant at around 23°C while the relative humidity ranged between 44% and 52%

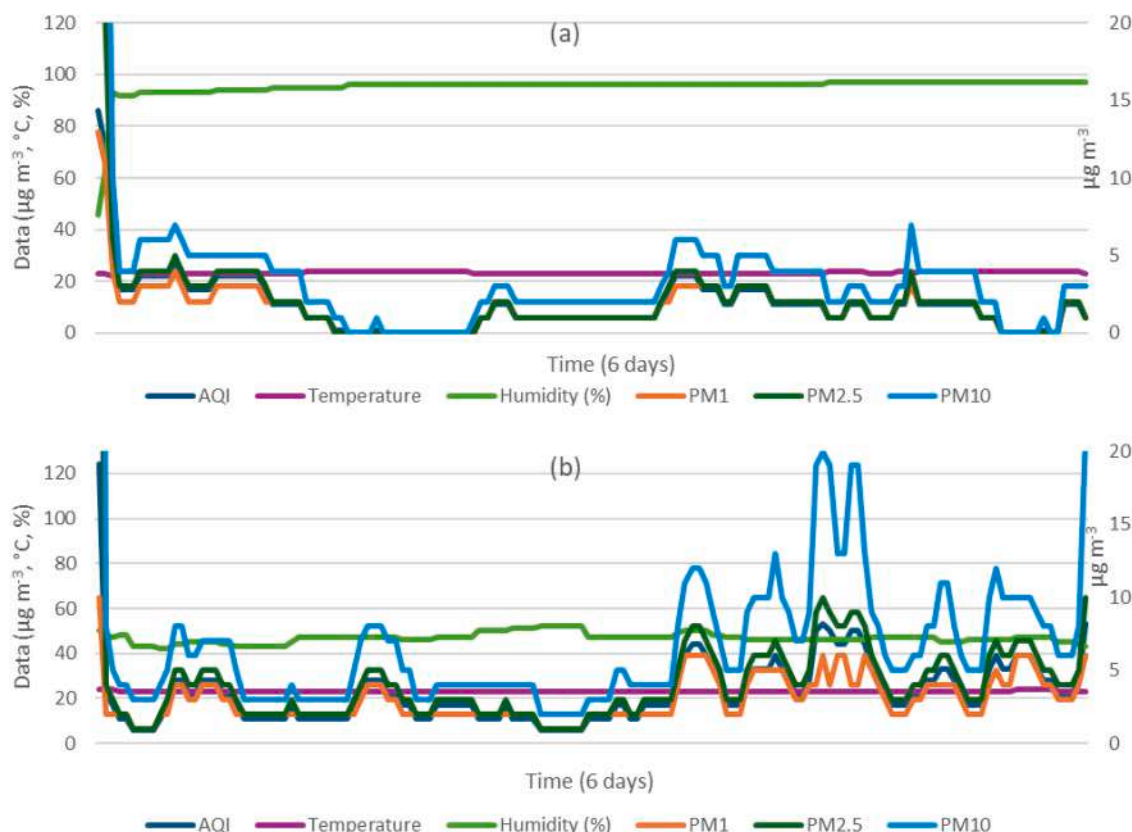


Fig. 7. Trend in concentration of AQI, PM₁, PM_{2.5} and PM₁₀ $\mu\text{g m}^{-3}$ inside the experimental chamber with the AGW installed (a) and in the control experiment (b). Curves related to AQI, temperature and humidity are referred to axis 1 (0–120) while curves related to PM₁, PM_{2.5} and PM₁₀ are referred to axis 2 (0–20).

in the control test. In contrast, with the AGW inside the chamber, humidity increased from 46% to a peak of 96%, due to the presence of plants. The humidity increase observed here was similar to the high values reported in some studies [53,54] but higher than the reported by others [29], where humidity remained between 45% and 70%, thanks to the introduction of calcium chloride, a hygroscopic salt, into the experimental chamber.

These results suggest that PM deposition inside the chamber took place under different microclimatic conditions than those registered in other GWs. In particular, the very high humidity strongly affected PM retention dynamics via wet-deposition processes, as demonstrated by the deeper penetration of particles into leaf micromorphological structures.

