

Report Luglio 2023

Monitoraggio sull'efficacia di specie vegetali di un sistema di verde verticale in termini di raccolta delle polveri sottili al fine di monitorare gli effetti delle soluzioni proposte dai laboratori CAL (ovvero Clever Action Lab) nell'ambito del Progetto Europeo "CLEVER Cities – Co-designing Locally tailored Ecological solutions for Value added, socially inclusivE Regeneration in Cities

Sito di riferimento: Deposito ATM Giambellino, Milano

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Introduction

Air quality in urban areas is fundamental for people well-being, since air pollution represents one of the environmental issues with the highest impact in terms of mortality and morbidity in Europe and worldwide (Forouzanfar et al., 2016; Gaglio et al., 2022), which has caused 412,000 premature deaths in 2018 (EEA, 2019; HEI, 2018). The main source of urban pollution is currently represented by road traffic (DEFRA, 2017; Karagulian et al., 2015). Although the gradual transition to electric will lead to a decrease in the exhaust components, it will not, however, decrease the sources of particulate matter (PM_x), produced by the vehicles' friction points and of them with the road (e.g., tires, brakes, resuspensions) (Air Quality Expert Group, 2019; Pearce et al., 2021).

Under the European Green Deal's Zero Pollution Action Plan (European Commission, 2021), the European Commission set the 2030 goal of reducing the number of premature deaths caused by fine particulate matter (PM_{2.5}, a key air pollutant), by at least 55% compared with 2005 levels (EEA, 2008). Consequently, it is mandatory reduce the emission from one side and mitigate the air pollution from the other side to improve life quality in urban areas.

Plant communities and their assemblages (i.e., vegetation) in urban areas provides several ecosystem services, among which air quality improvement (Muhammad et al., 2019), through their ability to capture PM_x by deposition on leaves and stems (Grote et al., 2016; Ysebaert et al., 2021). Nature-based Solutions (i.e., actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature, (IUCN, 2016), especially urban forests and green facades (due to their position near to the vehicle emissions), can contribute to the reduction of PM_x in urban areas (Abhijith and Kumar, 2020; Perini et al., 2017; Tong et al., 2015). In highly urbanised and contaminated contexts, such as that of Milan (European Environment Agency, 2022) the use of Nature-based Solutions (NbS) can play a key role in increasing local biodiversity (European Commission, 2020), restoring the functionality of ecosystems altered by humans, increasing their resilience, and bringing measurable environmental, social and economic benefits, like mitigation of air pollution.

Instead, the presence of trees along the roads, depending on the urban morphology can increase the local pollution concentration, due to the decrease in air flows caused by their presence, specifically in an urban canyon (Tong et al., 2015). On the other hand, the use of green facades can

overcome this problem, allowing free air flows inside the urban canyons (Ysebaert et al., 2021). Furthermore, the spatial location of the green facades (i.e., proximity to the road and to the sources of vehicular emissions) and the choice of performing plant species (Perini et al., 2017) can allow optimizing their absorption capacity of PM_x (Ysebaert et al., 2021). Indeed, several studies have already assessed the ability of higher plants to collect fine dust (Muhammad et al., 2019; Perini et al., 2017; Przybysz et al., 2021; Sgrigna et al., 2020).

In addition to the several benefits of vertical greening systems, studies highlight also limitations to their widespread use in the urban environment, in particular in relation to high costs and maintenance needs (Ottelé et al., 2011; Rakhshandehroo et al., 2015; Rosasco and Perini, 2019). However, current approaches for the mitigation of air pollution rely on a massive use of plants (e.g., urban forestry, green facades (Ottelé et al., 2010; Perini et al., 2017), and vertical greening systems can positively contribute as small-sized systems that can be applied in spots within the urban fabric (Villani et al., 2021).

Objectives of the monitoring activity

This monitoring activity, commissioned by the Municipality of Milan (Italy), focuses on the assessment of the ability to capture PM_x by four different plant species within a living wall, 10 months before the installation of this NbS on the building of the Azienda Trasporti Milanesi 'deposito Giambellino' located in Via Giambellino 121, Milan, in the frame of the CLEVER CITIES project to evaluate air pollution mitigation at the building scale.

The main aims of the study can be summarised as follows:

- To evaluate the PM_x capture by four different plant species in terms of PM_x number of particles and diameters, i.e., if the collection capacity varies depending on the species, in relation with morphology of leaves.
- To evaluate if and how position and distance from a contamination hotspot (stop at the traffic light) could affect PM_x deposition and removal by the four different plant species.

Materials and methods

Study area

Milan's [Giambellino district](#) (Fig. 1) was constructed in the first half of the twentieth century from the extension of the industrial area of Porta Genova, due to the proximity of the Naviglio Grande and the Milan-Mortara railway. The district was conceived as an industrial area that accommodates workers' houses, but after the Second World War the first underground line was built on the northern edge of the area. The district develops with south-north and east-west directions, starting from the city center and the communication routes on which the factories were born, until it reaches a considerable density, retaining an extremely significant share of public housing. The historical site of the 'deposito Azienda Trasporti Milanesi - ATM' (Fig. 1) hosts about 300 vehicles and 500 workers.



Figure 1. Location and site of the 'deposito ATM', Via Giambellino 121, Milan (Italy). Giambellino area within the city; location of the bus station and previous appearance of the building before installing the living wall, where section 1 and 3 will subsequently be covered by green wall and section 2 covered with an informative panel (credit: Paolo Pignataro).

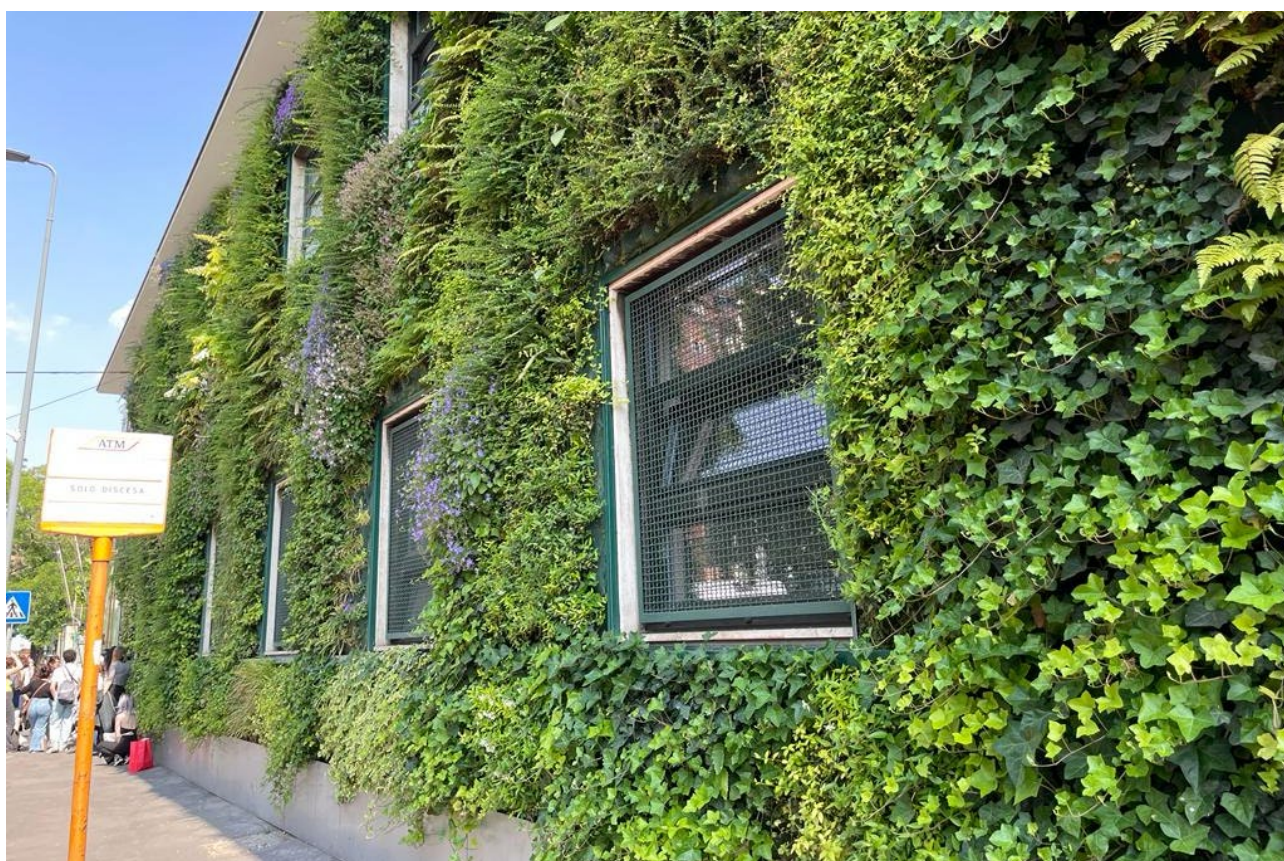


Figure 2. Giambellino green wall, Via Giambellino 121, Milan (Italy), 'deposito ATM Giambellino' on the sampling day, 22 March 2023

Giambellino's green wall (Fig. 2) is the first green envelope installation to be created in Milan thanks to the European CLEVER Cities programme, which funded the design within the Horizon2020 project. The City of Milan's BE2 announcement funds 35% of the green wall total costs. The façade, 75 meters long and 8 meters high, hosts 350 m² of vertical green wall with more than 10,000 plant individuals belonging to 24 different *taxa* (Fig. 3).

