**Highlights**

- The living wall located by New Street Station, Birmingham, UK has a promising potential for removal of atmospheric PM pollutants with reference to different PM size fractions ($PM_1$, $PM_{2.5}$ and $PM_{10}$).
- Inter-species variation in the ability to capture PM is considerable and careful species selection is crucial to optimize living wall systems as PM filters.
- Smaller-leaved species, hairy leaf surfaces and epicuticular wax enhance the PM capture potential of living wall-plants.

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# Particulate Matter pollution capture by leaves of seventeen living wall species with special reference to rail-traffic at a metropolitan station


## Abstract

Atmospheric Particulate Matter (PM) constitutes a considerable fraction of urban air pollution, and urban greening is a potential method of mitigating this pollution. The value of living wall systems has received scant attention in this respect. This study examined the inter-species variation of particulate capture by leaves of seventeen plant species present in a living wall at New Street railway station, Birmingham, UK. The densities of different size fractions of particulate pollutants ($PM_1$, $PM_{2.5}$ and $PM_{10}$) on 20 leaves per species were quantified using an Environmental Scanning Electron Microscope (ESEM) and ImageJ image-analysis software. The overall ability of plant leaves to remove PM from air was quantified using PM density and LAI (Leaf Area Index); any inter-species variations were identified using one-way Anova followed by Tukey's pairwise comparison. This study demonstrates a considerable potential for living wall plants to remove particulate pollutants from the atmosphere. PM capture levels on leaves of different plant species were significantly different for all particle size fractions ($P < 0.001$). Smaller-leaved *Buxus sempervirens* L., *Hebe albicans* Cockayne, *Thymus vulgaris* L. and *Hebe x youngii* Metcalf showed significantly higher capture levels for all PM size fractions. PM densities on adaxial surfaces of the leaves were significantly higher compared to abaxial surfaces in the majority of the species studied (t-test, $P < 0.05$). According to EDX (Energy Dispersive X-ray) analysis, a wide spectrum of elements were captured by the leaves of the living wall plants, which were mainly typical railway exhaust particles and soil dust. Smaller leaves, and hairy and waxy leaf surfaces, appear to be leaf traits facilitating removal of PM from the air, and hence a collection of species which share these characters would probably optimize the benefit of living wall systems as atmospheric PM filters.



**Keywords:** Outdoor air pollution; Urban green infrastructure; Green walls; Railway pollution


## 1. Introduction

Outdoor air pollution caused an estimated 3.7 million premature deaths worldwide in 2012, mainly due **to** atmospheric Particulate Matter (PM) less than 10 µm in aerodynamic diameter ($PM_{10}$), ozone, nitrogen dioxide and sulphur dioxide (WHO, 2014). The European Environment Agency (EEA, 2016) estimated that in the 2012-2014 period 50-63% and 85-91% of the urban population in Europe were exposed to levels of $PM_{10}$ and $PM_{2.5}$ (respectively) which exceeded the recommended World Health Organisation (WHO) annual limits ($PM_{10}$: 20 µg $m^{-3}$ and $PM_{2.5}$: 10 µg $m^{-3}$). EEA (2016) also estimated that 467,000 premature deaths in Europe could be attributed to $PM_{2.5}$ (PM less than 2.5 µm in aerodynamic diameter) in 2013. Out of 40,000 annual deaths estimated to be caused by outdoor air pollution in the UK, 29,000 were caused by PM pollution (Royal College of Physicians, 2016). Long-term exposure to airborne PM is directly associated with potentially fatal childhood diseases including post-neonatal infant mortality (Laden *et al*., 2006), Sudden Infant Death Syndrome (SIDS) (Woodruff *et al*., 2006) and various other diseases which affect all segments of the community such as cardiopulmonary diseases, lung cancer (Pope III *et al.*, 2011) atherosclerosis (Araujo, 2011) and asthma (Anderson *et al*., 2013). Ultrafine particles ($PM_{0.1}$), PM less than 0.1 µm in aerodynamic diameter can cause serious damage by entering the liver, spleen, kidney and the brain (via the olfactory nerves) (Solomon *et al.,* 2012). They can also reach the lower respiratory system and change

alveolar macrophage functions due to toxic chemicals carried by the particles (e.g. polycyclic aromatic hydrocarbons (PAHs) and heavy metals) (Riddle *et al*., 2009). On entering the human bloodstream, they can create systemic inflammatory changes, which can lead to serious complications in blood coagulability (Seaton *et al.* 1995). The annual cost to society due to particulate pollution in the UK has been estimated at £16 billion (COMEAP, 2010).

Coarse particles can originate from natural sources and anthropogenic activities, while fine particles mainly originate from vehicle emissions (gasoline and diesel), combustion, and industrial processes (Chow *et al*., 2006). Ultra-fine particles mostly originate from transport and photochemical reactions in the atmosphere (Chow *et al*., 2006). These particles contain toxic compounds such as heavy metals, PAHs, polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) and polychlorinated biphenyls (PCBs), making them more hazardous and carcinogenic (Dzierzanowski *et al.,* 2011). The International Agency for Research on Cancer (IARC) classified diesel exhaust as a Group 1 (carcinogenic to humans) carcinogen (Silverman *et al.*, 2012). The railway network is one of the main sources of air pollution in the UK due to diesel and electric train emissions (Thornes *et al*., 2016). In addition to particles generated via rail traffic exhaust, particles can also be generated due to wheel friction, friction with overhead cables and when applying brakes; the particles generated in these circumstances fall mainly within the ultrafine range (Thornes et al., 2016).

Particulate levels in many large cities in the UK exceed both the WHO guidelines and EU safe limits; air pollution mitigation approaches such as emission reduction, enhancing atmospheric dispersion and building high emission sources away from currently polluted or highly populated areas (Pugh *et al*., 2012) are unlikely to have any impact on city PM levels generate from transport. Increasing surface deposition has been identified as an effective short-term strategy to reduce atmospheric particulate pollutants (Pugh *et al*., 2012), especially those locally produced within cities due to transportation systems. Since vegetation can act as a sink for particulates (Beckett *et al*., 2000; Fowler *et al*., 2004; Freer-Smith *et al*., 2004) it has the potential to have a high impact in this respect. Trees are often the main source of greening considered in urban landscapes, however, there are several limitations and barriers to achieving urban greening purely by using trees, including (but not limited to): prevailing soil conditions, space utilisation, sub-surface infrastructure, availability of sunlight and the size of the trees compared to the adjacent buildings (Johnston and Newton, 2004). Green walls (vertical greening) could overcome most of these limitations by transforming building walls to greenery while minimizing land-take and providing additional benefits including thermal insulation, noise reduction and conservation of urban biodiversity and rewilding of cityscapes (Alexandri *et al*., 2007; Chiquet *et al.*, 2013; Dover, 2015; Jepson, 2016; Johnston and Newton, 2004). Previous studies on green walls have focused more on the value of climbing plants, such as ivy, in reducing PM pollution and little information is available on the value of living walls in this respect (Cheetham *et al*., 2012) though see Perini *et al.* (2017) and Shackleton *et al*. (undated). Living walls are vertically growing hydroponic green wall systems which facilitate the growth of a variety of plant species with a potential for greater artistic expression than simply using climbing species (Dover, 2015). PM filtering behavior of living wall systems with reference to different PM size fractions of particulates and the optimal species composition for living wall systems to act as effective particulate matter traps are not well understood. This study explores the role of living wall systems in the reduction of PM pollution; in contrast to the work of Perini *et al.* (2017), particulate capture is investigated at street level adjacent to a pedestrian walkway.

In early research different technical approaches were taken to quantify particulate capture by vegetation, including comparison of dust-fall measurements between the canopy area and open space (Dochinger, 1980), atmospheric aerosol screening (Bache, 1979; Wiman, 1985) and deposition velocity models (Bache, 1979). The gravimetric method, which collects particulate matter in water by washing material off the leaves followed by filtering and weighing the residue has frequently been used (Beckett *et al*., 2000; Freer-Smith *et al*., 2005; Ram *et al*., 2012). However, there are several drawbacks to the latter technique: particulates held on the epicuticular wax or microstructures of leaves may not be washed-off and hence may not be weighed. In some research chloroform was used as the solvent to dissolve epicuticular wax and collect the PM trapped in the wax component (Dzierzanowski *et al*., 2011; Sæbø *et al.*, 2012 and Song *et al.,* 2015). However, as chloroform is used as a solvent to dissolve non-polar molecules and the soluble fraction of PAHs (Castelli *et al*., 2002) eluting with such solvents has the potential to dissolve some particulates comprises of non-polar materials. In addition, according to pulmonary toxicity studies, the particle surface area and particulate count are more appropriate measures for smaller particles than particle mass (Sager and Castranova, 2009). Ottele *et al*. (2010) quantified the number of particulates captured by leaves of *Hedera helix* by using a Scanning Electron Microscope (SEM) to image the particulates in situ and used an image analysis program to count and size-range the particles deposited on the leaves. However, SEM scanning areas are much smaller compared to leaf surface area; and hence, a representative number of micrographs should be taken to draw any conclusions on PM levels on leaves using this approach.

