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RESEARCH ARTICLE

Assessment of plant species suitability in green walls based on API, heavy metal accumulation, and particulate matter capture capacity

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Abstract

One of the most pressing issues confronting the civilized and modern world is air pollution. Particulate matter (PM) is a well-known pollutant that contributes significantly to urban air pollution and has numerous short- and long-term adverse effects on human health. One method of reducing air pollution is to create green spaces, mainly green walls, as a short-term solution. The current study investigated the ability of nine plant species to reduce traffic-related PM using a green wall system installed along a busy road in Mashhad, Iran. The main aims were (1) estimate the tolerance level of plant species on green walls to air pollution using the air pollution tolerance index (APTI); (2) assess the PM capture on the leaves of green wall species using scanning electron microscopy (SEM), energy dispersive X-ray (EDX) analysis, and accumulation of heavy metals using inductively coupled plasma (ICP); (3) select the most tolerance species for reducing air pollution using anticipated performance index (API). The plants' APTI values ranged from 5 to 12. The highest APTI value was found in *Carpobrotus edulis* and *Rosmarinus officinalis*, while *Kochia prostrata* had the lowest. Among the APTI constituents, leaf water content (R^2 = 0.29) and ascorbic acid (R^2 = 0.33) had a positive effect on APTI. According to SEM analysis, many PM_s were adsorbed on the adaxial and abaxial leaf surfaces, as well as near the stomata of *Lavandula angustifolia*, *C. edulis*, *Vinca minor*, and *Hylotelephium* sp. Based on EDX analysis, carbon and oxygen formed the highest amount (more than 60%) of metals detected in the elemental composition of PM deposited on the leaves of all species. The *Sedum reflexum* had the highest Cr, Fe, Pb, and As accumulation. The concentrations of all heavy metals studied in green wall plants were higher than in the control sample. Furthermore, the *C. edulis* is the best plant for planting in industrial, urban areas of the city based on APTI, biological, economic, and social characteristics. It concludes that green walls composed primarily of plants with small leaves can significantly adsorb PM and accumulation of heavy metal.

Keywords Air pollution · APTI · Plant species · Leaf properties Urban area

Introduction

Air pollution is one of the most significant environmental problems that affect health. This pollution is a complex combination of hazardous substances, including gases (e.g., ozone, carbon monoxide, nitrogen, and sulfur oxides) and particulate matter (e.g., $PM_{2.5}$ and PM_{10}) (Heal et al. 2012). Traffic-related PM is known to be responsible for significant volumes of urban pollution (Pant and Harrison 2013; Ranft et al. 2009). Globally, it is estimated that 25% of $PM_{2.5}$ and PM_{10} are generated from road traffic (Karagulian et al. 2015). PM is composed of inorganic and organic matter. Suspended particles with the composition of carbon, hydrocarbons, metals, nitrogen oxides, sulfate, ammonium originate from vehicle exhaust (Fauser 1999; Sharma et al. 2005). Besides, some particles emanate from brake wear, wheel wear, clutch wear, and dust which are called non-exhaust emissions (Thorpe and Harrison 2008; Timmers and Achten 2016; Wåhlin et al. 2006). Some studies have shown a direct link between traffic-related PM and their detrimental effects on health, for example, premature death, cardiovascular disease, allergies, lung cancer, and brain damage (Brook et al.

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2010; Hyun Cho et al. 2005; Maher et al. 2016; Pascal et al. 2014; Ranft et al. 2009).

Despite the gradual improvement in vehicle manufacturing, industrial technologies, and their gas emission control system, air pollution was not reduced. Urgent solutions are still needed to find a sustainable, environmental-friendly alternative that helps prevent pollution levels and their elimination (Prerita Agarwal et al. 2019). Creating green spaces structures is considered a critical way to reduce air pollution in cities. Vegetation act as a pollutant sink (Prerita Agarwal et al. 2019). In the process of photosynthesis, plant leaves absorb and remove air pollutants (e.g., carbon dioxide, nitrogen oxides, sulfur dioxide, and ozone) and result in a reduction in remarkable air pollution (Janhäll 2015). The various types of plants under different environmental conditions have been shown to filter air pollutants, especially PM (Inès Galfati et al. 2011; Innes and Haron 2000; Janhäll 2015; Jun Yang and Gong 2008; Mo et al. 2015; Prerita Agarwal et al. 2019).

Vertical greenery systems received attention because of fast installation, minor land use, decreased dependency on existing soil conditions, and further ecosystem services (Dover 2015; Green 2004). Vertical green structures are divided into two primary forms green facades (green walls) and green wall systems. The green facade is composed of ivy plants with roots in the soil and grows upwards using climbing aids such as frames and wires, giving the wall a green cover facade. Green facades are cheap and stable and require less care than green walls. The limited choice of plants species, the need for time to complete the entire green facade, destruction of the walls of buildings are its main drawbacks (Dover 2015). An advanced type of vertical greenery system is living green walls, which simplify the growth of various plant species (Dover 2015). The green wall system consists of plants, each planted independently in pots and boxes attached to the wall, and a regular irrigation system (Bustami et al. 2018). In a green wall system, various plant species, including mosses, lichens, herbaceous plants, shrubs, and climbing plants, can be planted side by side; if a plant is damaged, it can easily be replaced without damaging other plants (Ottelé et al. 2010). To implement these systems, more costs are required for the standard installation and maintenance of structures (Perini and Rosasco 2013). Using living and green walls has many benefits in the urban environment, including visual beauty, improving air quality, trapping PM, energy storage, temperature control in indoor and outdoor environments, playing the role of sound insulation, increasing biodiversity, enhancing the health of residents, as well as their many cultural and social benefits (Madre et al. 2015; Bustami et al. 2018; Weerakkody et al. 2018a; Veisten et al. 2012).