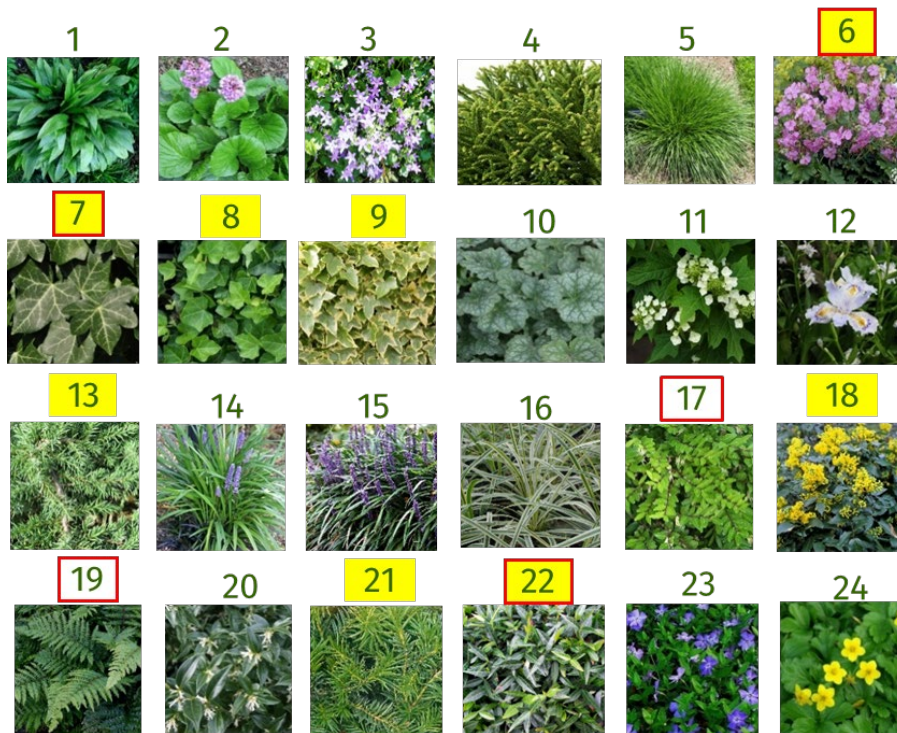


Figure 3 Plant *taxa* used for the greening of the living wall. Highlighted yellow, *taxa* with documented ability to capture PM_x (Perini et al., 2017; Perini and Roccotiello, 2018; Viecco et al., 2018; Weerakkody et al., 2018, 2017). In red, sampled *taxa* (images courtesy of P. Pignataro).

Plant species selection

Plant species were selected based on their coverage percentage, representativeness on the living wall and different macro- and micromorphological characteristics (Fig. 4, sampling scheme) that could affect different level of PM_x capture (Perini et al., 2017; Perini and Roccotiello, 2018; Viecco et al., 2018; Weerakkody et al., 2018, 2017).

Based on this, the species selected for this purpose were: *Hedera helix* L. 'Ibernica', *Trachelospermum asiaticum* Nakai 'Angustifolium' (syn. *T. angustifolium*), *Lonicera ligustrina* var.

yunnanensis Franch. Maigrun (syn *Lonicera nitida*), *Polystichum luctuosum* (Kuntze) T. Moore (syn *Polystichum poliblefarum*).

A nomenclature check based on current taxonomic determination was carried out on the different plant *taxa*; sampled plant *taxa* are underlined (Tab. 1).

n.	<i>Taxa on the Giambellino living wall</i>
1	<i>Aspidistra elatior</i> Blume
2	<i>Bergenia crassifolia</i> var. <i>crassifolia</i> 'Purpurescens'
3	<i>Campanula poscharskyana</i> Degen 'Blue'
4	<i>Cryptomeria japonica</i> (Thunb. ex L.f.) D.Don 'Little Diamond'
5	<i>Deschampsia cespitosa</i> (L.) P.Beauv. 'Scotland'
6	<i>Geranium x cantabrigiense</i> P.F.Yeo 'Karmina'
7	<u><i>Hedera helix</i> L. 'Ibernica'</u>
8	<u><i>Hedera helix</i> L. 'Ibernica Mini'</u>
9	<u><i>Hedera helix</i> L. 'Gold Child'</u>
10	<i>Heuchera americana</i> L. 'Dales Strain'
11	<i>Hydrangea quercifolia</i> W.Bartram 'Snow Queen'
12	<i>Iris japonica</i> Thunb.
13	<i>Juniperus communis</i> L. 'Repandens'
14	<i>Liriope muscari</i> (Decne.) L.H.Bailey 'Majestic'
15	<i>Liriope muscari</i> (Decne.) L.H.Bailey 'Evergreen Giant'
16	<i>Liriope muscari</i> (Decne.) L.H.Bailey 'Silvery Sunproof'
17	<u><i>Lonicera ligustrina</i> var. <i>yunnanensis</i> Franch. 'Maigrun'</u>
18	<i>Berberis aquifolium</i> Pursh 'Apollo'
19	<u><i>Polystichum luctuosum</i> (Kunze) T.Moore</u>
20	<i>Sarcococca hookeriana</i> var. <i>digyna</i> Franch.
21	<i>Taxus baccata</i> L. 'Repandens'
22	<u><i>Trachelospermum asiaticum</i> (Siebold & Zucc.) Nakai 'Angustifolium'</u>
23	<i>Vinca minor</i> L. 'Big Blue'
24	<u><i>Waldsteinia ternata</i> (Stephan) Fritsch</u>

Table 1. Plant *taxa* used for the greening of the living wall in Milan's Giambellino district. Species documented as PMx accumulator, selected in the greening phase for this aim, are marked in bold; the selection of sampled *taxa* (underlined) was based on their representativeness on façade, documented ability to capture PMx and biomass development and phenological stage.



Plant sampling

Given the wall structure and plants distribution, 60% of the individuals of the 4 species were sampled on the left section of the façade, closer to the traffic light, and 40% of the individuals were sampled on the right section, about 60-75 meters away from the former. The sampling was performed during a single day, on March 16th 2023, about 10 months after the construction of the Giambellino green wall. Plants were sampled at three different heights from the ground: 1-2 m (pedestrian height), 3-4 m and 5-6 m (sampling height classes: 1, 2 and 3 respectively), excluding borders to avoid margin effects (Fig. 4). For each of the 4 species, 10-20 leaves were collected (Fig. 5). To exclude the possibility of contamination after sampling, the leaves of each specimen were stored and sealed in a dedicated labelled plastic bag.