Removal of atmospheric particulates by vegetation is mainly driven by the interactions between the particles and plant surfaces including their morphological properties such as shape, size and orientation (Petroff *et al*., 2008). Particulate deposition on plants is thought to be influenced by particle diameter and the micro-roughness or micro-topography of the plant (Slinn, 1982). However, there is much debate on the impact of leaf size and morphology on particulate capture. Therefore, this study examined inter-species variation in PM removal by living wall species in order to understand the best species combinations to capture PM employing a SEM/image analysis approach. Particulate densities (the number of particulates deposited per unit area of leaf surface) on the adaxial (upper) and abaxial (under) surfaces of the leaves were also examined to understand any variation due to leaf size or morphology. Further to this, the elemental composition of the captured particulates was also studied to detect the elements which can be removed using living wall plants.

## 2. Material and methods

### 2.1 Site selection

Birmingham is a large city located in the West Midlands of England (Fig. 1) with a population of over 1.1 million (Birmingham City Council 2014). In Birmingham, PM accounted for 6.4% of the premature mortality rate in 2009 (Gowers *et al*., 2014). Birmingham New Street railway station is one of the busiest railway stations in the UK, with up to 140,000 commuters and staff passing through daily (Thornes *et al*., 2016). Approximately 1,000 trains/day (comprising equal numbers of diesel and electric powered trains) pass through this station (Thornes, 2016) and $PM_{2.5}$ levels of up to 58 μg $m^{-3}$ for hourly intervals have been reported within the station (Zulkifli, 2015 cited in Thornes *et al*., 2016). Given the amount of pollution generated in and around the station, a free-standing modular living wall located on it's north side, 5 m above

the railway (which is sunk below street level) and 3.2 m from the closest platform (Fig. 1) ($52^0$28'41.2" N $10^0$53'48.7" W) was selected as the experimental site. The living wall was manufactured by ANS Global in 2012 and was subsequently managed by Network Rail; the structure is 77 m long and varies in height from 4.5 m near the station to 3.5 m at its furthest point (300 $m^2$ in total) and hosted twenty different species of plants (Table 1). A low (0.5 m) stone-clad planter with low-growing shrubs was present at the base of the wall (Fig. 2). A mean wind speed of 4.1 m/s, a mean temperature of 15 $^0$C, a mean daily rainfall of 101.2 mm and a mean humidity of 64% were reported from the study area during the period of sampling (Met Office - GOV.UK).

2.2 Sampling

Twenty leaves per species (n =20) of sixteen healthy plant species present in the living wall (Table 1) were randomly sampled (avoiding damaged leaves) at 2.0-2.5 m height above the footpath. In addition, 40 leaves of *Thymus vulgaris* L. were sampled (see section 2.3 for more details) at the same height (360 leaves in total). *Fragaria vesca* L. was only located in the uppermost rows of the living wall (was inaccessible), *Galanthus nivalis* L. and *Lysimachia nummularia* L. were not healthy within the sampling period; and hence these three species were not included in the study. Sampling dates and times were selected based on weather conditions and carried out on six occasions with similar weather conditions (Table 2) between April and July 2016. Sampling was carried out only during dry weather conditions (having at least four consecutive non-rainy days immediately before sampling) and all the species were equally sampled on each sampling day (at least 3 leaves per species) to avoid differential influence from daily weather differences (Table 2). Leaves were hand-picked and stored in plastic containers in such a way that they did not rub against one another or against the container (to avoid disturbing the particles) and sealed.

2.3 Quantifying the PM densities on leaf surfaces

Samples were carefully stored in a refrigerator (approximately 9 $^0$C) in the same storage boxes to prevent any dehydration and structural changes until sample preparation and analysis within two days of sampling. A pilot study (unpublished data) was conducted using common living wall plant species with a representative sample of different morphologies and showed less variable particulate distributions on the leaf-blade compared to other leaf areas (tip, edges, base and mid rib) and the leaf-blade was thus selected as the most appropriate area to sample leaf sections for all the species. Samples were prepared for microscopic examination by removing six leaf sections 5.0 x 5.0 mm in size, from every leaf blade of all the species apart from small-leaved species (less than 250 $mm^2$). Three sections were used to examine the adaxial surface and three for the abaxial surface for each leaf. Leaf sections were mounted on aluminium stubs using double-sided carbon sticky tabs. Environmental Scanning Electron Microscope (ESEM) (Model: JSM-6610LV) micrographs were taken at three random points per leaf section (providing nine micrographs per each side of every leaf) using Back Scattered Electrons (BSE) under a low vacuum (LV mode) at 450X and 1,000X (resulting micrographs were 60,681.5 $\mu m^2$ and 12,288.0 $\mu m^2$ in size) without any conductive coating. Leaves can be imaged in the ESEM without any conductive coating due to their natural carbon content and their cuticle minimising dehydration (Ensikat *et al*., 2010). Small-leaved species (less than 250 $mm^2$), which were too small to physically cut into sections were cut into halves and mounted without cropping, to scan adaxial and abaxial surfaces (using each half); nine micrographs were taken from the leaf blade of each half

of the leaf adhering to the same protocol. However, leaves of *T. vulgaris* were too small to section into halves and, hence, adjacent leaves were used to image the abaxial surfaces using forty leaves in total. Micrographs were taken using the same working distance, while maintaining contrast and brightness levels as consistent as possible to avoid any difficulties in defining the threshold of the image analysis process.

The amount of $PM_{10}$ (excluding $PM_{2.5}$ and below), $PM_{2.5}$ (excluding $PM_1$ and below) and $PM_1$ (all the measurable PM less than 1 µm aerodynamic diameter) on each micrograph was quantified using ImageJ image analysis software (Collins, 2007; Ottele *et al*., 2010; Sternberg *et al.,* 2010) and its auto threshold tool was used to minimise human error. The smallest particle size that could be accurately counted (with enough resolution and less conductive charging) using this technique was 0.1 µm in diameter. Particles between 0.1 µm and 1 µm have similar aerodynamic behaviour resulting in similar deposition velocities (Slinn, 1982). Because smaller particles are linked to more severe health effects, $PM_1$ was quantified as a separate fraction in addition to the more commonly reported $PM_{10}$ and $PM_{2.5}$ fractions. The most appropriate threshold was chosen for the image analysis process using 10 micrographs with reference to their respective secondary electron images (at high resolution) to ensure only the particles were filtered and the leaf surfaces were subtracted. The mean PM density (per 1 $mm^2$) on each side of each leaf was calculated taking the mean of the PM density on each micrograph. The overall PM density on leaves per 1 $mm^2$ was calculated by combining the PM densities on both the adaxial and abaxial surfaces. The mean PM density on leaves of each species was calculated using the average PM density on each of the 20 leaves/species. A total of 360 random micrographs per species were used to estimate the mean PM densities on each species.

## 2.4 Leaf Area Index

Leaves of different plants have different surface areas and are distributed differently in space. The total particulate capture on leaves of different species may vary depending on the available leaf surface area to capture particles. As living walls are vertical, the LAI was measured relative to the unit vertical area of the living wall. The number of leaves distributed on a unit vertical area was calculated using a 100 mm x 100 mm quadrat for all seventeen species; the average number of leaves present within a quadrat was calculated using three random quadrats per species. The surface area of individual leaves was measured using ImageJ, the mean leaf surface area of leaves of each species was calculated using ten random leaves per each species. The LAI of each species was calculated using the following formula:

$$LAI = La \times Nl / Qa$$

La = Mean surface area of an individual leaf, Nl = Average number of leaves per quadrat, Qa = Total area of the quadrat

## 2.5 Quantifying the overall PM removal capacity including LAI by different species of plants

The ability of each species of plant to remove PM using a 100 $cm^2$ area of living wall was calculated using the mean PM density on each species and the LAI:

PM removal by 100 $cm^2$ area of each species = Number of PM on 100 $cm^2$ area of the leaves x LAI = Mean PM density on the leaves x $10^4$ x LAI

### 2.6 Observation of leaf characteristics

The surface morphology of leaves was examined using the ESEM at a range of magnifications as appropriate (100X, 250X, 350X, 450X and 900X) to understand any variability in PM density associated with specific leaf surface characteristics.

### 2.7 Statistical analyses

R statistical software version 3.2.5 (R Core Team, 2016) was used for all statistical tests in this study. Any significant variations in PM density on leaves of different plant species and any significant variations in PM removal ability (including LAI) of different plant species with reference to different particle size fractions were analysed using one-way ANOVA following confirmation of normality using the Shapiro-Wilk test. Significant differences in pairwise comparisons of species were identified and clustered using Tukey's HSD post-hoc test (package: Agricolae). As the adaxial and abaxial surfaces of the leaves of the same species may have different micro-morphology, they were separately analysed to explain any variation between plant species due to the differences in leaf properties (size, shape and texture). Any significant differences in PM density between adaxial and abaxial surfaces of the same species were identified using a Student's t-test.

### 2.8 Elemental analysis of particulates

Elemental composition of particulates captured on leaves was determined using Energy Dispersive X-ray analysis (EDX) using the INCA software coupled with the ESEM (Williamson *et al*., 2004). Ten leaf sections per species (randomly selected, representing all sampling dates) were scanned using the SEM at 1,000X using an accelerating voltage of 15 kV and back scattered electrons. The scanning images were acquired in INCA software and the elemental composition of the particles was analysed using the Point and ID analyser. The Point and ID analyser works as both a qualitative and quantitative analytical tool to identify and quantify the elements in particles as their percentage weight (Wt%) (INCA energy operator manual, 2006). The mean quantity of each identified element in each species was calculated (mean Wt%) by taking the mean of ten random particles scanned for each species of plant.