Green infrastructure was recognized as a short solution to PM pollution remediation (Perini et al. 2011; Weerakkody et al. 2017a). Recently, several studies focused on the effectiveness of vertical greenery systems for capturing PM. For example, Weerakkody et al. (Weerakkody et al. 2018b) investigated the effect of individual leaf traits on traffic-generated PM accumulation in green walls in the UK. Their findings indicated that the size (smaller) and shape (lobed) of leaves was two influencing factors in capturing and retaining PM. Also, the impact of planting designs and topographical dynamics in green walls on PM deposition was examined by Weerakkody et al. (Weerakkody et al. 2019). They found that a planting design with heterogeneous topography using a plant with varying heights deposited more PM than homogenous topography consisting of plants with the same heights. Moreover, Paull et al. (Paull et al. 2020) assessed the effectiveness of 12 green walls in Sydney to reduce PM, noise pollution, and temperature conditions. The results revealed that PM concentrations and temperature did not significantly vary between the green wall and reference wall sites. They proposed that the active green walls may have a higher capacity for PM removal, and more research in this area is required. In addition, Srbinovska et al. (2021) quantified the impact of the small green wall on PM concentration in Skopje, North Macedonia. Their findings showed a 25 and 37% reduction in $PM_{2.5}$ and PM_{10} levels compared to neighboring non-green areas. Further research on the capacity of green infrastructure for air pollution removal in dense urban areas is recommended. Besides, Weerakkody et al. (2017b) studied the inter-species variation among green walls species for PM removal at New Street railway station, Birmingham, UK. Their results displayed that hairy-leaved species adsorbed smaller PM while a plant with epicuticular wax and surface morphology of leaves trapped all sizes of PM. They stated that to draw more precise conclusions, further research on more plant species is needed. Based on the above studies, several parameters, including climate, pollutant conditions, type of plant species, and type of green structures, affected the ability of vertical greenery systems to reduce PM. Therefore, not only the potential of inter-species variation for capturing PM on green walls was investigated but also the impact of PM on physiological and biochemical characters of the plants (APTI index) and their social and economic characteristics (API index) for determining the sensitivity of plant species to air pollutants was studied.

In the light of discussion as mentioned earlier, the current research was conducted to follow three main objectives: (1) assess the PM capture of various green wall species using SEM and EDX analysis and accumulation of heavy metals on their leaves; (2) estimate the tolerance level of plant species on green walls to air pollution using the APTI and API; (3) and select the most tolerant species for air pollution reduction in Mashhad.

Materials and method

Chemicals

All chemicals including nitric acid (HNO_3), hydrogen chloride (HCl), acetone 80%, metaphosphoric acid, 2,6 dichlorophenolindophenol (DCIP), 2,4-dinitrophenylhydrazine (DNPH), thiourea, and sulfuric acid (H_2SO4) were purchased from the German company Merck.

Site description

This study was conducted in Mashhad with 59° 36′ and latitude of 36° 17′ in Khorasan Razavi province, located in northeastern Iran. Mashhad, with a population of 3.2 million inhabitants, is the second most populous metropolis in Iran and the 95th most populous city in the world. The high rate of population growth, manufacturing industrial activities, and the high number of vehicles are all reasons for air pollution. Two green wall structures were designed with the following characteristics and installed at the crossroads of South Khayyam Boulevard along the side of the street in the autumn of 2019 (Fig. 1). According to the information obtained from the air pollution monitoring station, which was located near the green wall, this crossroads is one of the most polluted places in Mashhad.

Active green wall design and plant materials

The green walls had dimensions of 2.09 m × 3.98 m and were waterproof steel. This body had a vertical and horizontal grid network, and wicker baskets were installed on its sides to use more space for planting plants. A total of 48 pot boxes made of compressed plastic were placed on floors of the walls (six boxes in each row). At the bottom of these boxes, there were holes for water to pass through. To keep more strength and durability of the green wall for a long time, the boxes were connected from the back of the pot body with metal wire. After filling pots with soil and fertilizer, 260 plants (ten different plant species) were planted on the green wall floors. Three replicates of each plant species were also grown in a greenhouse, away from air pollution sources, with similar soil and watering conditions. This sample served as a control. Ten plant species belonging to seven families, with various leaf morphotypes including morphology, size, and shape, were chosen. Table 1 shows the scientific and common names of these plants, their biological characteristics as well as the morphological characteristics of their leaves.