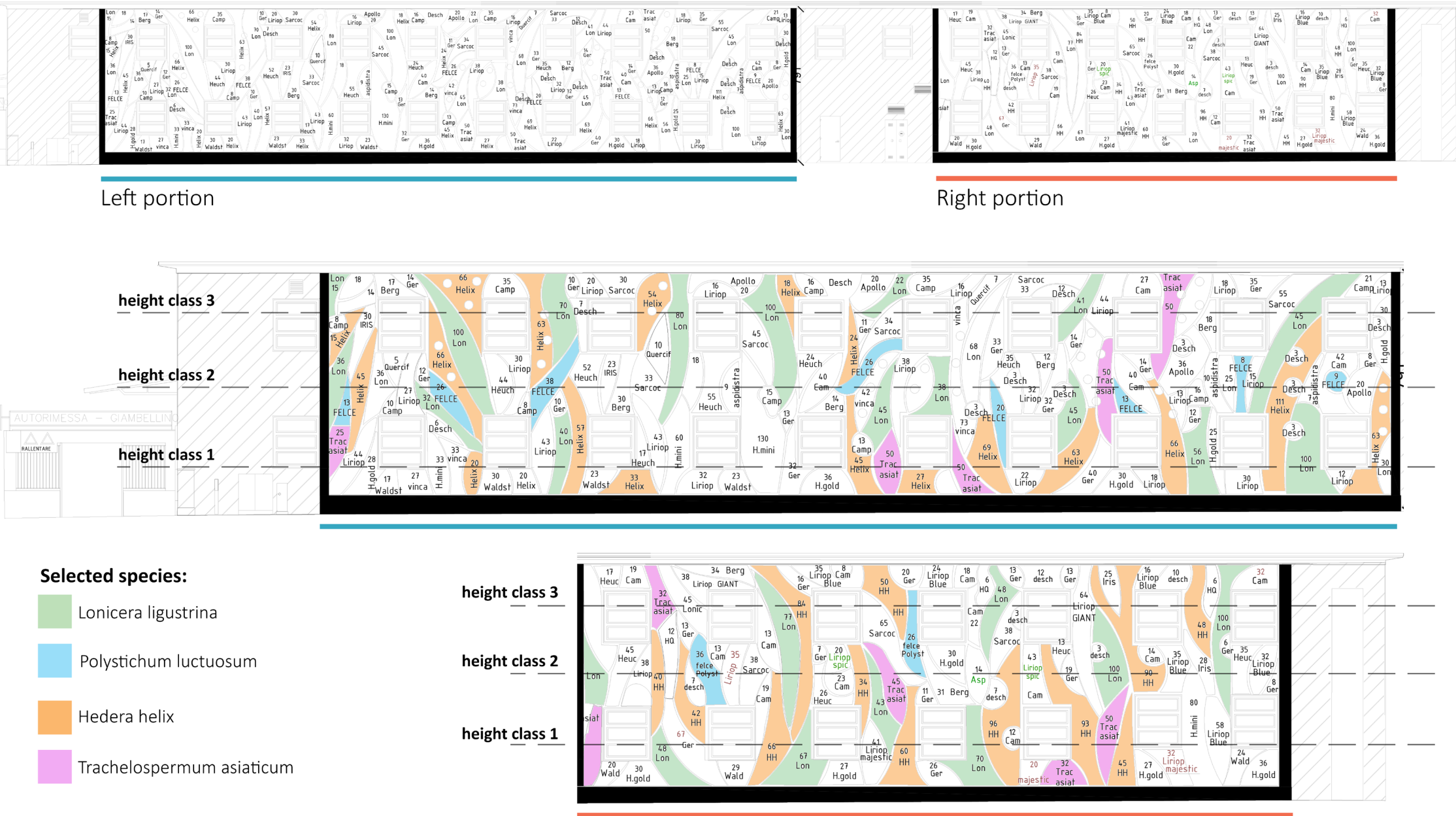


Figure 4. Green wall analysis scheme, identification of the species and sampling heights, facade drawing by Paolo Pignataro (modified).



Figure 5. Plant leaf sampling along the whole living wall, 4 *taxa* at three different heights from the ground; sampling of the 16th of March 2023.

Sample preparation

At the laboratory, all the leaves were visually inspected, photographed, and selected under a stereomicroscope Leitz(sche) Camera (LEICA, Wetzlar, Germany) application suite (LAS EZ) software (Fig. 6). A subsample of 2x2 cm of 10 leaves for each of the 4 selected species was subsequently prepared for Scanning Electron Microscopy (SEM) analysis, fresh-mounted onto a 0.22 μm polycarbonate filter on aluminium stubs (Fig. 7), oven-dehydrated at 35°C for 24 h and sputter coated with graphite using a precision etching coating system (Emitech K950), to preserve them, avoiding any artifact or powder loss. The Coater applies sputter graphite conducting layers on to scanning electron microscope samples to prevent charging effects. Sputtering happens at high rate with minimal specimen heating.

Prepared leaves were subsequently analysed at electron microscopy core facility of the Department of Earth Environment and Life Sciences (DISTAV) at the University of Genoa.

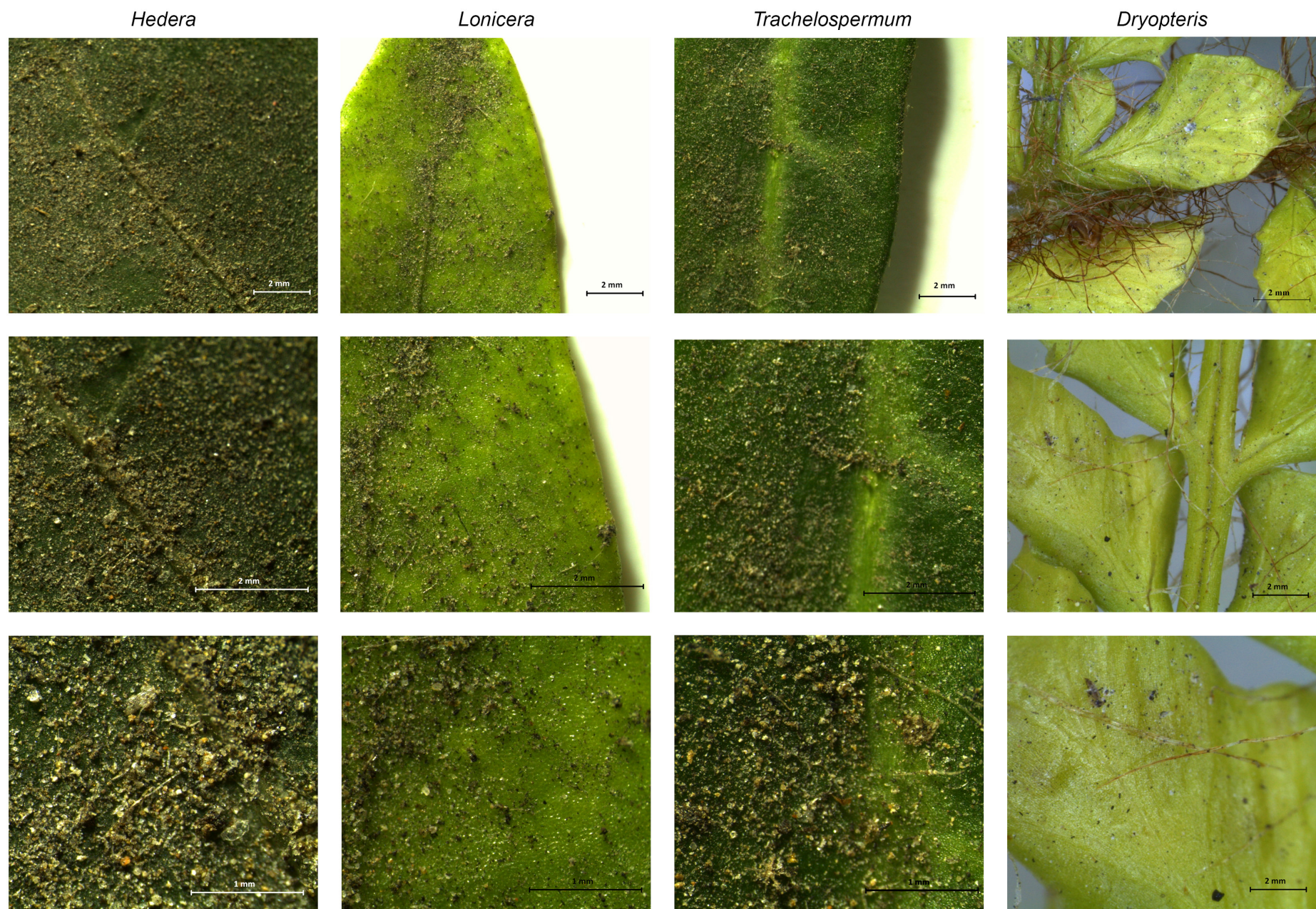


Figure 6. Stereomicroscopic evaluation of leaves and first screening of samples for SEM analysis. *Hedera helix* 'Ibernica' (HH), *Trachelospermum asiaticum* 'Angustifolium' (TA), *Lonicera ligustrina* var. *yunnanensis* (LL), *Polystichum luctuosum* (PL).