## 3. Results

### 3.1 Overall PM capture and inter-species variation of PM removal by plants

#### 3.1.1 PM density on leaves

Analysis of ESEM micrographs revealed differential PM densities on leaves of different plant species at all particulate size ranges ($PM_1$: $F = 39.97$, $p < 0.001$; $PM_{2.5}$: $F = 55.83$, $p < 0.001$; $PM_{10}$: $F = 44.08$, $p < 0.001$) (Table 3). The highest mean densities of $PM_1$ and $PM_{2.5}$ (45,000 ± 3,300 $mm^{-2}$ and 16,500 ± 900 $mm^{-2}$ respectively) were found on leaves of *B. sempervirens* and they were significantly higher than all the other species ($p < 0.05$) apart from *H. albicans* and *T. vulgaris* (Table 3). *T. vulgaris* had the highest mean density of $PM_{10}$ on its leaves (4,040 ± 200 $mm^{-2}$; Table 3) which was significantly higher ($p < 0.05$) than most of the species apart from *B. sempervirens* and *H. albicans*. The lowest densities of $PM_1$, $PM_{2.5}$ and $PM_{10}$ were found on leaves of *L. nivea*, *B. spicant* and *P. scolopendrium* respectively (Table 3).

### 3.1.2 PM capture incorporating LAI measures

The PM numbers given in this section incorporate the LAI; as this generates exceptionally large numbers we have given the data in terms of millions of particles, hence they should be multiplied by $10^6$. On average 250 ±17 of $PM_1$, 99 ± 5 of $PM_{2.5}$ and 27 ± 1 of $PM_{10}$ were estimated to have been removed by a 100 $cm^2$ of the living wall (assuming an equal area of each plant species). There was a significant variation in the ability of different species of plants to remove PM in all size fractions ($PM_1$: $F = 77.1$, $p < 0.001$; $PM_{2.5}$: $F = 122.9$, $p < 0.001$; $PM_{10}$: $F = 88.73$, $p < 0.001$) (Fig. 3) these variations can be attributed to the varied PM capture rate per unit leaf area (Table 3) and their LAI values (Table 1). $PM_1$ removal by *H. albicans* (876 ± 130) was significantly higher than for all the other species ($p < 0.05$) apart from *B. sempervirens* ($p = 1.00$) and *T. vulgaris* ($p = 0.81$) (Fig. 3a), and removal of $PM_{2.5}$ (282 ± 30) was also significantly higher than for most other species ($p < 0.05$) apart from *B. sempervirens* ($p = 1.00$), *T. vulgaris* ($p = 0.85$) and *H. youngii* ($p = 0.26$) (Fig. 3b). The best performing species in $PM_{10}$ capture (79.9 ± 5.2) was *T. vulgaris* (Fig. 3c) and this was significantly higher than for most of the species ($p < 0.05$) apart from *H. youngii* ($p = 0.99$), *H. albicans* ($p = 0.78$) and *B. sempervirens* ($p = 0.13$). If higher PM-capturing species are arranged in descending order (only those species in Tukey's HSD post-hoc test groups with higher PM levels are considered i.e. – those given a, b and c in Fig. 3):

$PM_1$: *H. albicans* > *B. sempervirens* > *T. vulgaris*> *G. macrorrhizum* > *H. youngii*;
$PM_{2.5}$: *H. albicans* > *B. sempervirens* > *T. vulgaris*> *H. youngii*> *H. helix*> *H. salicifolia*> *A. maritima;*
$PM_{10}$: *T. vulgaris*> *H. youngii*> *H. albicans* > *B. sempervirens*> *A. maritima*> *H. helix*> *H. salicifolia*.
Considering all three particle size fractions, *B. sempervirens*, *H. albicans, T. vulgaris and H. youngii* were the species with highest PM removal capacity.

The worst performing species in PM capture, in all particle size fractions, was *B. spicant* ($PM_1$: 18.2 ± 2.1, $PM_{2.5}$: 4.41± 0.35 and $PM_{10}$: 1.33 ± 0.16) (Fig. 3). $PM_1$ capture by *P. scolopendrium* and *L. nivea* was significantly lower than most of the other species but not significantly different from the lowest (*B. spicant*). $PM_{2.5}$ captured by *B. spicant* was significantly lower than all the other species of plants and $PM_{10}$ captured by *B. spicant* was significantly lower than all the other species apart from *P. scolopendrium*.

### 3.2 PM density on adaxial and abaxial surfaces of the leaves

The comparison of PM densities on adaxial and abaxial surfaces of leaves (Fig. 4) showed that PM density on adaxial surfaces were almost always higher than on the abaxial surfaces; the exceptions to this were PM densities on *E. amygdaloides* and $PM_{10}$ densities on *H.albicans* which were a little higher on the abaxial surfaces, though not significantly so ($p > 0.05$).

There were significant variations in PM densities (excluding LAI) on both leaf surfaces, among different species of plants (Table 4). The highest mean densities of $PM_1$ and $PM_{2.5}$ (34,633 $mm^{-2}$ and 12,839 $mm^{-2}$ respectively) on the adaxial surfaces of leaves were found in *B. sempervirens* and the highest average density of $PM_{10}$ was found on leaves of *T. vulgaris* (2,991 $mm^{-2}$). On the abaxial surfaces of the leaves, *H. albicans* showed the highest average PM density in all particle size fractions ($PM_1$: 18,464 $mm^{-2}$, $PM_{2.5}$: 6,290 $mm^{-2}$ and $PM_{10}$: 1,547 $mm^{-2}$). Similar to the results for total PM removal ability (Fig. 3), *B. spicant, P. scolopendrium, L. nivea, H. sternii* and *P. veris* showed relatively low PM densities on both adaxial and

abaxial surfaces in all PM size fractions (Fig. 4), these levels were significantly lower than most of the other species (Table 4).

### 3.3 Observations of leaf characteristics

Average leaf size, shape and any specific micro-morphological characters observed are given in Table 1. Out of all the species studied, micromorphology of *T. vulgaris* was noticeably more complex in both leaf-surfaces due to their densely arranged short stubby trichomes and essential oil secretory glands/glandular hairs (Fig. 5). Epicuticular wax layers on both surfaces of *T. vulgaris* and on the adaxial surface of *H. helix* were prominent compared to other species. In addition, slightly prominent wax plates or wax layers were observed on adaxial surfaces of *H. youngi*, *H. albicans* and *H. sternii*. Both leaf surfaces of *G. macrorrhizum* were hairy with densely arranged hairs and glandular trichomes, and there were a few other species with sparsely arranged hairs (Table 1).

### 3.4 Elemental analysis

A wide range of elements were found in the PM captured on all species of plants in various quantities (Fig. 6). The mean weight percentage (Wt%) of elements found in PM captured on leaves of different species of plants are given in Table 5 (as C and O are mostly derived from plant material, they were excluded from the analysis). The most abundant element, Fe, was found in the PM captured by all species of plants. Ca, K, Mg and Si were also found in all plant species in variable quantities with levels being Ca> Si> K> Mg on average. The heavy metals Ti, Cr, Cu, Mn, Sb, Co and Zn were also found in these particles; however, they were found in trace quantities. The amount of Ti was relatively high compared to other heavy metals.

## 4. Discussion

### 4.1 PM removal capacity of living walls

Plants growing in a living wall near a train station were shown to be capable of capturing a considerable amount of particulate pollution. It is likely that variable PM capture levels between different PM size fractions was due to their different aerodynamic behaviour and hence variable deposition velocities (Slinn, 1982). Dry deposition of PM on leaves occurs via different processes (e.g. sedimentation under gravity, impaction, interception), resulting in different deposition velocities. PM trapping on leaves could also be temporary since there is a possibility of remobilisation, e.g. wash-off by rain or re-suspension by wind (Currie and Bass, 2008; McPherson *et al*., 1994; Terzaghi *et al*., 2013). Gregory (1973) found different remobilisation rates of different particle masses, this may also influence the quantities of PM on leaves. Here, it was found that the smaller the diameter of particles the higher the quantities captured, reflecting the findings of Freer-Smith *et al*. (2005) on conifers and Ottele *et al*. (2010) on *Hedera helix*. If we consider all seventeen plant species, the average number of $PM_1$ was 2.5 times higher than $PM_{2.5}$ and 9 times higher than $PM_{10}$, suggesting that the living wall is more effective in removing smaller sized-particles or that the leaves are better at retaining the smaller sized particles (Przybysz *et al*., 2014). In contrast, Dzierzanowski *et al*. (2011) found relatively larger numbers of bigger particles on plant leaves compared to smaller particles using a gravimetric method (weight/area). This disparity might be attributed to different techniques applied in PM quantification. The higher mass of coarse particles compared to fine particles may result in higher weight/area in the gravimetric method, whereas the SEM/image analysis approach quantifies the number of different PM size fractions

captured on leaves. The proportion of different PM size fractions in the atmosphere in different locations may also be a reason for this disparity.