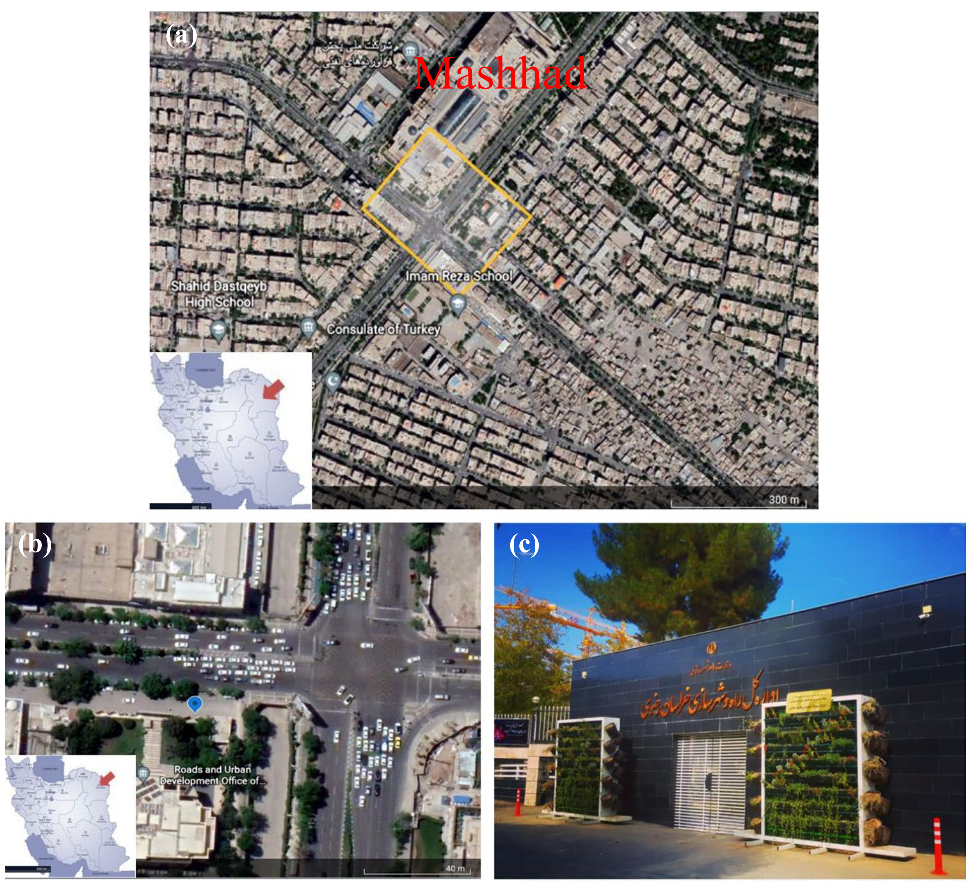
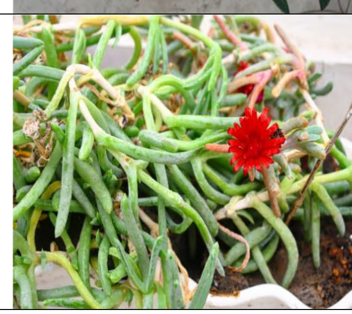


Fig. 1 **a** The location of the study site in Mashhad, Iran, **b** and the location of the living green wall relative to the road, and **c** its location in street

Table 1 The characteristics of plant species used in this study

Scientific Name	Common name	Family	Morphological characterizes	Image
Rosmarinus officinalis	Rosemary	Lamiaceae	Aromatic evergreen shrub plant with many leaves, tall (about 2.5 cm), hard, needle-like leaves	
Lavandula angustifolia	English Lavender	Lamiaceae	Aromatic shrub, evergreen and semi-woody plant with long, soft and hairy leaves, lilac and purple flowers	
Carpobrotus edulis	Ice plant	Aizoaceae	ground-creeping plan, Evergreen succulent, thick, fleshy and curved leaves	
Malephora crocea	Red ice plant	Aizoaceae	Green cover plant with succulent, thick, simple and linear leaves	

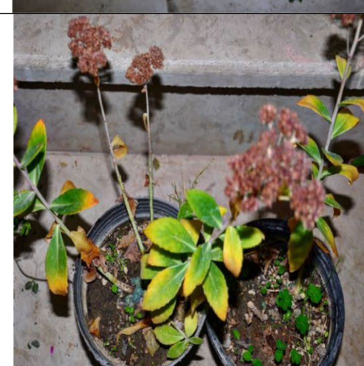
Leaf sampling

The leaf sampling was carried out after 10 weeks exposing the green wall to air pollution. Before sampling, all plants were washed once with high-pressure water to clean the leaf surfaces from air-suspended particles. Sampling was performed in dry air condition for 6 days. Three mature and healthy leaves were randomly taken from each species per day (6 days × 3 leaves per day = 18 leaves) from the six middle rows of each green wall. The samples were all placed in a plastic box that was pre-washed and cleaned.

Air pollution tolerance index

All plant leaves samples were transferred to the laboratory immediately after sampling to conduct APTI tests. Four

Table 1 (continued)

Vinca minor	Dwarf periwinkle	Apocynaceae	Trailing subshrub, evergreen, broad, glossy dark green leaves with a leathery texture	
Frankenia thymifolia	Sea heath	Frankeniaceae	Evergreen shrub or subshrub, simple , generally small and somewhat heather-like leaves	
Sedum reflexum	reflexed stonecrop	Crassulaceae	Flowery shrub plant with simple, alternate and succulent leaves	
Hylotelephium sp	Stone crop	Crassulaceae	Herbaceous plant with smooth fleshy leaves, thick, opposite and oval shape	
Kochia Prostrata	Forage Kochia	Amaranthaceae	Shrub with alternate, simple, oval, linear and slender leaves	

factors involved in APTI were analyzed together simultaneously, according to the following procedure.

pH

The pH of plant leaves was measured based on the method of Liu and Ding (Liu and Ding 2008). Four grams of fresh leaves were crushed with liquid nitrogen and then homogenized with 40 mL of distilled water. The mixture was centrifuged (14R, Velocity, Germany) for 20 min at 3000 rpm, and the pH of the supernatant was measured using a pH meter (Milwaukee 151, Romania).