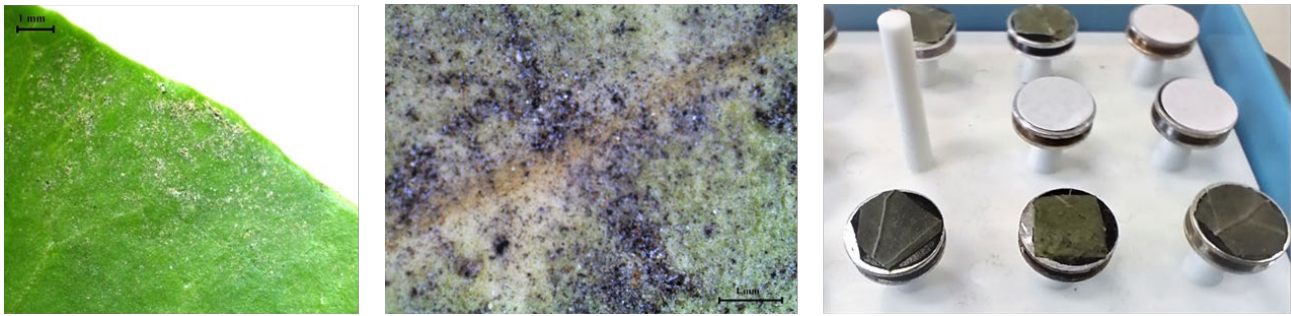


Figure 7. Plant leaf selection under stereomicroscope, evaluation of PM_x capture, and mounting on aluminium stubs for dehydration.

Scanning Electron microscopy EDX analysis

The aim of this task was counting fine and ultrafine dust particles on Scanning Electron microscopy (Vega 3 LMU electron microscope) micrographs.

During SEM analyses, three, non-overlapping, randomly chosen spot per leaf were photographed (4 species, 3 positions per leaf, 3 magnifications, 10 leaf per magnification) for a total of 120 micrographs (100×, 250×, 500× magnifications) taken to assess PM_x deposition on leaf epidermis. To evaluate the number and dimension of dusts, the counting method (Ottel   et al., 2010) was used.

Data analysis

The software Image J (<http://imagej.nih.gov/ij/>) was used to count and measure the particles found on each magnification (100×, 250×, 500×, respectively). Image J allows creating binary images and distinguishing particles from the leaf epidermis (background), with the threshold function. Once overlapping particles are separated, with the function watershed, particle size and number are analysed. Image J counts particles, their relative area and average Feret diameter (i.e., the longest distance between any two points along the selection boundary, also known as maximum caliper). To provide an overview on the number of deposited particles on the analysed leaves, different magnifications are used to count the following particle sizes: 100× for particles > 10 µm, 250× for particles 2.5–10 µm, 500 for <2.5 µm. Weighting factors were used to compensate the loss of

counting area due to the zoom in 250× and 500×. Considering all the particles counted on each magnification (100%), the number of particles of different size were counted, e.g., >20 µm or <2.5 µm.

Additionally, as leaf papules were difficult to remove from binary images from several samples of *T. asiaticum* (TA), we measured two perpendicular diameters of 20 papules for each of the different magnifications. These diameters were then averaged, and the range of average TA papule diameter was recorded to be used later as a filter in the analytical process.

Statistical Analysis

The performances of the four different plant species under the same conditions (pollution exposition and weather conditions) were compared and height from the ground and position within the façade were used as secondary predictive variables to assess their potential effect on particles deposition on leaf surface. R studio v (RStudio Team, 2020) was used to import, merge, and analyse the outputs of Image J. We generated two sets of data, one including all particles data and one where we subtracted the particles in the range 2.5-3.5 µm from TA samples, to correct for papules effect. Subsequently, we divided the particles into discrete diameter classes (<0.5 µm; 0.5-1 µm; 1-1.5 µm; 1.5-2 µm; 2-2.5 µm; 2.5-5 µm; 5-7.5 µm; 7.5-10 µm; >10 µm) based on their environmental and health importance. For both generated data sets, we calculated the number of total particles, as well as the number of the particles in each category for each sample and then divided it by the sampled leaf area to obtain the relative numbers of particles for mm² that was subsequently used for testing for statistically significant differences between species. Finally, since our secondary predictor variables (sampling height and façade position) were nested within species (i.e., we assume that particles capturing is first linked to intrinsic species features and then to their position in space) we performed a nested analysis of variance (ANOVA), a type of ANOVA in which at least one factor is nested inside another factor to assess differences within species by sampling height and by façade position respectively. To this aim we used the function `aov` of the stats R package, using the syntax '`aov(response ~ factor A / factor B)`' to indicate that the second predictor variable (either sampling height or façade position) factor B is nested within factor A (species).

Results and Discussion

The analysis on the particle deposition (Fig. 8) on *Hedera helix* 'Ibernica' (HH), *Trachelospermum asiaticum* 'Angustifolium' (TA), *Lonicera ligustrina* var. *yunnanensis* (LL), *Polystichum luctuosum* (PL) leaves shows their peculiar macro- and micromorphology and a concentration of particles in relation to their position on the green wall.

For both analysed datasets, TA showed consistently the highest number of particles of diameter up to ca. 12 μm (Fig. 9). In addition, in the papules corrected data, the removal of particles between 2.5 and 3 μm in TA only exacerbated a negative peak that is also evident in the non-corrected data. For this reason, only corrected data is presented hereafter. In all species curves upward peaks in correspondence with certain diameter values are evident and coherent (Fig. 9) and overall, after TA, PL and HH were the species with the highest number of particles across the range up to 12 μm (Fig. 9). Although towards the higher end of the diameter values the curves are overlapping, slightly higher values of particle accumulation are noticeable for LL in this part of the spectrum. Notably, PL was the only species showing a moderate downward peak in correspondence with particles of diameter around 3 μm . More in detail, concerning the accumulation peaks by particle size, at particle size of ca. 1.5 μm (first peak from the left, Fig. 9), TA was the species that accumulated more particles, followed by PL, HH and the LL; at particle size of around 4 μm , both TA and HH performed best, followed by LL and PL. At higher particle sizes, TA was the species scoring the highest number of particles, followed by HH, LL and PL of ca. 6 μm and by LL, HH and PL at particle size of ca. 8 and 10 μm .