4.2 Inter-species variation in PM capture

There was a considerable variation in PM removal capacity by different species of plants. Higher capture levels of all PM size fractions by *H. albicans*, *B. sempervirens*, *T. vulgaris* and *H. youngii* show their greater potential to remove particulates from the atmosphere. Reflecting the findings of Freer-Smith *et al.*, (2004) on woodland species, all these best PM-capturing species are smaller-leaved (Table 1). PM densities on leaves of these species (ignoring the impact of LAI) were also high suggesting an important role of leaf size in removing PM from air. The LAI of these species further enhances their PM removal capacity. Regardless of having smaller leaves, relatively low PM densities found in *H. officinalis* and *G. odoratum* (Table 3) may be due to their soft nature (less rigidity). Soft leaves with low rigidity may have a reduced ability to withstand the air-flow (containing PM) and hence have less turbulence around the leaf boundaries resulting in low levels of PM deposition. Also, their simple leaf arrangement, with larger gaps between their leaves than other small-leaved species, might create less turbulence around the foliage leading to lower levels of impaction and interception. The relatively low LAI of these species further reduces their PM removal capacity resulting in significantly lower capture levels in all particle size fractions (Fig. 3).

PM capture levels on the poorly performing *B. spicant* (Fig. 3) was 50 and 65 times lower (for $PM_1$ and $PM_{2.5}$ respectively) than the highest capture levels on *H. albicans*, and sixty-fold lower than the $PM_{10}$ capture levels on the best performing species, *T. vulgaris*. The second lowest performing plant, *P. scolopendrium*, also showed very poor PM capture levels on its leaves and these quantities were significantly lower than majority of other species (Fig. 3). Interestingly, regardless of their different leaf morphology (Table 1), both of these lower performing species are ferns which are commonly grown on living walls. In contrast to their important role in removing some VOCs (eg. formaldehyde) (Kim *et al.,* 2008), ferns may not be considered as good PM filters.

Low PM densities on leaves of wide leaved species (*P. scolopendrium*, *H. sternii* and *P. veris*) with the exception of *G. macrorrhizum* reflect the findings of Beckett *et al*. (2000) and Hwang *et al*. (2011) that those species with broad leaves have low PM capture potential. Hairy leaves with a complex micromorphology have frequently been cited as being effective in capturing more particulates than smooth leaved plants by trapping them on the leaf-hairs/trichromes (Beckett *et al*., 2000; Leonard *et al*., 2016; Ram *et al*., 2012; Sæbø *et al*., 2012). The high $PM_1$ densities on *G. macrorrhizum* may have resulted, in part, due to dense surface hair of their leaves (Table 1). In contrast, the densities of $PM_{2.5}$ and $PM_{10}$ on *G. macrorrhizum* leaves were relatively low; however, the PM removal ability in those particle size fractions were higher once its relatively high LAI was taken into account. In addition to their smaller leaves, high PM densities on *T. vulgaris* may also be attributed to their larger number of trichomes and glandular hairs. As there were no other hairy-leaved species present in this living wall system, the impact of leaf hair/trichomes on trapping and retaining particles with reference to different PM size fractions requires more research using more hairy-leaved species.

Sæbø *et al*. (2012) found a positive correlation between PM accumulation on leaves and the leaf-wax content using trees and shrubs. In contrast, Dzierzanowski *et al*. (2011) concluded that PM accumulation

on leaves is not related to wax content but to the chemical composition and structure of epicuticular wax; nevertheless, both waxy-leaved species used in this study, *T. vulgaris* and *H. helix*, showed relatively high PM densities in all size fractions suggesting an important role of leaf surface wax in removing particles. However, high PM capture levels on *T. vulgaris* could be attributed to any of those leaf properties (trichomes, essential oil glands, epicuticular wax and smaller size) or their collective impact combined with complex morphology and LAI (Fig. 5). In contrast to the findings of Shackleton *et al*. (undated) on the higher PM removal capacity of "grass like" (linear) species, *L. nivea* showed a very low potential in removing PM from the air. Currie and Bass (2008) found grass performed less well in PM removal compared to trees and shrubs and Dochinger (1980) mentioned that PM capture levels of deciduous species without leaves (as in late autumn and winter) are equivalent to the PM removal capacity of grasslands indicating their poor capture levels. Leonard *et al.* (2016) also found relatively low capture levels on linear shaped leaves. Effectiveness of "grass like" species in removing PM requires more research using multiple species.

### 4.3 PM densities on adaxial and abaxial surfaces of the leaves

Similar to the findings of Ottele *et al.* (2010) and Ram *et al.* (2012), PM capture levels on adaxial surfaces of the leaves were generally higher compared to abaxial surfaces. This could be due to the orientation of the leaves in space where the adaxial surface gets more exposure to particulates through sedimentation under gravity. Compared to the density of $PM_1$, a greater number of species show significant differences in their $PM_{2.5}$ and $PM_{10}$ levels between the adaxial and abaxial surfaces of the leaves, probably due to the higher influence of sedimentation on larger particulates.

### 4.4 Elemental composition

The PM captured by all plant species showed a wide range of important elements including heavy metals, regardless of their PM capture efficiency. Rail traffic was the closest pollution source to the living wall with the nearest potential road pollution source some 47 m away. Carbon and Oxygen were present, mainly due to the organic materials of leaves. However, since the hourly level of black carbon has been reported as being up to 29 μg $m^{-3}$ in Birmingham New Street Station (Zulkifli, 2015 cited in Thornes *et al*., 2016) a considerable portion of carbon can probably be attributed to diesel exhaust from trains. In addition to diesel exhaust, hydrocarbons from lubrication oils, wooden sleepers, and wheel flanges could also be sources of these C and O levels (Burkhardt *et al*., 2008). Higher quantities of Fe in PM are mainly due to engine wear (Lombaert *et al*., 2004) and abrasion of wheels and brake pads (Burkhardt *et al*., 2008; Thorpe and Harrison, 2008). Removing these Fe-rich metal particles from the air may be particularly beneficial due to their potential of causing oxidative brain damage which potentially leads to neurodegenerative conditions such as Alzheimer's disease and Parkinson's disease (Allsop *et al*., 2008; Maher *et al.* 2013). Phosphorus, S and Si were found on almost all of the species and are typical diesel exhaust particles and Cu, Ca, and Mg probably originate from exhaust particles (Abbasi *et al*., 2013). In addition to Al and Si from road dust (Chow *et al*., 2006), Ca, Si, Na, and Al were probably emitted by the friction between wheels and railway lines, from being the main elements of ballast and concrete sleepers. Ca, Mg, Cu and Zn could have also resulted from lubrication oil additives in rail traffic (Lombaert *et al*., 2004). The trace quantities of Ti, Mn, Ba, Cu, Sb and K found in the particulates can be mainly attributed to wear of brake pads (Thorpe and Harrison, 2008).

Trace amounts of Ni and Cr could be associated with particles generated through wheel abrasion (Burkhardt *et al*., 2008).

### 4.5 Implications for the use of Living walls in PM reduction

This study showed a considerable potential for living wall plants to remove PM pollutants from the atmosphere and the efficiency of smaller particle removal was notable. However, high variability in PM removal capacity of different species of plants highlights the importance of careful species selection for living wall systems when using them as PM filters. Smaller leaved species with complex morphology were found to be the best performing species in this respect. Beckett *et al*. (2000) noted that evergreen species retain their leaves for several years and reach a saturation point, whereas Dzierzanowski *et al.* (2011) argued that PM captured on leaves can be washed-off with rain allowing them to act as a sink for PM throughout the year. As living wall species are mostly evergreen, PM remobilisation behaviour of the species is an important factor to be explored and requires more research. However, plants in most living wall systems are easily removed and can be replaced after a few seasons if required.

## 5. Conclusion

The living wall located by New Street Station showed a promising potential for capture of atmospheric PM pollutants. The effectiveness of capturing smaller particles appeared to be substantially higher compared to larger particles. Inter-species variation of PM capture by living wall plants was significant and smaller leaved species with a high LAI were found to have a higher PM removal potential compared to species with wider leaves. Results suggested that hairy-leaved species could be better in capturing the particularly hazardous $PM_1$ fraction, and the epicuticular wax and surface morphology of leaves may be important traits helping in the trapping all PM size fractions. However, further research using a greater number of species is required to draw more accurate conclusions in this respect. All the plant species studied were shown to have removed a wide range of elements from the atmosphere including potentially hazardous heavy metals.

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594 **Figures**

595 Fig 1: Map showing the location of New Street station in Birmingham, UK (upper image) Contains OS data
596 © Crown copyright and database right (2017). The living wall located by the footpath adjacent to
597 Birmingham New Street Train Station is marked by the arrow in the bottom image (Google Maps,
598 2017)

599 Fig 2: An image of a section of the living wall system located adjacent to the New Street station in
600 Birmingham, UK in 2016.

601 Fig. 3: Estimated mean ±1SE ($x10^6$) PM removal by leaves of different species of plants on a living wall at
602 New Street Station, Birmingham, UK in 2016; taking into account the leaf area index. a) $PM_1$ b)
603 $PM_{2.5}$ c) $PM_{10}$ (species sharing the same letter are not significantly different using Tukey's HSD post
604 hoc test with 95% confidence level, P>0.05). Note the different values on the Y-axis.

605 Fig. 4: Mean PM densities ±1SE ($x10^2$) on adaxial and abaxial surfaces of the leaves of different species
606 of plants on a living wall at New Street Station, Birmingham, UK in 2016. a) $PM_1$, b) $PM_{2.5}$, c) $PM_{10}$;
607 * PM densities between adaxial and abaxial surfaces are significantly different ($p < 0.05$). Error bars
608 not shown for clarity; contractions of species names given on the x-axis of panel c) are used in
609 panels a) and b).