Relative water content (RWC)

The RWC of plant leaves was determined based on the protocol of Liu and Ding (Liu and Ding 2008). The fresh weight (FW) of plant leaf was measured with a digital scale (GR-200, Germany). Then, the samples were transferred to beakers containing distilled water and refrigerated for 24 h at 4°C. After that, they were dried with Whatman filter paper, and their turgid weight (TW) was re-measured. Finally, the samples were placed in an oven at 70°C for 24 h, and the dry weight (DW) was measured. The RWC was calculated with the following formula.

$$\text{RWC} = \frac{FW - DW}{TW - DW} \times 100 \tag{1}$$

Total chlorophyll content (TCC)

To calculate the total chlorophyll concentration, the chlorophyll a and b contents were measured with the method described by (Arnon 1967). Of fresh leaves, 0.5 g were crushed in liquid nitrogen and then homogenized in 20 mL of 80% acetone (v/v). The mixture was centrifuged for 10 min at 6000 rpm. The supernatant was passed through a filter paper to remove any suspended solids, and its absorption at 663 and 645 nm was recorded using a UV-Vis spectrophotometer (DR 5000, HACH, USA). The quantity of chlorophyll a, chlorophyll b, and total chlorophyll were calculated using the following equations.

$$\text{Chlorophyll a} = \left[\left(12.7 \times \text{A}_{663} \right) - \left(2.69 \times \text{A}_{645} \right) \right] \times \text{final volume} \tag{2}$$

$$\text{Chlorophyll a} = \left[\left(22.9 \times \text{A}_{645}\right) - \left(4.68 \times \text{A}_{663}\right) \right] \times \text{final volume} \tag{3}$$

$$\text{TCC} = (\text{chlorophyll a} + \text{chlorophyll b}) \times \text{final volume} \tag{4}$$

Ascorbic acid content (A)

The ascorbic acid content of leaves was measured using the method of Hewitt and Dickes (Hewitt and Dickes 1961) using spectrophotometric analysis. One gram of leaf sample was homogenized entirely with 20 mL of 5% metaphosphoric acid solution. Then, the obtained samples were centrifuged at 8000 rpm for 20 min at 4°C. After that, 0.5 mL of 2,6-dichloroindophenol (DCIP) solution was added to a 1-mL supernatant oxidize ascorbic acid to dehydroascorbic acid. Then, 1 g of thiourea was dissolved in 100 mL of a 5% metaphosphoric acid solution to make 1% thiourea solution. One milliliter of 1% thiourea was added to two tubes (for measuring total ascorbic acid and oxidized ascorbic acid). The samples remained stationary for 20 min. To form 2 and 4 dinitrophenyl hydrazine derivatives of dehydroascorbic acid, 1 ml of a solution of DNPH (10 mM) was added to samples. All test tubes were immersed in a 50°C water bath for 1 h and then kept in an ice bath for 20 min. The absorbance of each sample was measured at 520 nm using a spectrophotometer model (UV/VIS, SP-3000 Plus, Japan). The detection and quantification limits of ascorbic acid were found to be 0.5 and 2 μg /mL, respectively. The calibration curve, shown in Fig. 1S, was used to quantify the ascorbic acid content of samples.

Air pollution tolerance index calculation

APTI indicates the tolerance and tolerance of plants planted in green walls against air pollution. It was calculated from above discussed biochemical parameters using the following formula described by Singh et al. (Singh et al. 1991):

$$\text{APTI} = \frac{A(T + P) + R}{10} \tag{5}$$

where A is the ascorbic acid content of the fresh plant (mg/g), T is the total chlorophyll content of the fresh plant (mg/g), P is the pH of the leaf extract, and R is the relative water content (%).

Anticipated performance index

API was estimated by integrating the findings of APTI accompanied with biological (plant habitat, canopy structure, type of plant, canopy structure, and laminar structure), social, and economic characteristics of plants. These properties of all green wall plants were initially identified. The grades (+ or −) for each attribute were assigned based on various plant-related criteria shown in Table 2. A negative score is given to plants with small habitats, scattered and irregular and spherical canopy, deciduous, with small

Table 2 Gradation of plant species based on APTI values and other biological and socio-economic characters

Grading	Characters assessed	Pattern assessment	Category	Grade allotted
Tolerance	Air pollution tolerance index (APTI)	5–6		+
		6.1–7		++
		7.1–8		+++
		8.1–9		++++
		9.1-10		+++++
		10.1–11		++++++
		11.1–12		+++++++
Biological and socio-economic	Plant habitat	Small		-
		Medium		+
		Large		++
	Canopy structure	Sparse/irregular/globular		-
		Spreading crown/open/semi-dense		+
		Spreading dense		++
	Type of plant	Deciduous		-
		Evergreen		+
	Laminar structure	Size	Small	-
			Medium	+
			Large	++
		Texture	Smooth	-
			Coriaceous	+
		Hardiness	Delineate	-
			Hardy	+
	Economic value	Less than three uses		–
		Three or four uses		+
		Five or more uses		++

A plant's maximum grade is 16

size, soft texture, and low hardness. In contrast, plants with medium and large habitats, spreading and open canopy, dense and semi-dense, evergreen, with medium and large size, leathery texture, and high hardness are given positive points. After that, the grades were aggregated for each plant and transformed into scores. Scoring of plant species was performed according to their multifaceted traits (Mondal et al. 2011; Rai 2019). The maximum score assigned to each plant is 16 based on the number of positive points (+). Next, according to Kaur and Nagpal (2017), the score was converted to percentages using the equation below to represent the API quantity of a specific species. Finally, the API percentage were used to classify the plant species' performance levels, which ranged from not recommended to best (Table 3).

$$\%\ score = \frac{\text{Grades obtained by plant species}}{\text{Maximum possible grades for any plant species}} \times 100 \quad (6)$$

Table 3 Evaluation criteria for determining API values and assessment categories of plants

API value (grade)	Score (%)	Assessment category
0	Up to 30	Not recommended
1	31–40	Very poor
2	41–50	Poor
3	51–60	Moderate
4	61-70	Good
5	71–80	Very good
6	81–90	Excellent
7	91–100	Best

Scanning electron microscope analysis

Leaves sample preparation for visualization under SEM was conducted according to Pathan et al. (Pathan et al. 2010). All samples were air-dried slowly without pre-treatment at room temperature. An SEM apparatus (LEO, 1450VP, Germany) was employed to image the suspended particles on the leaves and the leaf micromorphology (stomata and leaf roughness).