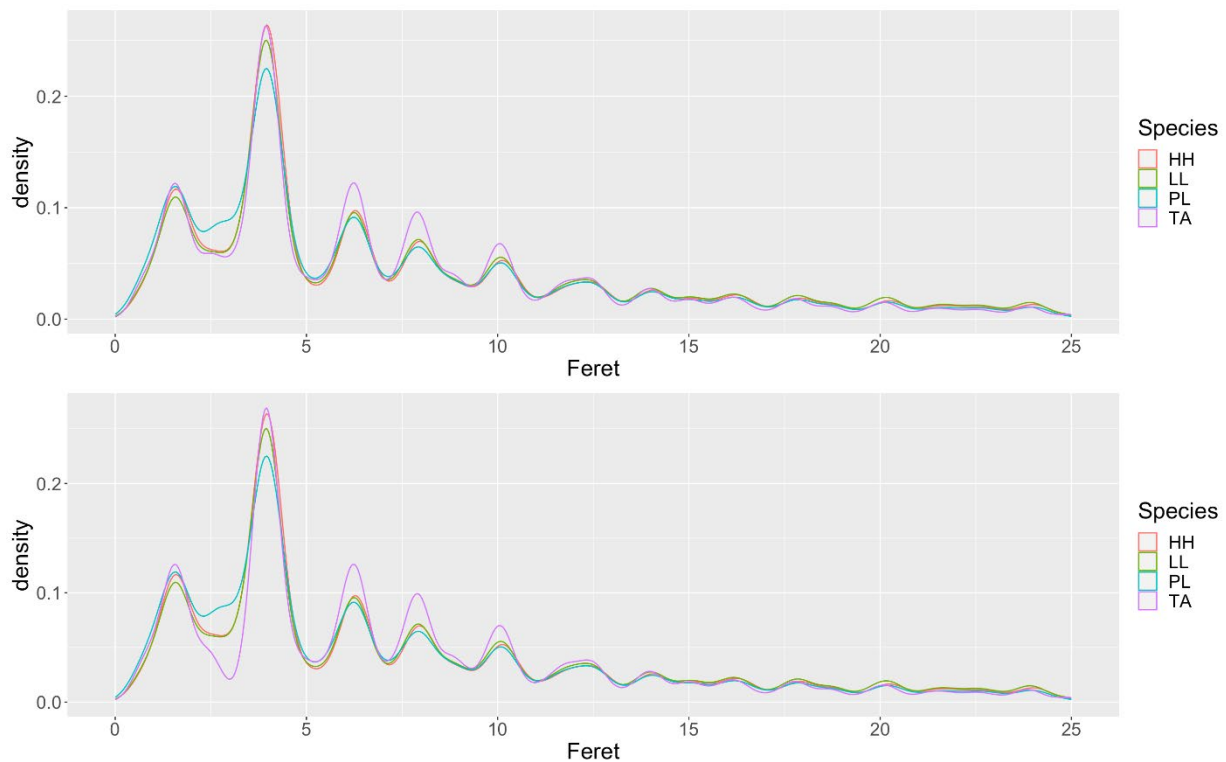


Figure 9. Density plot of particle diameter (Feret), colour coded by species. The upper frame shows the dataset without papules correction and the lower frame shows the corrected dataset. *Hedera helix* 'ibernica' (HH), *Trachelospermum asiaticum* 'Angustifolium' (TA), *Lonicera ligustrina* var. *yunnanensis* (LL), *Polystichum luctuosum* (PL).

Trachelospermum asiaticum was the best performing species in overall PM capture for all particles classes; the overall capture ability of the four species can be synthetised as $TA > PL > HH > LL$, where TA, PL and HH had similar trends from fine particles up to PM₁₀ capture, while LL proved more effective in capturing the coarse fractions (PM₂₅). Similarly to our findings, a recent paper highlighted the ability to capture particulate matter by TA thanks to its peculiar epidermic micromorphology, even if in a simulation chamber (Jeong et al., 2021). In addition, TA's leaf micromorphology is similar to *T. jasminoides*, a well-documented dust accumulator (Perini et al., 2017; Perini and Roccatiello, 2018). The nested ANOVA retrieved no significant differences in total particle number between species ($F(4,3) F = [1.617], p = [0.191]$) and sampling height ($F(12, 7) F = [0.261], p = [0.967]$), nor between species ($F(4,3) F = [1.645], p = [0.184]$) and position on façade ($F(8, 4) F = [0.115], p = [0.977]$), with a total accumulation up to ca. 15000 particles for HH, LL and PL and

up to ca. 20000 particles/ mm² for TA , overall, much higher than what reported by previous studies (Perini et al., 2017) where the highest values were up to 6000 particles/ mm².

However, statistically significant differences between species were retrieved when comparing the different particles categories (Table 2). Significant differences between species were found for categories 0.5-1 µm; 1-1.5 µm; 1.5-2 µm; 5-7.5 µm; 7.5-10 µm; >10 µm (Table 2).

Interestingly, significant differences were found for all particles' class except for 2-5 µm, underlying different capture abilities for fine and mildly coarse and coarse dust. This can suggest a different leaf composition at the epidermal level that allows better performances in fine dust capture.

However, this result might also be related with the exclusion of the particle class between 2.5 and 3 in TA, even if a lower peak between 2.5 and 3.5 µm was evident before the correction compared with the other species. Since all the selected species showed thick cuticles, waxes or ornamented leaf epidermis, they have all the necessary leaf traits for an effective PM_x removal, especially PM₁ and PM 2.5 (Redondo-Bermúdez et al., 2021).

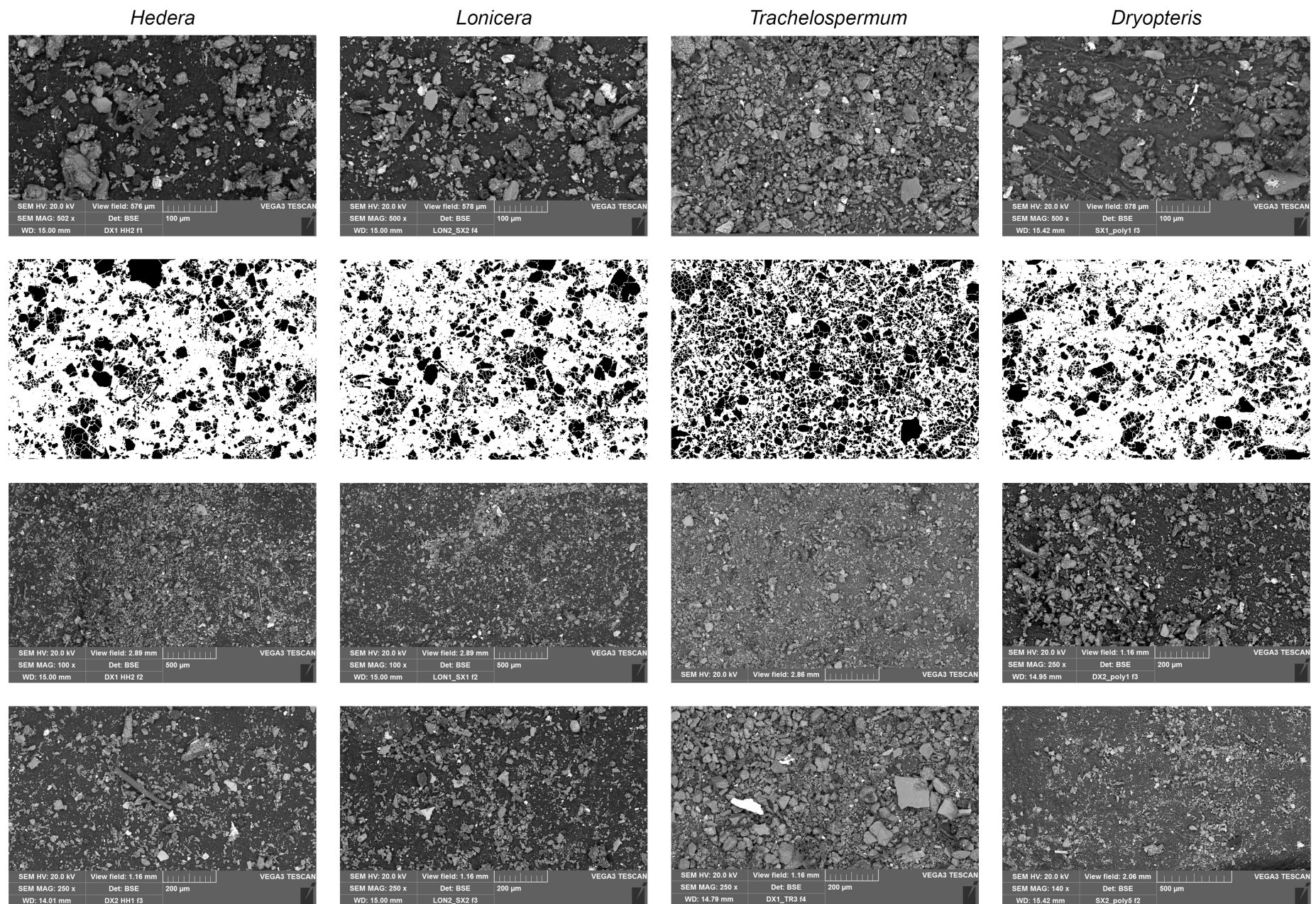


Figure 8 Leaf samples analysed with the Scanning electron Microscope at 100, 250, 500X magnification, respectively, and related binarized samples at 500X for each species: *Hedera helix* 'Ibernica' (HH), *Trachelospermum asiaticum* 'Angustifolium' (TA), *Lonicera ligustrina* var. *yunnanensis* (LL), *Polystichum luctuosum* (PL).