610 Fig. 5: Sample Scanning Electron Microscope image of leaf micromorphology on the a) adaxial surface of
611 *T. vulgaris* (x350), b) adaxial surface of *P. scolopendrium* (x450), c) abaxial surface of *H. youngii*
612 (x450), d) adaxial surface of *H. sternii* (x450), e) adaxial surface of *G. macrorrhizum* (x450), f)
613 abaxial surface of *B. sempervirens* (x450), g) adaxial surface of *H.albicans* (x450), h) adaxial
614 surface of *H.helix* (x900), and i) adaxial surface of *E. amygdaloide.*

615 Fig. 6: Sample EDX spectra of elemental compositions of PM captured on leaves of *B. sempervirens* (top)
616 and *B. spicant* (bottom) grown on a living wall at New Street Station, Birmingham, UK in 2016.

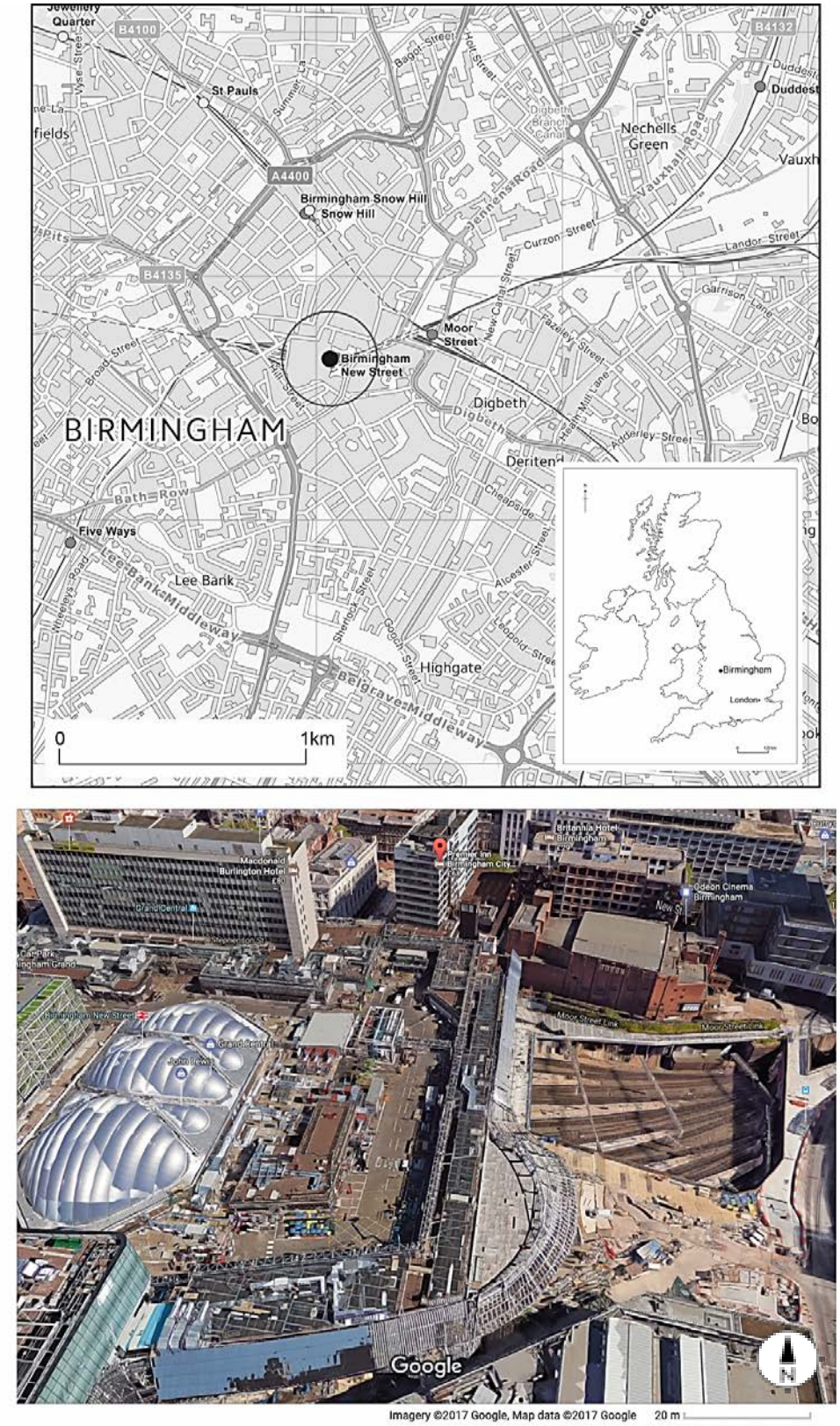


Fig. 1: Map showing the location of New Street station in Birmingham, UK (upper image) *Contains OS data © Crown copyright and database right (2017).* The living wall located by the footpath adjacent to Birmingham New Street Train Station is marked by the arrow in the bottom image (Google Maps, 2017)

Fig. 2: An image of a section of the living wall system located adjacent to the New Street station in Birmingham, UK in 2016.

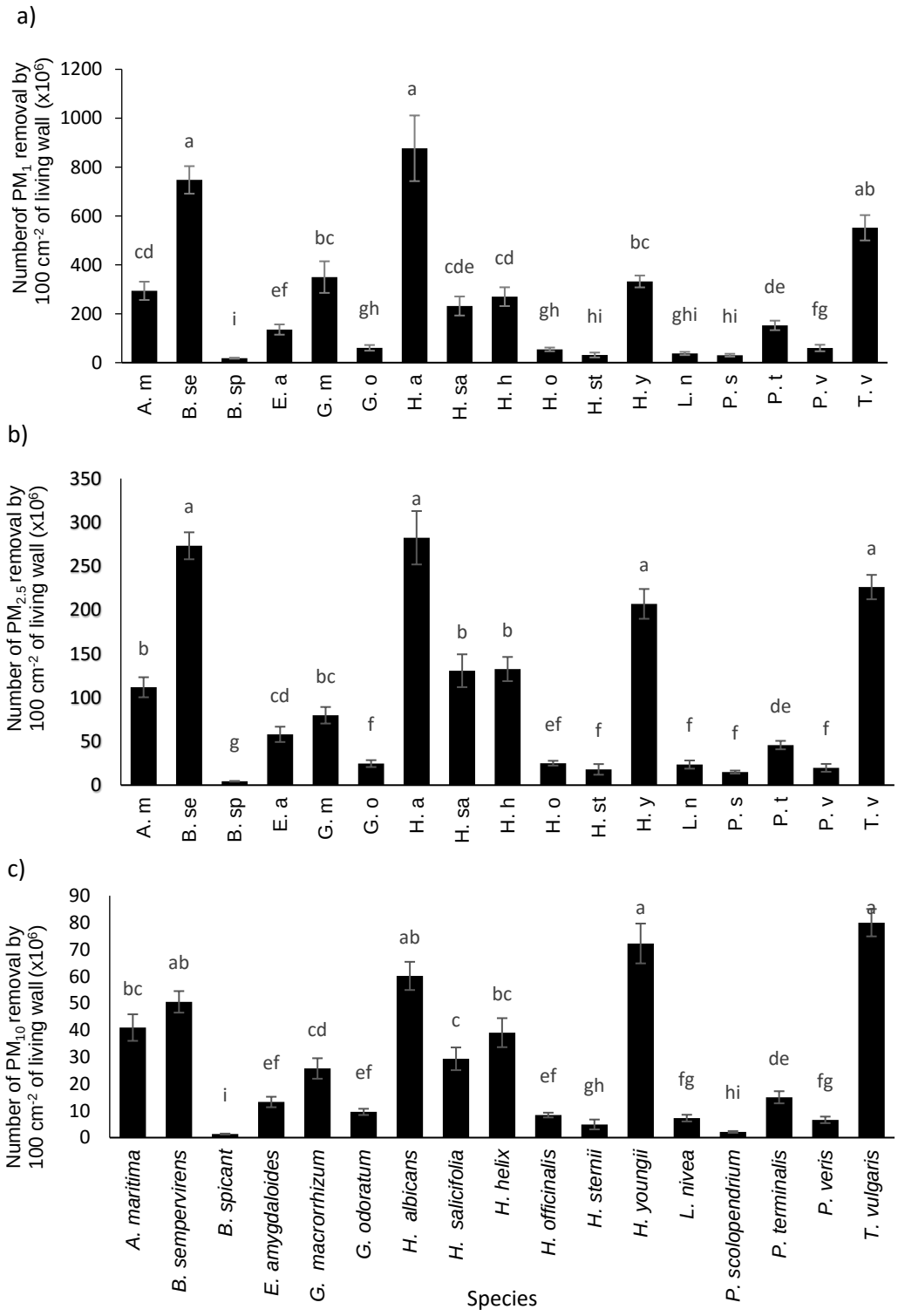


Fig. 3: Estimated mean ±1SE (x$10^6$) PM removal by leaves of different species of plants on a living wall at New Street Station, Birmingham, UK in 2016; taking into account the leaf area index. a) $PM_1$ b) $PM_{2.5}$ c) $PM_{10}$ (species sharing the same letter are not significantly different using Tukey's HSD post hoc test with 95% confidence level, P>0.05). Note the different values on the Y-axis.