The adaxial and abaxial surface of each leaves larger than 2.5 mm^2 was split. For smaller leaves, it is cut into two halves and then one-half to image the adaxial surface and one for the abaxial surface. Needle leaves were examined without fragmentation, and the scanned points were selected only from the middle part of the leaf. The SEM images of surface structures (e.g., leaf hairs and trichomes) were taken at 90×, 100×, and 250× while leaf stomata, grooves, and ridges were scanned at 350× and 400×. For each character of plant species, ten random micrographs were taken due to their uneven distribution on leaves. Using ImageJ's particle analyzer, the number of PM on the micrographs was counted. On leaf surfaces, the density of each PM size fraction was calculated as particle counts per one mm^2. By adding the PM densities on the adaxial and abaxial surfaces of individual leaves, the densities of each PM size fraction on individual leaves were calculated.

EDX analysis

The elemental composition of captured PM was determined while the leaves were scanned with SEM for their PM characteristics ("Scanning electron microscope analysis"). When PM focused at 1000× at 15 Kv accelerating voltage, the scanned leaves areas were obtained in INCA software (integrated measurement and calibration environment) coupled with the SEM. The identification of elements and their amounts (as the total weight of the PM, wt. %) was conducted with the point and ID analyzer.

Heavy metal analysis

The heavy metal contents of the plant were measured by the acid digestion method described by Uddin et al. (2016). First, 0.5 g of powdered plant sample, which dried at 70°C in the oven, was placed in a PTFE tube. Next, 2.25 mL of HNO_3 (65%) and 6.75 mL of HCl (37%) were added. Then, the mixture was heated at 95°C for 5 h. After that, the samples were filtered with Whatman filter paper, and the extract was diluted with deionized paper to make the volume of 20 mL. Finally, the concentration of heavy metals in the filtrate was measured using ICP (76004555, SPECTRO ACROS System).

Statistical data analysis

Data analysis was performed using MINITAB 17 statistical software. Linear regression analysis was conducted between independent variables (e.g., chlorophyll, ascorbic acid, RWC, and pH) and the dependent variable (APTI). One-way ANOVA was utilized to investigate the significant differences between the independent variables. Each sample analysis was carried out with triplicate, and data were expressed as mean ± standard deviation.

Results and discussions

APTI analysis

Biochemical parameters of the leaves (e.g., pH, RWC, ascorbic acid, total chlorophyll) and their APTI data are shown in Table 4.

pH

The pH values of leaf extract ranged from 5 to 7 (Table 4). The highest amount (7.05) was related to *Hylotelephium sp* from Crassulaceae, and the lowest amount (5.4) was related to *Malephora crocea* from Aizoaceae. According to the literature, the pH extracted from plant leaves is lower in the presence of acidic contaminants (Achakzai et al. 2017;

Table 4 The calculated indices and the obtained results of APTI of green wall plants, species that do not have common letters, are significantly different

Plants	APTI factors				Results
Species	pH	RWC (%)	Total chlorophyll (mg/g)	Ascorbic acid (mg/g)	APTI
Frankenia thymifolia	$(6.4\pm0.3)^{a}$	$(79.73\pm5)^{a}$	$(1.27\pm0.08)^{a}$	$(2.004\pm0.99)^{cd}$	$(9.51\pm1.21)^{bc}$
Carpobrotus edulis	$(6.5\pm0.2)^{a}$	$(81.94\pm0.04)^{a}$	$(0.49\pm0.009)^{cd}$	$(5.76\pm0.66)^{ab}$	$(12.29\pm0.59)^{a}$
Malephora crocea	$(5.8\pm0.5)^{b}$	$(83.58\pm4.1)^{a}$	$(0.27\pm0.01)^{cd}$	$(1\pm0.17)^{d}$	$(8.97\pm0.25)^{bc}$
Lavandula angustifolia	$(6.8\pm0.1)^{a}$	$(49.04\pm12.7)^{bc}$	$(0.7\pm0.68)^{bc}$	$(5.57\pm2.22)^{ab}$	$(9.19\pm0.68)^{bc}$
Rosmarinus officinalis	$(6.8\pm0.07)^{a}$	$(55.35\pm5.7)^{b}$	$(1.43\pm0.03)^{a}$	$(6.23\pm3.73)^{a}$	$(10.7\pm2.44)^{ab}$
Sedum reflexum	$(6.8\pm0)^{a}$	$(56.87\pm6.3)^{b}$	$(0.1\pm0.03)^{d}$	$(4.69\pm0.21)^{abc}$	$(8.93\pm0.78)^{bc}$
Hylotelephium sp	$(6.8\pm0.2)^{a}$	$(77.61\pm10.7)^{a}$	$(1.37\pm0.07)^{a}$	$(1.38\pm0.69)^{cd}$	$(8.84\pm1.59)^{bc}$
Vinca minor	$(6.8\pm0)^{a}$	$(46.74\pm1.9)^{bc}$	$(0.14\pm0.05)^{d}$	$(3.93\pm0.4)^{abcd}$	$(7.41\pm0.05)^{cd}$
Kochia Prostrata	$(6.8\pm0.07)^{a}$	$(38.96\pm0.8)^{c}$	$(1.17\pm0.006)^{ab}$	$(2.37\pm0.21)^{bcd}$	$(5.81\pm0.06)^{d}$

Different letters show the statistical significance

Pandey et al. 2016; Scholz and Reck 1977). The presence of acidic pollutants such as SO_2 and NO_2, and PM from industrial emissions in the air may change the leaf pH to acidic in the plant (Chauhan 2010; Swami et al. 2004). When plants are exposed to air pollution (especially SO_2), they produce large amounts of H^+ ions in their cell fluid to combine with the SO_2, which enter through guard cells, stomata; therefore, H_2SO_4 is produced and decreases the plant pH (Zhen 2000a). This reduction rate is much higher in susceptible plants than tolerant plant species (Scholz and Reck 1977). Besides, the high pH of plants, especially in polluted conditions, indicates an increase in their tolerance to acidic air pollutants (Govindaraju et al. 2012).