In both experiments, PM concentration values (and consequently AQI) peaked immediately after the injection of synthetic PM into the chamber (2 g of the same synthetic PM were injected at time 0). In the presence of the AGW, the initial post-injection concentrations were 13 $\mu\text{g m}^{-3}$ for PM₁, 28 $\mu\text{g m}^{-3}$ for PM_{2.5}, 64 $\mu\text{g m}^{-3}$ for PM₁₀ and an AQI of 86. In the control test, the concentration values in the same moment reached 10 $\mu\text{g m}^{-3}$ for PM₁, 45 $\mu\text{g m}^{-3}$ for PM_{2.5}, 126 $\mu\text{g m}^{-3}$ for PM₁₀ and an AQI of 124.

Shortly after injection, a rapid decrease of PM concentration was observed in both cases. This sharp reduction was due to the deposition of particles not only on plant leaf surfaces or on plastic features, but on every other surface within the chamber. In both experiments, in about one hour, the AQI and all PM fraction concentration values dropped to near zero and then fluctuated in the following hours and days. A similar exponential decay was also observed in other studies [29,55], which noted greater PM removal in the experiment with plants than in the control.

Throughout the experiments, all the PM fractions' concentrations and the AQI were significantly lower in the presence of the GW than in

the control experiment (Fig. 7a–b), demonstrating that plants effectively enhanced PM removal and improved indoor air quality inside the chamber. In particular, the presence of the plants reduced 45% of PM₁, 51% of PM_{2.5}, 50% of PM₁₀, calculated as the difference between the average value recorded by the IQAir in the control experiment and the average value recorded in the presence of AGW, while improving the AQI by 52% (Table 2).

Differences in the total PM mass between treatments were also assessed by analysing the PM accumulation deposition on the quartz air filters inside the chamber. In the control experiment, the air filters accumulated 3.8 mg of PM₁₀, compared with 2.4 mg in the experiment with GW, corresponding to a reduction of 1.4 mg (36.8%). These results are consistent with previous studies, which, reported PM concentration reductions due to the presence of plants of 24.8% [56], 53.4% [57] and 42.6% [30], or even between 40% and 75% [29,53]. However, some of these studies assessed PM filtration in a single air pass rather than filtration efficiency in recirculation mode, which is higher as it is repeated over time.

It should be noted that in our study, control treatment was designed to compare the overall PM removal performance of the AGW system with that of an inert vertical surface under similar airflow conditions. However, the AGW should be considered as an integrated biofiltration system composed of plant foliage, the polyamide support structure, the

Table 2

Mean concentration ($\pm$ standard error) of particulate matter size fractions (PM₁, PM_{2.5}, PM₁₀) expressed in $\mu\text{g m}^{-3}$ and Air Quality Index (AQI) along the six days experiment in the chamber with and without an active green wall.

Treatment	AQI	PM1	PM2.5	PM10
Control	22.32 $\pm$ 1.21	3.01 $\pm$ 0.13	4.17 $\pm$ 0.34	7.31 $\pm$ 0.89
AGW	10.72 $\pm$ 0.92	1.66 $\pm$ 0.13	2.04 $\pm$ 0.25	3.64 $\pm$ 0.54

expanded-clay substrate, the irrigation water and the root zone, all of which might contribute to PM removal. Similar interactions occur in passive green walls, where PM deposition is not restricted to leaf surfaces but may also take place on the substrate and structural components. Therefore, the present experimental design does not allow to quantify separately the relative contribution of each AGW component which is somehow a limitation. In particular, the irrigation system and the associated increase in humidity may have enhanced PM deposition and retention. Consequently, the PM removal values reported here should be interpreted as the performance of the complete AGW system rather than the effect of the plant component alone. Overall, the AGW experiment demonstrates that microclimatic conditions can affect PM removal processes. The combination of forced airflow and elevated humidity not only enhanced PM removal from the chamber atmosphere but also altered deposition dynamics compared with the passive systems. These findings support the hypothesis that microclimatic modifications associated with active green walls can significantly improve air purification performance and should therefore be considered alongside plant selection when designing phytoremediation systems.