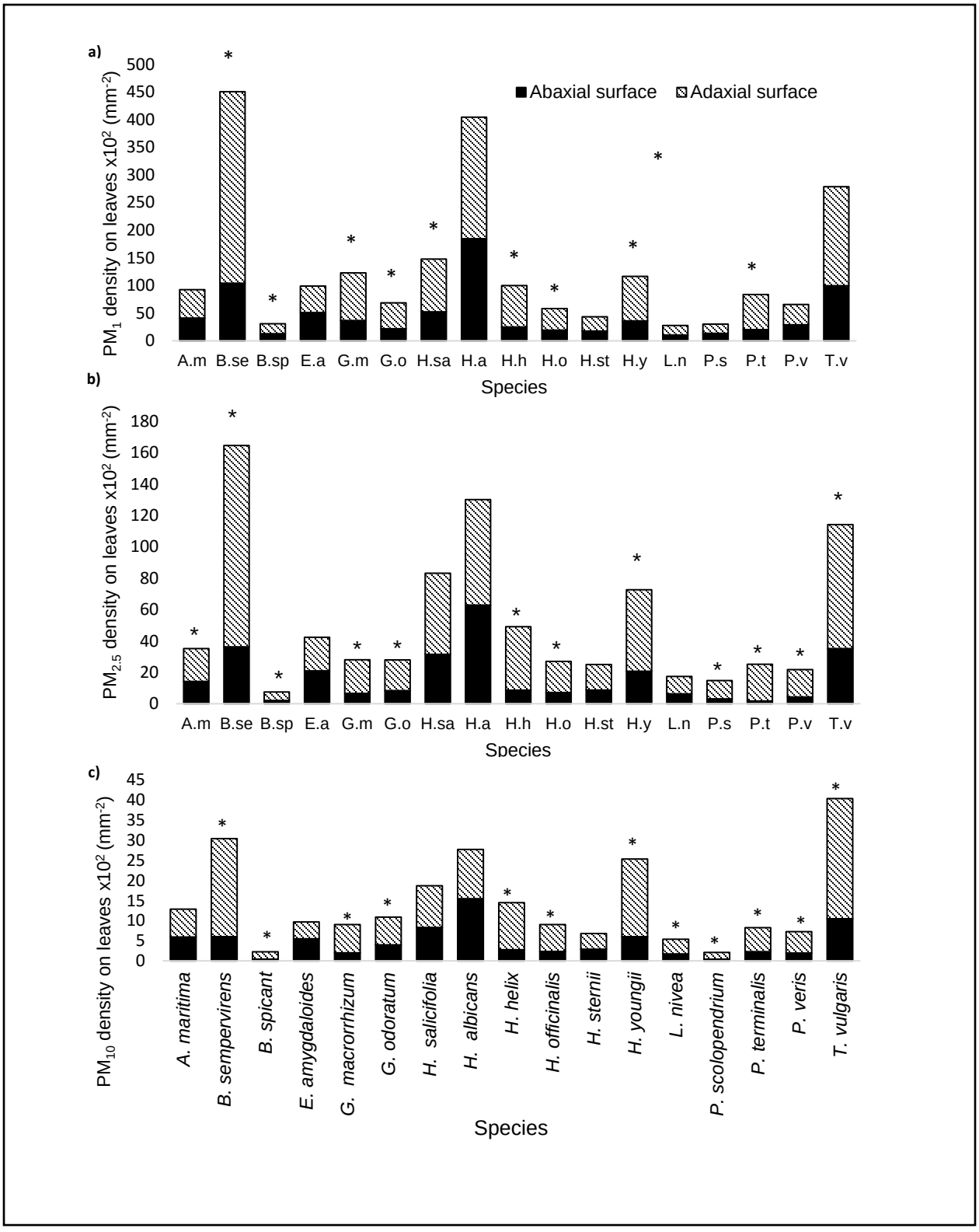


Fig. 4: Mean PM densities ±1SE (x$10^2$) on adaxial and abaxial surfaces of the leaves of different species of plants on a living wall at New Street Station, Birmingham, UK in 2016. a) $PM_1$, b) $PM_{2.5}$, c) $PM_{10}$; * PM densities between adaxial and abaxial surfaces are significantly different ($p < 0.05$). Error bars not shown for clarity; contractions of species names given on the x-axis of panel c) are used in panels a) and b).

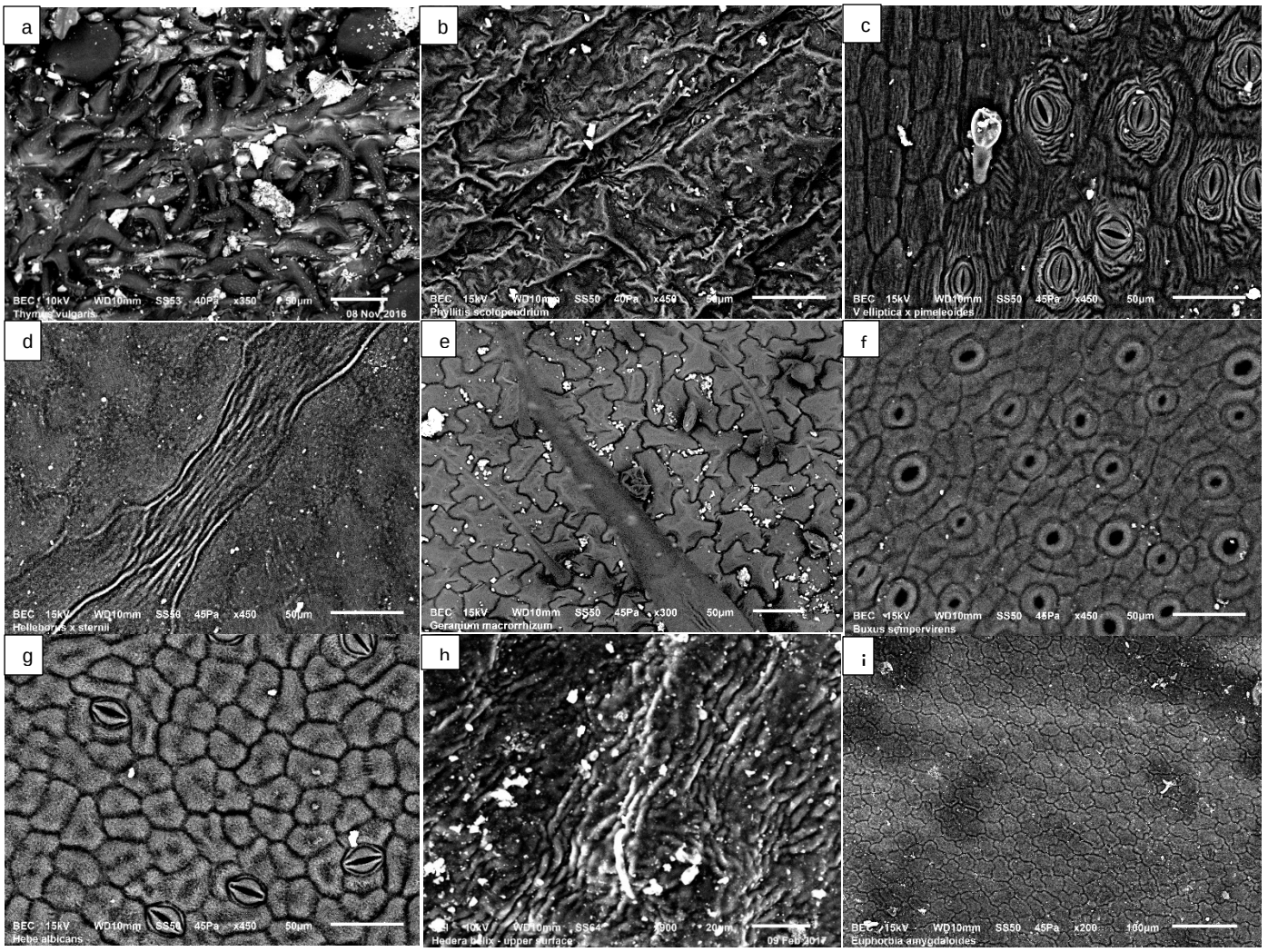


Fig. 5: Sample Scanning Electron Microscope images of leaf micromorphology on the a) adaxial surface of *T. vulgaris* (x350), b) adaxial surface of *P. scolopendrium* (x450), c) abaxial surface of *H. youngii* (x450), d) adaxial surface of *H. sternii* (x450), e) adaxial surface of *G. macrorrhizum* (x450), f) abaxial surface of *B. sempervirens* (x450), g) adaxial surface of *H.albicans* (x450), h) adaxial surface of *H.helix* (x900), and i) adaxial surface of *E. amygdaloide.*