Relative water content

The relative water content (RWC) of the green wall plants was summarized in Table 4. Their average values vary significantly from 30 to 90%. *M. crocea* (83%) and *Hylotelephium* sp. (81%) had the highest amounts. *K. prostrate* (38%), *Vinca minor* (46%), and *L. angustifolia* (49%) had the lowest. The high leaf water content helps plants retain physiological balance under stressful conditions such as air pollution (Dedio 1975; Meerabai et al. 2012). When plant exposure to air contaminants, the rate of transpiration frequently becomes higher, which may lead to their drying; therefore, RWC can be considered an influential factor in resistance to pollution stress (Krishnaveni et al. 2013). Increasing the amount of RWC in plant species indicates better performance concerning drought tolerance, indicating the typical performance of biological processes (Rai et al. 2013). Besides, differences between RWC values are dependent on plant species (Jyothi and Jaya 2010; Singh et al. 1991). For example, *L. angustifolia*, a small evergreen shrub with scented leaf and blooms, belongs to the Lamiaceae family. In moderate drought circumstances, *L. angustifolia* has morphological traits that limit water loss while maintaining visual attractiveness. Furthermore, the gray-blue, hairy features of its leaves restrict light absorbance and airflow across the leaves, lowering water loss.

Ascorbic acid

Ascorbic acid contents of plants located in the green wall were summarized in Table 4, displaying a 0.5–9 (mg/g) (Table 4). The highest values (8.875 mg/g) were related to *R. officinalis* from *Lamiaceae*, and the lowest values were related to *M. crocea* (0.878 mg/g) and *Hylotelephium* sp. (0.845 mg/g) from *Aizoaceae and Crassulaceae*. A statistically significant variation was perceived in the concentration of ascorbic acid among plant families. Ascorbic acid plays a crucial role in cell wall synthesis, defense, photosynthetic process, and cell division (Conklin 2001). Ascorbic acid acts as an antioxidant in the plant, often found in the growing parts of plants, and increases the plant's tolerance to air pollution (Liu and Ding 2008; Pathak et al. 2011). In other words, it reduces the accumulation of active oxygen in the leaves of plant species as a defense mechanism, thus raising the plant's tolerance to air pollution (Chaudhary and Rao 1977; Pandey et al. 2016). Due to its importance in plant life, it is one of the factors examined in the APTI formula (Nwadinigwe 2014). Ascorbic acid, as a stress-reducing agent, is generally higher in stress-tolerant plant species, while its low content in plant species makes them sensitive to air pollution stress (Rai 2016; Zhang et al. 2016).

Chlorophyll content

Table 4 shows the total chlorophyll content of the studied plants, ranging between 0.05 and 1.5 (mg/g). The highest amount (more than 1.4 mg/g) of total chlorophyll is related to *R. officinalis* from *Lamiaceae* and *Hylotelephium* sp. from *Crassulaceae*. The lowest value (0.08 mg/g) was found in *S. reflexum* from *Crassulaceae*. Chlorophyll is one of the most significant plant metabolites in stressful situations, and its high levels cause tolerance to environmental contaminants (Joshi and Chauhan 2008; Prajapati and Tripathi 2008). Air pollution degrades photosynthetic pigments in plant leaves, and this degradation is widely used as an indicator of air pollution (Joshi et al. 2009; Joshi and Chauhan 2008; Ninave et al. 2001; Rai 2016). In air pollution stress, the alkaline and acidic contaminants (SOx and NO_X) cause chlorophyll degradation in the plant by blocking the guard cells and forming pheophytin (Joshi et al. 2011; Rai 2016). In general, high levels of chlorophyll in plants increase tolerance to air pollution (Prajapati and Tripathi 2008). However, the chlorophyll content of plants varies based on the level of contamination in their environment and their tolerance or susceptibility (Rai and Panda 2015).

Linear regression analysis

Fig. 2S exhibits the linear regression analysis between biochemical variables and APTI values. As shown, there is no significant influence of pH (R^2= 0.059) and total chlorophyll content (R^2= 0.001) on APTI. On the contrary, the leaf water content (R^2 = 0.2959) and ascorbic acid (R^2= 0.33) showed a positive effect on APTI. These results agree with Kaur and Nagpal (Kaur and Nagpal 2017), which reported the significant strong positive impact of ascorbic acid on APTI.

APTI

Calculated APTI values of green wall plants are shown in Table 4. The APTI values of the plants varied between 5 and 12. The highest value (more than 12) of APTI was obtained