4. Conclusions

The results addressed the three objectives of this study. First, PM accumulation patterns differed among species, but species rankings changed across green wall systems, indicating that PM retention cannot be explained by morphology alone and is strongly influenced by environmental and microclimatic conditions. Second, species-specific associations with PTEs suggest that physicochemical interactions occurring in the phyllosphere contribute to PM retention, although these relationships were highly context-dependent and did not reveal universal species-element patterns. Third, the AGW improved indoor air quality and PM removal efficiency, highlighting the importance of humidity and forced-air conditions in determining PM capture performance.

PM capture efficiency varied with climatic and environmental conditions but no clear relationship between PM accumulation levels and macromorphological traits (limited to the parameter relating to the ratio between leaf perimeter and area) was found. Therefore, it is not possible to propose guidelines for plant species selection that might be valid for all vertical systems. A reasonable strategy is to prioritise species adapted to the microclimatic context, tolerant to air pollution, and characterised by a combination of different micromorphological and macromorphological traits.

The contrasted behaviour of *N. exaltata* across GWs illustrates how species may shift from low to high-performance depending on the dominant deposition regime, reinforcing that microclimatic drivers can outweigh morphological predictors. In some cases, the absence of discrimination among species related to elemental composition suggests that the PM deposited in the three GWs shared similar chemical characteristics, and that differences were mostly related to the amount of PM retained rather than to its composition.

The active green wall substantially reduced indoor PM concentrations—by 45% for PM₁, 51% for PM_{2.5}, and 50% for PM₁₀—and improved the AQI by 52%. However, these values must be contextualized within the specific environmental conditions of the chamber, where the reduced volume and high quantity of injected particles produced unusually high humidity and pollution levels compared with typical indoor environments. To better reproduce real conditions in future experiments, the use of humidity-controlling materials such as hygroscopic salts may be advisable.

Furthermore, these results should also be contextualized in relation to the period during which the experiments were conducted (September 2024–February 2025), which encompasses the autumn and winter seasons but not spring and summer. In Mediterranean climates, seasons are very different in terms of atmospheric conditions, which can affect plant physiological performance, the physicochemical characteristics of atmospheric pollutants and, consequently, plant–PM interactions and PM

accumulation efficiency. Therefore, further studies covering the entire annual cycle are needed to determine whether the observed patterns remain consistent across seasons and under different environmental conditions.

From an applied perspective, the results suggest that species selection should be adapted to the specific type of green wall and its microclimatic conditions. Under the conditions tested, *C. comosum* showed the highest PM accumulation in the outdoor and indoor passive systems, whereas *T. zebrina* and *N. exaltata* performed particularly well in the AGW. These findings indicate that species performance may vary substantially according to the environmental context and deposition regime. Therefore, selecting species based on their performance under conditions comparable to the intended application may be more effective than relying solely on morphological traits. Although the present results provide useful indications for preliminary species selection, further studies under a wider range of environmental conditions are needed before general recommendations can be established.

In conclusion, GWs proved to be effective experimental systems for comparing different species under shared environmental conditions and for assessing their potential to retain particulate matter and contribute to indoor air quality improvement. These findings highlight the importance of integrating species traits with environmental and microclimatic factors when designing and implementing green walls as nature-based solutions for air pollution mitigation.

CRedit authorship contribution statement

Alessandro Campiotti: Writing – original draft, Investigation, Formal analysis. **Antonio José Fernández-Espinosa:** Writing – review & editing, Validation, Methodology, Data curation. **Carlo Calfapietra:** Funding acquisition. **Luis Pérez-Urrestarazu:** Writing – review & editing, Resources, Conceptualization. **Rafael Fernández-Cañero:** Writing – review & editing, Writing – original draft, Software. **Sabina Rossini-Oliva:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization, Data curation. **Chiara Baldacchini:** Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.buildenv.2026.115347](https://doi.org/10.1016/j.buildenv.2026.115347).

Data availability

Data will be made available on request.

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