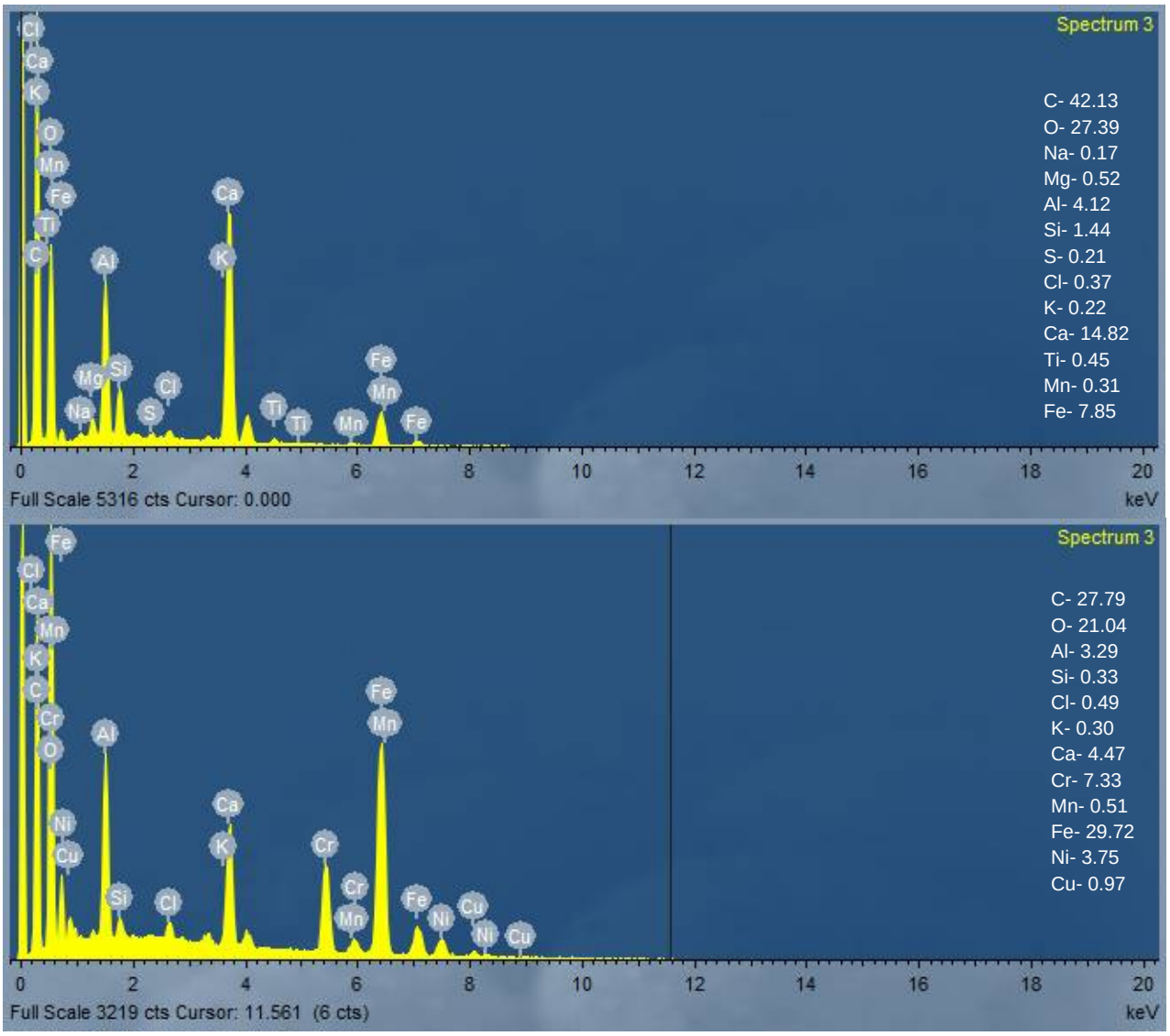


Fig. 6: Sample EDX spectra of elemental compositions of PM captured on leaves of *B. sempervirens* (top) and *B. spicant* (bottom) grown on a living wall at New Street Station, Birmingham, UK in 2016.

**Table 1**: LAI ±SE and leaf characteristics of different species of plants present in the living wall at New Street Station, Birmingham, UK in 2016

| **Plant species** | **English name** | **LAI ±SE** | **Mean leaf size±SE ($cm^2$)** | **Description of the leaf characteristics and any specific micro-morphological features*** |
|---|---|---|---|---|
| *Armeria maritima* L. | thrift | 3.18 ±0.02 | 1.48± 0.06 | Small, linear leaves forming tufts. Ridges, groves and a few sparsely arranged glandular hairs were present on both surfaces. |
| *Geranium macrorrhizum* L. | cranesbill 'Bevan's Variety' | 2.85 ±0.09 | 31.69±2.24 | Large, palmately lobed, broad leaves. Both leaf surfaces had densely arranged hair and glandular trichomes. |
| *Hebe* x *youngii* Metcalf. (*Veronica elliptica* x *pimeleoides* Carl Teschner) | hebe youngii | 2.85 ±0.05 | 0.74±0.03 | Small, ovate leathery leaves. Glandular trichromes, ridges and groves were prominent on both leaf surfaces. Epiculticular wax plates were slightly prominent on the adaxial surface |
| *Hedera helix* L. | ivy (gold child) | 2.69 ±0.07 | 9.64±0.65 | Medium, palmately lobed leaves. The adaxial surface was covered with thick epicuticular wax layers. |
| *Hebe albicans* Cockayne | white hebe | 2.17 ±0.08 | 1.41±0.08 | Small, oval leaves forming a broad mound. Epicuticular wax plates were slightly prominent on the adaxial surface. |
| *Thymus vulgaris* L. | common thyme | 1.98 ±0.01 | 0.05±0.00 | Small, ovate leaves forming whorls. Both leaf surfaces were waxy and had a complex microstructure with densely arranged short stubby trichomes, and glandular hairs. |
| *Pachysandra terminalis* Siebold & Zucc. | Japanese spurge | 1.82 ±0.08 | 8.28±0.51 | Medium, dentate, glabrous leaves. Smooth, leaf surfaces with very few wax glands. |
| *Buxus sempervirens* L. | common box | 1.66 ±0.03 | 0.9± 0.04 | Small, oval, leathery leaves Smooth leaf surfaces with very few trichomes. The abaxial surface was slightly folded due to embossed stomata. |
| *Hebe salicifolia* (G. Forst.) Pennell | koromiko | 1.57 ±0.09 | 2.31±0.21 | Small, narrowly lanceolate willow-like leaves. Leaf surfaces with few ridges, groves and few glands. Epicuticular wax was localized around the glands and less prominent. |

| | | | | |
|---|---|---|---|---|
| *Primula veris* L. | common cowslip | 1.57 ±0.04 | 16.56±0.62 | Large, broad, obovate leaves forming a rosette. Leaf surfaces with sparsely arranged hair, ridges and groves. |
| *Euphorbia amygdaloides* L. | purpurea | 1.37 ±0.07 | 2.86±0.39 | Medium, oblong, leaves forming rosettes. Leaf surfaces were leathery. Less prominent epicuticular wax plates were observed on the adaxial surface. |
| *Luzula nivea* (L.) DC. | snow rush | 1.35 ±0.03 | 4.87±0.22 | Medium, linear leaves ("grass-like") with hairy margins. Parallel ridges present in both leaf surfaces. Very few hairs were observed on the leaf blades. |
| *Phyllitis scolopendrium* L. | hart's tongue fern | 1.01 ±0.07 | 18.74±0.87 | Large, broad, leathery fronds forming a rosette. The adaxial surface had deep ridges and groves and abaxial surfaces were smooth or some consist of sori**. |
| *Hyssopus officinalis* L. | hyssop | 0.93 ±0.02 | 0.46±0.03 | Small, lanceolate leaves with a soft (gentle) texture. Leaf surfaces with few glandular hairs and localised, less prominent, epicuticular wax. |
| *Galium odoratum* (L.) Scop. | sweet woodruff | 0.88 ±0.01 | 1.04±0.04 | Small, lanceolate, glabrous leaves forming whorls. Leaf surfaces were smooth. |
| *Helleborus* x *sternii* Turrill | blackthorn strain | 0.72 ±0.01 | 17.9±0.38 | Large, broad leaves with a serrate margin and a leathery surface. Localised deep ridges, groves and slightly prominent epicuticular wax layers were present on the adaxial surface. |
| *Blechnum spicant* (L.) Sm. | hard-fern | 0.59 ±0.04 | 6.67± 0.30 | Medium, pinnate, leathery fronds. The adaxial surface was smooth with few folds and abaxial surfaces were smooth or some consist of sori**. |
| *Fragaria vesca* L. | wild strawberry | not included in the study | | |
| *Galanthus nivalis* L | common snowdrop | not included in the study | | |
| *Lysimachia nummularia* L | golden creeping Jenny | not included in the study | | |

*Leaf shapes as in Hickey and King (2000) **Sori are groups of sporangia find in ferns (Bowler, 1899)

**Table 2**: Weather conditions at the study site during the time of sampling

| Date | Time | Temperature | Wind speed | Humidity | Precipitation |
|---|---|---|---|---|---|
| 19th April 2016 | 11.30 - 13.00 | 14 $^0$C | 3.04 $ms^{-1}$ | 51% | 0 |
| 6th May 2016 | 11.30 - 13.00 | 18 $^0$C | 2.77 $ms^{-1}$ | 49% | 0 |
| 14th May | 11.30 - 13.00 | 15 $^0$C | 2.68 $ms^{-1}$ | 54% | 0 |
| 9th June 2016 | 11.30 - 13.00 | 19 $^0$C | 2.64 $ms^{-1}$ | 56% | 0 |
| 18th June 2016 | 11.30 - 13.00 | 15 $^0$C | 2.68 $ms^{-1}$ | 72% | 0 |
| 4th July 2016 | 11.30 - 13.00 | 19 $^0$C | 3.13 $ms^{-1}$ | 56% | 0 |