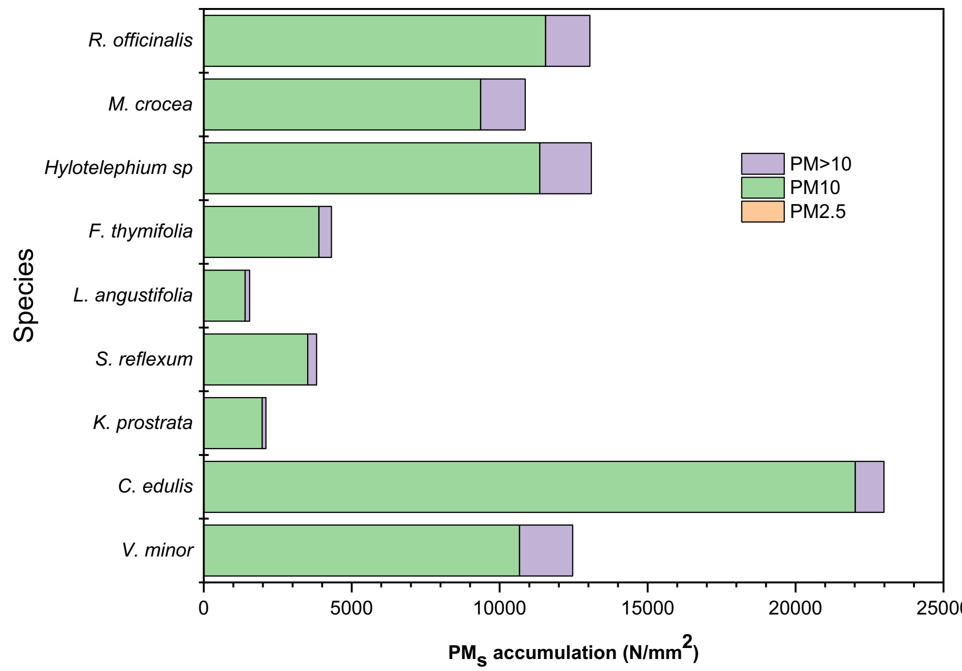


Fig. 2 Accumulation of particles on leaves of plant species

for *C. edulis* and *R. officinalis*, while *K. prostrata* presented the lowest quantity (5.7). APTI is calculated using those as mentioned above four biochemical parameters, which examine the level of sensitivity of any plant to air pollution (Singh et al. 1991). The importance of APTI in detecting tolerance or susceptibility of plant species was investigated by many researchers (Bamniya et al. 2012; Kaur and Nagpal 2017; Prajapati and Tripathi 2008; Rai 2016). In general, plants with high levels of APTI are tolerant to air pollution and can be used as filters to absorb and reduce air pollution, while plants with low levels of APTI are sensitive and can be used as environmental bioindicators (Nayak et al. 2018). Different plants presented various APTI index values (shown in Table 4), which depend on the concentration of air pollution and the environment in they are planted or grown (Gupta et al. 2016; Rai 2016). For instance, suspended particles increase APTI in the plant after deposition on the leaf surface (Gupta et al. 2016). This study indicated that *C. edulis* and *R. officinalis* are tolerant to air pollution, while *K. prostrata* is sensitive species.

API analysis

The calculated API index of the plant species planted in green walls is shown in Table 5. Based on the evaluation of the tolerance index, biological, economic, and social characteristics, *C. edulis* is the best plant for planting in industrial, urban areas of the city. After that, *L. angustifolia* and *R. officinalis* were assessed as excellent plants, while *M. crocea* and *S. reflexum* were considered good plants. Despite having a moderate APTI index when compared to other plant species, *L. angustifolia* was considered the excellent choice for several reasons: (1) large habitat size, (2) dense canopy, (3) evergreen nature, (4) hard texture, and (5) various socio-economic features (use in medicine, industry cosmetics, landscape design, etc. (Cavanagh and Wilkinson 2005)). *Hylotelephium* sp. and *Frankenia. thymifolia* were classified as poor and very poor plants due to the lack of suitable characteristics, e.g., low APTI values. *V. minor* and *K. prostrata* obtained the lowest API index value are not recommended for planting in polluted areas.

The API score, like the APTI value, can be used as a bio-accumulation indicator, while a low API value is considered a biomarker of vehicle pollution. Determining the performance of plants using APTI and API is a reliable method for selecting appropriate species for planting in green spaces of industrialized regions and traffic points (Kaur and Nagpal 2017).

SEM analysis

The leaf surface characteristics of plants play a critical role in capturing atmospheric PM and their different effect on their capability to retain atmospheric PM (Mo et al. 2015). To investigate the effects of plant leaf structure on adsorbing particles, the leaves of plant species located in green walls were observed with SEM. From Table 6, many particles adsorbed on the adaxial and the abaxial leave surfaces and the vicinity of the stomata in lavender, *C. edulis*, *V. minor*, and *Hylotelephium* sp. Some researchers, for example, Ram et al. (2014), Ottelé et al. (2010), and Weerakkody et al. (2017b, 2018c) proved that the highest accumulation

Table 5 API of plant species located in the green walls

Plant names	APTI value	Habit	Canopy structure	Plant type	Laminar structure			Economic Values	Grades Allotted		API degree	Assessment
					Size	Texture	Hardiness		Total+	Score (%)		
Carpobrotus edulis	++++++	++	++	+	++	-	+	+	15	93.75	7	Best
Malephora crocea	+++	++	++	+	+	-	-	+	10	62.5	4	Good
Hylotelephium sp	+++	+	+	-	+	-	+	+	8	50	2	Poor
Lavandula angustifolia	++++	++	++	+	+	+	+	++	14	87.5	6	Excellent
Rosmarinus officinalis	+++++	++	+	-	+	+	+	++	13	81.25	6	Excellent
Sedum reflexum	+++	++	+	+	-	+	+	+	10	62.5	4	Good
Frankenia thymifolia	++++	-	-	-	-	+	+	-	6	37.5	1	Very poor
Vinca minor	++	-	-	-	-	-	-	-	2	12.5	0	Not Recommended
Kochia Prostrata	-	-	-	+	+	+	+	-	4	25	0	Not recommended

of particulate matters happened on adaxial surfaces of leaves. Although the PM accumulation on the adaxial and abaxial leaf surfaces was different, some plant structure parameters have affected this, which cannot be observed by SEM images. Plant hairs, trichomes, and non-smooth surfaces have been identified as auxiliaries in the accumulation and storage of suspended particles (Aguilera Sammaritano et al. 2021; Barima et al. 2014; Räsänen et al. 2013; Weerakkody et al. 2017a, 2018b; Zhang et al. 2017b). Besides, the grooves and their properties, deep or shallow, play a crucial role in PM adsorption. In other words, deep grooves capture more particles. Stomatal density in the plant leaf dreaminess the quantity of PM capturing. The plants, which have relatively low stomatal density, exhibit a high potential retention of fine particles (Mo et al. 2015). This phenomenon can be seen from the SEM image of *R. officinalis*, *S. reflexum*, and *K. prostrata*, in which large numbers of particles accumulate on its adaxial leaf surfaces. The *S. reflexum* image shows the accumulation of large numbers of particles, probably due to small, needle-shaped leaves, as well as the existence of grooves.