variables	Df	Sum Sq	Mean Sq	F value	Pr(>F)	variables	Df	Sum Sq	Mean Sq	F value	Pr(>F)
totparticle number						totparticle number					
SP	3	164700000000	54909413	1.617	0.191	SP	3	164700000000	54909413	1.645	0.184
sampling_height	7	62010000000	8858902	0.261	0.967	position	4	15330000000	3832980	0.115	0.977
Residuals	93	315800000000	33954417			Residuals	96	320400000000	33379595		
0.5-1						0.5-1					
SP	3	12171993	4057331	6.371	0.00249 **	SP	3	12171993	4057331	5.89	0.00314 **
sampling_height	7	4966919	709560	1.114	0.38643	position	4	1651984	412996	0.60	0.66613
Residuals	24	15283594	636816			Residuals	27	18598529	688834		
1-1.5						1-1.5					
SP	3	1538718	512906	4.500	0.0122 *	SP	3	1538718	512906	4.195	0.0147 *
sampling_height	7	865378	123625	1.085	0.4034	position	4	299716	74929	0.613	0.6570
Residuals	24	2735347	113973			Residuals	27	3301008	122260		
1.5-2						1.5-2					
SP	3	3521191	1173730	3.346	0.025 *	SP	3	3521191	1173730	3.173	0.0303 *
sampling_height	7	3153894	450556	1.285	0.274	position	4	910635	227659	0.615	0.6532
Residuals	59	20694543	350755			Residuals	62	22937803	369965		
2-2.5						2-2.5					
SP	3	1382901	460967	1.281	0.292	SP	3	1382901	460967	1.233	0.308
sampling_height	7	3010059	430008	1.195	0.324	position	4	1234420	308605	0.825	0.515
Residuals	47	16919108	359981			Residuals	50	18694747	373895		
2.5-5						2.5-5					
SP	3	284817	94939	0.081	0.970	SP	3	284817	94939	0.082	0.97
sampling_height	7	3353833	479119	0.409	0.895	position	4	1366530	341632	0.296	0.88
Residuals	93	108983500	1171866			Residuals	96	110970802	1155946		
5-7.5						5-7.5					
SP	3	10992501	3664167	3.605	0.0163 *	SP	3	10992501	3664167	3.700	0.0144 *
sampling_height	7	921030	131576	0.129	0.9959	position	4	370347	92587	0.093	0.9843
Residuals	93	94516550	1016307			Residuals	96	95067233	990284		
7.5-10						7.5-10					
SP	3	3968169	1322723	3.776	0.0132 *	SP	3	3968169	1322723	3.866	0.0117 *
sampling_height	7	760157	108594	0.310	0.9478	position	4	494508	123627	0.361	0.8356
Residuals	93	32581516	350339			Residuals	96	32847166	342158		
>10						>10					
SP	3	5745428	1915143	5.655	0.00133 **	SP	3	5745428	1915143	5.427	0.00172 **
sampling_height	7	4861430	694490	2.051	0.05675 .	position	4	2477656	619414	1.755	0.14425
Residuals	93	31493516	338640			Residuals	96	33877290	352888		

Table 2. Nested ANOVAs results by sampling height (right) and position on façade (left) for all particles categories.

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

While there were visually noticeable differences in particle deposition by sampling height and façade position (Fig. 10 and 11) these were not statistically significant and overall, their contribution to explained variance was negligible. However, sampling height was mildly significantly different in category >10 μm (Table 2), probably because heavier particles are less mobile along the façade height.

Further analysing statistical differences between species for each particles category (only performed for sampling height as nested factor since position effects were even more negligible), Dunn's (Bonferroni) t-test for multiple comparisons at a confidence interval of 95% (Tab. 3) found that the mean value of particles of class 0.5-1 μm was significantly different between TA and HH ($p = 0.0052$) and TA and LL ($p = 0.0132$). Significant differences between TA and HH ($p = 0.0335$) and TA and LL

($p = 0.0216$) were also evident for particle class 1-1.5 μm . Statistically significant difference was also found for particle class 1.5-2 μm between TA and LL ($p = 0.0278$), for particle class 5-7.5 μm between TA and HH ($p = 0.0424$) and TA and PL ($p = 0.0387$), for particle class 7.5-10 μm between TA and HH ($p = 0.0417$) and TA and PL ($p = 0.0206$) and for particle class $> 10 \mu\text{m}$ between TA and HH ($p = 0.0698$), PL and LL ($p = 0.0483$), and TA and PL ($p = 0.0013$). Moreover, for particle class $> 10 \mu\text{m}$, particle deposition was also significantly different between sampling height nested within species for PL sampled at height 2 (where the species is mostly present) and TA sampled at height 1 ($p = 0.00093$), and HH sampled at height 3 and TA sampled at height 1 ($p = 0.01554$) (Table 3, Fig. 10).

pairwise comparison difference		lower 95% C.I.	upper 95% C.I.	p-value
0.5-1				
TA-HH	1529.160	372.918	2685.403	0.0052 **
TA-LL	1256.718	202.538	2310.898	0.0132 *
1-1.5				
TA-HH	517.954	28.803	1007.104	0.0335 *
TA-LL	500.510	54.537	946.482	0.0216 *
1.5-2				
TA-LL	566.354	41.032	1091.677	0.0278 *
5-7.5				
TA-HH	814.825	17.450	1612.201	0.0424 *
TA-PL	771.928	25.170	1518.685	0.0387 *
7.5-10				
TA-HH	479.469	11.309	947.623	0.0417 *
TA-PL	488.501	50.060	926.943	0.0206 *
>10				
TA-HH	439.446	-20.832	899.723	0.0698 .
PL-LL	-418.097	-834.258	-1.935	0.0483 *
TA-PL	615.190	184.131	1046.249	0.0013 **
PL:2-TA:1	-807.925	-1421.590	-194.261	0.00093 ***
HH:3-TA:1	-1036.432	-1979.889	-92.977	0.01554 *

Table 3. Dunn's (Bonferroni) t-test for multiple comparisons at a confidence interval of 95% by sampling height for different particles categories. Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Only significantly different pairwise comparisons are showed.

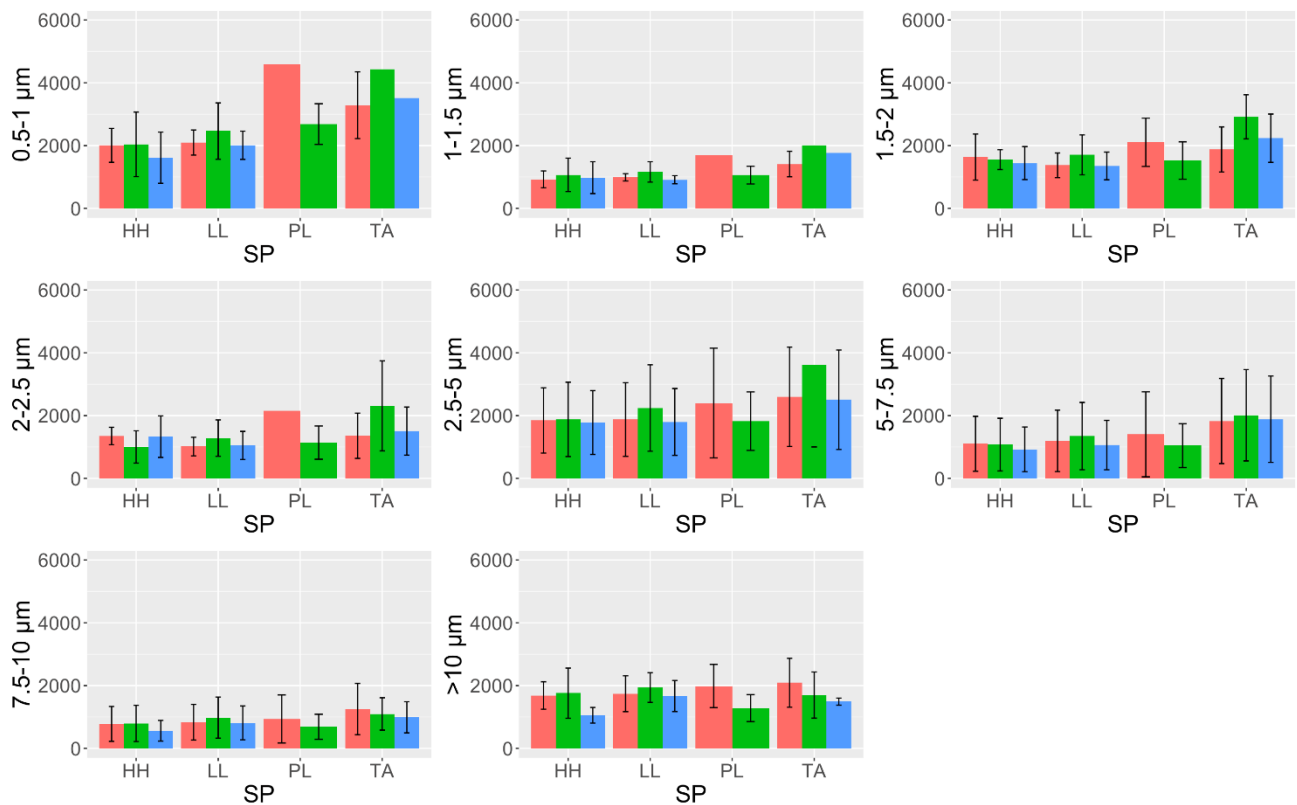


Figure 10. Barplot of different particles diameter categories by species and sampling height. The different sampling heights are colour coded as red = 1, green = 2 and blue = 3. Error bars display standard deviation. *Hedera helix* 'Ibernica' (HH), *Trachelospermum asiaticum* 'Angustifolium' (TA), *Lonicera ligustrina* var. *yunnanensis* (LL), *Polystichum luctuosum* (PL).