**Table 3**: Mean PM density (±SE) per 1 $mm^2$ of a leaf (data for adaxial and abaxial surfaces are combined) of different species of plants on the living wall at New Street Station, Birmingham, UK in 2016

| | **Mean PM density ± SE ($mm^{-2}$) and Tukey's groups of significance** | | | | | |
|---|---|---|---|---|---|---|
| **Species** | **$PM_1$ ± SE x $10^3$** | **Group** | **$PM_{2.5}$ ± SE x $10^3$** | **Group** | **$PM_{10}$ ± SE x $10^3$** | **Group** |
| *B. sempervirens* | 45.03 ± 3.3 | a | 16.46 ±0.9 | a | 3.04 ±0.2 | ab |
| *H. albicans* | 40.41 ±6.2 | a | 13.01 ±1.4 | ab | 2.77 ±0.2 | abc |
| *T. vulgaris* | 27.86 ±2.6 | a | 11.41 ±0.7 | abc | 4.04 ±0.2 | a |
| *H. salicifolia* | 14.76 ±2.4 | b | 8.32 ±1.1 | bcd | 1.87 ±0.2 | cd |
| *G. macrorrhizum* | 12.28 ±2.2 | bc | 2.79 ±0.3 | efgh | 0.90 ±0.1 | efg |
| *H. youngii* | 11.65 ±0.8 | bc | 7.26 ±0.5 | cd | 2.53 ±0.2 | bc |
| *H. helix* | 9.99 ±1.4 | bcd | 4.90 ±0.5 | de | 1.45 ±0.2 | de |
| *E. amygdaloides* | 9.88 ±1.5 | bcd | 4.23 ±0.6 | ef | 1.68 ±0.1 | efg |
| *A. maritima* | 9.24 ±1.1 | bcd | 3.51 ±0.3 | efg | 1.28 ±0.1 | de |
| *P. terminalis* | 8.37 ±1.0 | bcd | 2.51 ±0.2 | fghi | 0.83 ±0.1 | efg |
| *G. odoratum* | 6.87 ±1.3 | cde | 2.79 ±0.4 | efgh | 1.09 ±0.1 | def |
| *P. veris* | 6.58 ±0.8 | cde | 2.17 ±0.2 | ghi | 0.72 ±0.07 | efg |
| *H. officinalis* | 5.82 ±0.8 | def | 2.69 ±0.3 | fgh | 0.90 ±0.09 | efg |
| *H. sternii* | 4.35 ±0.7 | efg | 2.49 ±0.4 | fghi | 0.68 ±0.1 | fg |
| *B. spicant* | 3.08 ±0.3 | efg | 0.74 ±0.06 | j | 0.26 ±0.02 | hi |
| *P. scolopendrium* | 3.01 ±0.5 | fg | 1.47 ±0.1 | ij | 0.21 ±0.03 | i |
| *L. nivea* | 2.78 ±0.4 | g | 1.74 ±0.3 | hi | 0.54 ±0.09 | gh |

Species sharing the same letter/group for a specific PM size range are not significantly different using Tukey's HSD post hoc test with 95% confidence level, P>0.05

**Table 4**. Variations in PM density on adaxial and abaxial surfaces of leaves of different species of plants on a living wall at New Street Station, Birmingham, UK in 2016

| Species | Adaxial surface | | | Abaxial surface | | |
|---|---|---|---|---|---|---|
| | **$PM_1$** | **$PM_{2.5}$** | **$PM_{10}$** | **$PM_1$** | **$PM_{2.5}$** | **$PM_{10}$** |
| | F = 37.5, p <0.001 | F = 34.6, p <0.001 | F = 33.8, p <0.001 | F = 25.5, p <0.001 | F = 64.82, p <0.001 | F = 29.7, p <0.001 |
| *A. maritima* | cde | efg | cde | cde | cd | bcd |
| *B. sempervirens* | a | a | a | ab | ab | bc |
| *B. spicant* | fg | i | g | g | h | f |
| *E. amygdaloides* | cdef | efg | efg | bcde | bc | bcd |
| *G. macrorrhizum* | cd | efg | cde | def | ef | e |
| *G. odoratum* | def | efgh | cdef | efg | de | cde |
| *H. salicifolia* | c | bcd | cd | bcd | b | ab |
| *H. albicans* | b | b | bc | a | a | a |
| *H. helix* | cde | cd | bcd | efg | de | de |
| *H. officinalis* | ef | efgh | cdef | fg | def | de |
| *H. sternii* | fg | fghi | fg | g | de | de |
| *H. youngii* | cd | bc | ab | cde | bc | bc |
| *L. nivea* | g | hi | fg | g | ef | e |
| *P. scolopendrium* | g | ghi | g | g | gh | f |
| *P. terminalis* | cde | def | cdef | fg | h | de |
| *P. veris* | efg | fgh | def | defg | fg | e |
| *T. vulgaris* | b | ab | a | bc | b | Ab |

Species sharing the same letter/group are not significantly different using Tukey's HSD post hoc test with 95% confidence level, p >0.05

**Table 5**: The Mean weight percentage (Wt%) of elements* found in the PM captured on leaves of different species of plants on a living wall at New Street Station, Birmingham, UK in 2016.

| Species | Mean weight percentage of elements in particulates (Wt%) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Al | Ba | Ca | Cl | Co | Cr | Cu | Fe | K | Mg | Mn | N | Na | Ni | P | S | Sb | Si | Ti | Zn |
| *A. maritima* | 0.08 | 0.32 | 4.09 | 0.33 | - | - | 0.10 | 4.52 | 0.18 | 0.05 | - | - | - | - | 0.15 | 2.11 | - | 0.23 | 0.77 | 0.16 |
| *B. sempervirens* | 1.03 | | 7.38 | 0.88 | - | - | - | 0.65 | 0.46 | 0.23 | 3.03 | - | 0.06 | - | 4.84 | 0.50 | - | 0.33 | 30.44 | - |
| *B. spicant* | 1.80 | 1.38 | 2.23 | 1.32 | - | 2.01 | 0.15 | 6.17 | 1.19 | 0.21 | 0.03 | - | 0.54 | 0.67 | 0.07 | 1.33 | - | 3.60 | - | - |
| *E. amygdaloides* | 0.24 | | 2.97 | 0.18 | - | - | - | 0.21 | 0.39 | 0.15 | - | - | 0.02 | - | 0.57 | 0.03 | - | 0.56 | 0.02 | - |
| *G. macrorrhizum* | | 0.09 | 4.00 | 1.49 | - | - | 0.09 | 5.77 | 0.14 | 0.38 | - | - | 0.88 | - | 2.12 | 0.20 | - | 0.05 | - | - |
| *G. odoratum* | 0.07 | 0.21 | 2.60 | 0.36 | 0.05 | - | 0.07 | 17.02 | 1.06 | 0.37 | - | - | 0.04 | - | 0.49 | 0.92 | - | 2.23 | 0.10 | 0.04 |
| *H. albicans* | 0.22 | 0.65 | 1.69 | 2.79 | - | - | 0.53 | 3.29 | 0.21 | 0.34 | - | - | 1.60 | - | 0.14 | 1.09 | - | 2.10 | - | - |
| *H. salicifolia* | 1.87 | 0.04 | 0.86 | 0.01 | - | - | 0.09 | 4.21 | 1.53 | 0.17 | - | - | 0.28 | - | 0.03 | 0.51 | - | 3.99 | 0.03 | - |
| *H. helix* | 0.04 | 0.09 | 4.14 | 0.41 | - | - | 0.09 | 6.14 | 1.29 | 0.49 | - | - | 0.10 | - | 0.20 | 0.15 | - | 0.96 | - | - |
| *H. officinalis* | 0.66 | 0.09 | 2.15 | 0.77 | 0.05 | - | 0.61 | 6.95 | 0.49 | 0.44 | - | - | 0.01 | - | 0.20 | 0.95 | - | 1.84 | 0.21 | 0.42 |
| *H. sternii* | 0.49 | | 2.20 | 0.25 | - | - | 0.01 | 4.56 | 0.22 | 0.31 | 0.01 | - | 0.05 | - | 0.17 | 0.18 | - | 3.26 | 0.01 | - |
| *H. youngii* | 1.06 | 0.23 | 0.14 | - | - | - | 0.01 | 46.21 | 0.57 | 0.08 | 0.39 | 2.14 | - | - | - | - | - | 1.50 | 0.02 | - |
| *L. nivea* | 0.67 | 0.68 | 0.46 | 2.54 | - | - | 0.30 | 19.00 | 0.32 | 0.24 | 0.02 | - | 1.52 | - | 0.07 | 0.25 | - | 1.91 | 0.03 | 0.23 |
| *P. scolopendrium* | 1.19 | 0.09 | 1.11 | 1.24 | - | - | 0.54 | 14.84 | 0.23 | 0.51 | 0.05 | - | 0.32 | - | 0.10 | 0.13 | - | 3.15 | 0.16 | 0.08 |
| *P. terminalis* | 0.17 | - | 2.00 | 0.24 | - | 0.13 | - | 4.05 | 0.39 | 0.22 | 0.09 | 0.08 | 0.02 | - | 0.07 | 0.11 | - | 1.28 | - | - |
| *P. veris* | 0.38 | 0.11 | 8.04 | 0.58 | - | - | 0.30 | 3.64 | 0.60 | 0.98 | - | - | 0.01 | - | 2.11 | 0.26 | 0.11 | 2.06 | - | 0.05 |
| *T. vulgaris* | 0.72 | - | 1.34 | 0.23 | - | - | - | 14.46 | 0.63 | 0.14 | 0.09 | - | 0.04 | - | 0.23 | 0.02 | - | 3.52 | - | - |

*as C and O are mostly derived from plant material, they were excluded from the analysis and hence weight percentages do not add-up to 100%