These results are comparable with Weerakkody et al. (2017) who quantified the number of particles collected by 17 species of a living wall system with values (per mm²) in the range of 2800-45 000 PM₁, of 1700-16 460 PM_{2,5}, of 500-3000 PM₁₀.

Concerning different accumulation at different sampling height, literature is scarce and sometimes contradicting. For instance, (Öttel et al., 2010) found no relations between the different harvesting heights (0.25- 2.5 m). However, this previous finding might also be related to the lower tested sampling height. However, a paper by Abhijith and Kumar (2020) highlighted that PM mass deposition and number concentration on the leaves on traffic-facing side was up to 36% and 58% higher at 0.6 m compared with 1.5m height, respectively. This supports our findings that clearly showed that leaf sampling height significantly influenced PM deposition for specific classes of particle size, especially particles > 10 µm, heavier and less mobile along the facade.

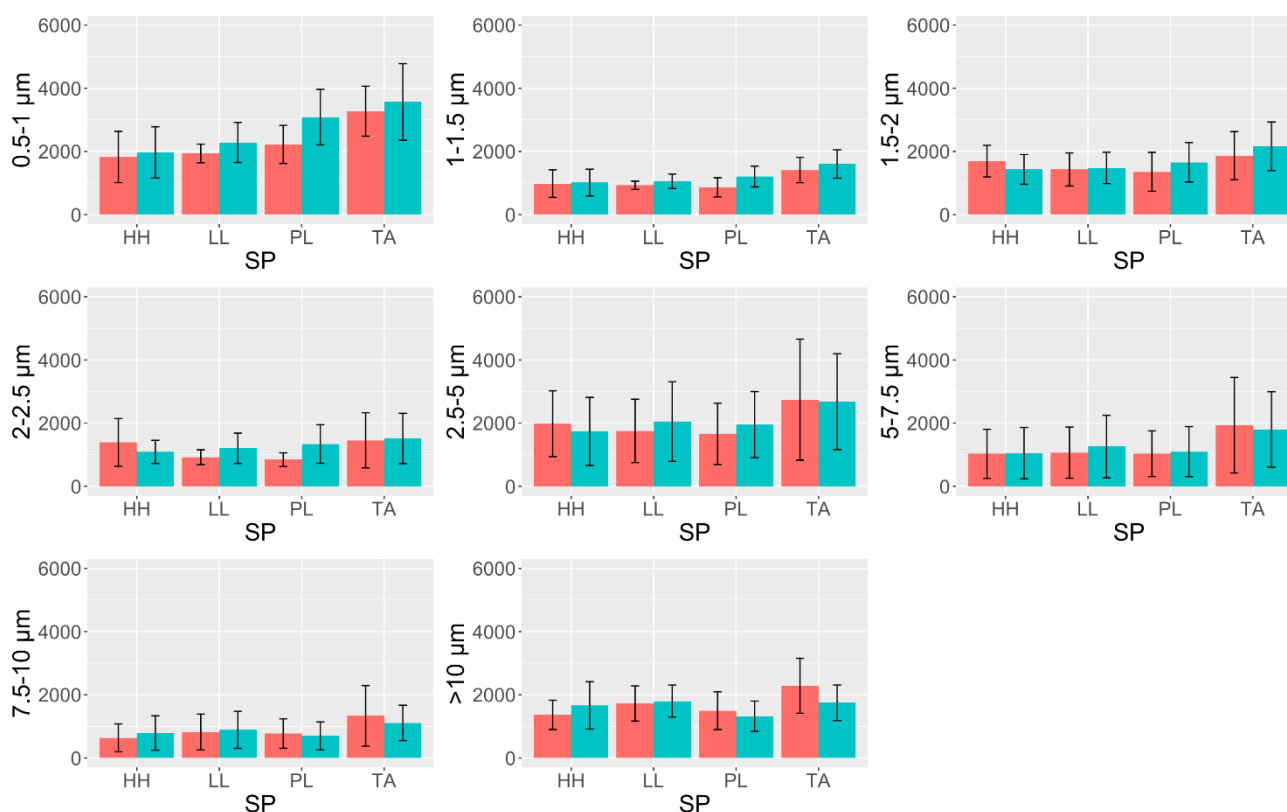


Figure 11. Barplots of different particles diameter categories by species and facade position. The two different positions are colour coded as red = DX, light blue = SX. Error bars display standard deviation. *Hedera helix* 'ibernica' (HH), *Trachelospermum asiaticum* 'Angustifolium' (TA), *Lonicera ligustrina* var. *yunnanensis* (LL), *Polystichum luctuosum* (PL).

Polystichum luctuosum is here documented for the first time as an effective species in PM_x capturing and seems promising species for green envelopes in relations with PM_x capture. The same is true for *Lonicera ligustrina*, that shows interesting potential for both green walls or different green arrangements like hedgerows, even if with a lower overall capture ability, than the other analysed species. *Hedera helix* is a well-known dust and fine dust collector, as confirmed by the current monitoring report, and in Milano Giambellino showed a higher rate of PM_x collection compared to previous studies (Ottel   et al., 2010; Perini et al., 2017), probably in relations with the highest concentration of PM_x in the study site.

Conclusions

The analysis on the plant species considered in the present monitoring activity, *Hedera helix*, *Lonicera ligustrina*, *Polystichum luctuosum*, *Trachelospermum asiaticum*, shows their ability to collect PM_x within the Giambellino green wall in Milan city.

The following main conclusions can be resumed:

- The four different plant species analysed showed different performances. *Trachelospermum asiaticum* is the best performing species in overall PM_x capture for all particle size classes; the capture ability of the four species is TA>PL>HH>LL.
- The collection capacity of PM_x can be related to their species-specific shape of leaves, depending on the leaf micromorphology, and does not show any relation with the distance to contamination hotspot (vehicle stop at traffic light). Also in this case T. asiaticum is the best performing species thanks to its leaf morphology.
- Single differences between species can be found in relations to sampling height, generally higher at 1-4 m sampling for fine dust and lower at 5-6 m height for coarse dust (PM₁₀>PM_{2.5}).
- The four species are confirmed to be effective for PM_x removal, specifically fine dust (PM₁₀).

Bibliography

- Abhijith, K.V., Kumar, P., 2020. Quantifying particulate matter reduction and their deposition on the leaves of green infrastructure. *Environ. Pollut.* 265, 114884.
<https://doi.org/10.1016/j.envpol.2020.114884>
- Air Quality Expert Group, 2019. Non-Exhaust Emissions from Road Traffic.
- DEFRA, 2017. Air Pollution in the UK 2017.
- EEA, 2019. Air quality in Europe 2019 — European Environment Agency [WWW Document]. URL <https://www.eea.europa.eu/publications/air-quality-in-europe-2019> (accessed 10.17.22).
- EEA, 2008. Directive 2008/50/EC, air quality — European Environment Agency [WWW Document]. URL <https://www.eea.europa.eu/policy-documents/directive-2008-50-ec-of> (accessed 11.16.22).
- European Commission, 2021. Register of Commission Documents - COM(2021)400 [WWW Document]. URL [https://ec.europa.eu/transparency/documents-register/detail?ref=COM\(2021\)400&lang=en](https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2021)400&lang=en) (accessed 11.16.22).
- European Commission, 2020. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND

THE COMMITTEE OF THE REGIONS EU Biodiversity Strategy for 2030 Bringing nature back into our lives.

European Environment Agency, 2022. Air quality in Europe 2022.

Forouzanfar, M.H., and al., 2016. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *The Lancet* 388, 1659–1724. [https://doi.org/10.1016/S0140-6736\(16\)31679-8](https://doi.org/10.1016/S0140-6736(16)31679-8)

Gaglio, M., Pace, R., Muresan, A.N., Grote, R., Castaldelli, G., Calfapietra, C., Fano, E.A., 2022. Species-specific efficiency in PM_{2.5} removal by urban trees: From leaf measurements to improved modeling estimates. *Sci. Total Environ.* 844, 157131. <https://doi.org/10.1016/j.scitotenv.2022.157131>

Grote, R., Samson, R., Alonso, R., Amorim, J.H., Cariñanos, P., Churkina, G., Fares, S., Thiec, D.L., Niinemets, Ü., Mikkelsen, T.N., Paoletti, E., Tiwary, A., Calfapietra, C., 2016. Functional traits of urban trees: air pollution mitigation potential. *Front. Ecol. Environ.* 14, 543–550. <https://doi.org/10.1002/fee.1426>

HEI, H.E., 2018. State of Global Air 2018: Over 7 billion people face unsafe air [WWW Document]. Health Eff. Inst. URL <https://www.healtheffects.org/announcements/state-global-air-2018-over-7-billion-people-face-unsafe-air> (accessed 10.17.22).

IUCN, 2016. Nature-based Solutions [WWW Document]. IUCN. URL <https://www.iucn.org/commissions/commission-ecosystem-management/our-work/nature-based-solutions> (accessed 9.20.21).

Jeong, N.R., Kim, J.-H., Han, S.W., Kim, J.-C., Kim, W.Y., 2021. Assessment of the Particulate Matter Reduction Potential of Climbing Plants on Green Walls for Air Quality Management. *J. People Plants Environ.* 24, 377–387. <https://doi.org/10.11628/ksppe.2021.24.4.377>

Karagulian, F., Belis, C.A., Dora, C.F.C., Prüss-Ustün, A.M., Bonjour, S., Adair-Rohani, H., Amann, M., 2015. Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level. *Atmos. Environ.* 120, 475–483. <https://doi.org/10.1016/j.atmosenv.2015.08.087>

Muhammad, S., Wuyts, K., Samson, R., 2019. Atmospheric net particle accumulation on 96 plant species with contrasting morphological and anatomical leaf characteristics in a common garden experiment. *Atmos. Environ.* 202, 328–344. <https://doi.org/10.1016/j.atmosenv.2019.01.015>

Ottelé, M., Perini, K., Fraaij, A.L.A., Haas, E.M., Raiteri, R., 2011. Comparative life cycle analysis for green façades and living wall systems. *Energy Build.* 43, 3419–3429. <https://doi.org/10.1016/j.enbuild.2011.09.010>

Ottelé, M., van Bohemen, H.D., Fraaij, A.L.A., 2010. Quantifying the deposition of particulate matter on climber vegetation on living walls. *Ecol. Eng., Special Issue: BioGeoCivil Engineering* 36, 154–162. <https://doi.org/10.1016/j.ecoleng.2009.02.007>

Pearce, H., Levine, J.G., Cai, X., MacKenzie, A.R., 2021. Introducing the Green Infrastructure for Roadside Air Quality (GI4RAQ) Platform: Estimating Site-Specific Changes in the Dispersion of Vehicular Pollution Close to Source. *Forests* 12, 769. <https://doi.org/10.3390/f12060769>

Perini, K., Ottelé, M., Giuliani, S., Magliocco, A., Roccotiello, E., 2017. Quantification of fine dust deposition on different plant species in a vertical greening system. *Ecol. Eng.* 100, 268–276. <https://doi.org/10.1016/j.ecoleng.2016.12.032>

Perini, K., Roccotiello, E., 2018. Chapter 3.4 - Vertical Greening Systems for Pollutants Reduction, in: Pérez, G., Perini, K. (Eds.), *Nature Based Strategies for Urban and Building Sustainability*.

- Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, pp. 131–140.
<https://doi.org/10.1016/B978-0-12-812150-4.00012-4>
- Przybysz, A., Popek, R., Stankiewicz-Kosyl, M., Zhu, Ch.Y., Małecka-Przybysz, M., Maulidyawati, T., Mikowska, K., Deluga, D., Griżuk, K., Sokalski-Wieczorek, J., Wolszczak, K., Wińska-Krysiak, M., 2021. Where trees cannot grow – Particulate matter accumulation by urban meadows. *Sci. Total Environ.* 785, 147310. <https://doi.org/10.1016/j.scitotenv.2021.147310>
- Rakhshandehroo, M., Mohd Yusof, M.J., Deghati Najd, M., 2015. Green Façade (Vertical Greening): Benefits and Threats. *Appl. Mech. Mater.* 747, 12–15.
<https://doi.org/10.4028/www.scientific.net/AMM.747.12>
- Redondo-Bermúdez, M. del C., Gulenc, I.T., Cameron, R.W., Inkson, B.J., 2021. ‘Green barriers’ for air pollutant capture: Leaf micromorphology as a mechanism to explain plants capacity to capture particulate matter. *Environ. Pollut.* 288, 117809.
<https://doi.org/10.1016/j.envpol.2021.117809>
- Rosasco, P., Perini, K., 2019. Selection of (Green) Roof Systems: A Sustainability-Based Multi-Criteria Analysis. *Buildings* 9, 134. <https://doi.org/10.3390/buildings9050134>
- RStudio Team, 2020. RStudio: Integrated Development for R. RStudio.
- Sgrigna, G., Baldacchini, C., Dreveck, S., Cheng, Z., Calfapietra, C., 2020. Relationships between air particulate matter capture efficiency and leaf traits in twelve tree species from an Italian urban-industrial environment. *Sci. Total Environ.* 718, 137310.
<https://doi.org/10.1016/j.scitotenv.2020.137310>
- Tong, Z., Whitlow, T.H., MacRae, P.F., Landers, A.J., Harada, Y., 2015. Quantifying the effect of vegetation on near-road air quality using brief campaigns. *Environ. Pollut.* 201, 141–149.
<https://doi.org/10.1016/j.envpol.2015.02.026>
- Viecco, M., Vera, S., Jorquera, H., Bustamante, W., Gironás, J., Dobbs, C., Leiva, E., 2018. Potential of Particle Matter Dry Deposition on Green Roofs and Living Walls Vegetation for Mitigating Urban Atmospheric Pollution in Semiarid Climates. *Sustainability* 10, 2431.
<https://doi.org/10.3390/su10072431>
- Villani, M.G., Russo, F., Adani, M., Piersanti, A., Vitali, L., Tinarelli, G., Ciancarella, L., Zanini, G., Donato, A., Rinaldi, M., Carbone, C., Decesari, S., Sängler, P., 2021. Evaluating the Impact of a Wall-Type Green Infrastructure on PM10 and NOx Concentrations in an Urban Street Environment. *Atmosphere* 12, 839. <https://doi.org/10.3390/atmos12070839>
- Weerakkody, U., Dover, J.W., Mitchell, P., Reiling, K., 2018. Evaluating the impact of individual leaf traits on atmospheric particulate matter accumulation using natural and synthetic leaves. *Urban For. Urban Green.*, Special feature: Strategic gardens and gardening: Inviting a widened perspective on the values of private green space 30, 98–107.
<https://doi.org/10.1016/j.ufug.2018.01.001>
- Weerakkody, U., Dover, J.W., Mitchell, P., Reiling, K., 2017. Particulate matter pollution capture by leaves of seventeen living wall species with special reference to rail-traffic at a metropolitan station. *Urban For. Urban Green.* 27, 173–186.
<https://doi.org/10.1016/j.ufug.2017.07.005>
- Ysebaert, T., Koch, K., Samson, R., Denys, S., 2021. Green walls for mitigating urban particulate matter pollution—A review. *Urban For. Urban Green.* 59, 127014.
<https://doi.org/10.1016/j.ufug.2021.127014>