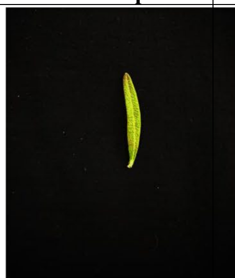
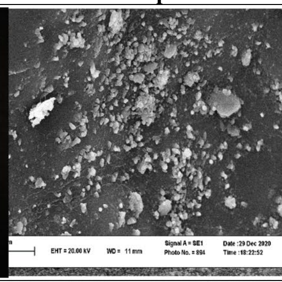
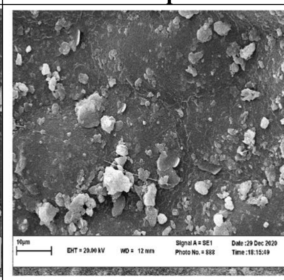
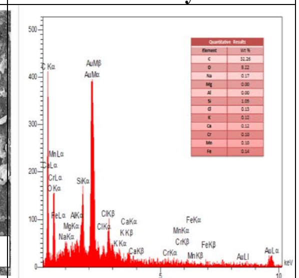
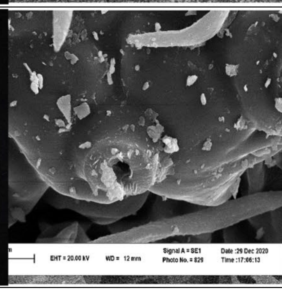
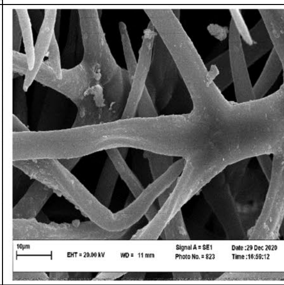
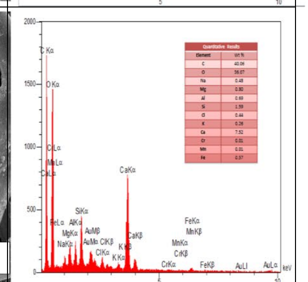
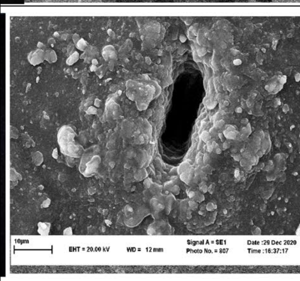
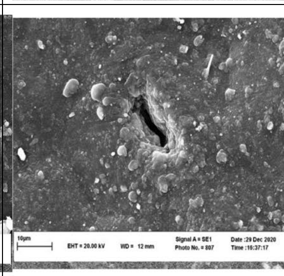
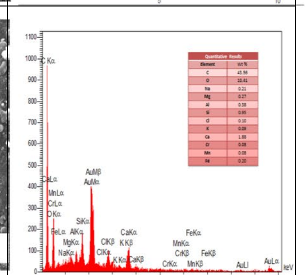
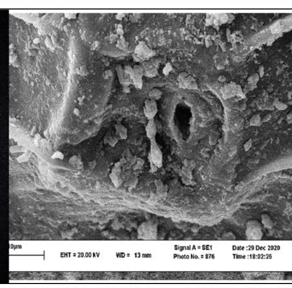
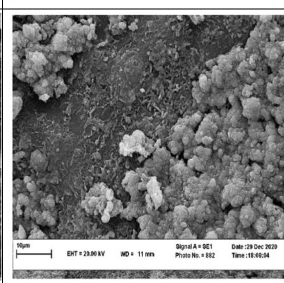
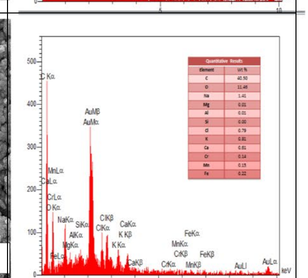
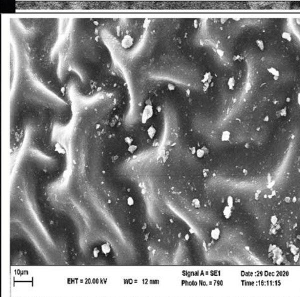
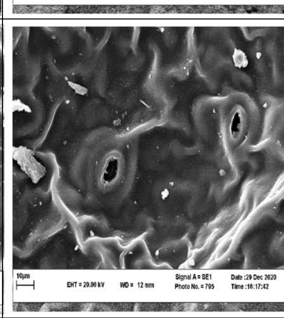
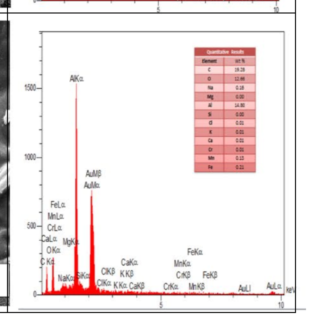
Although the PM accumulation on the adaxial and abaxial leaf surfaces was different, some plant structure parameters have affected this, which cannot be observed by SEM images. Plant hairs, trichomes, the non-smooth surface have been identified as auxiliaries in the accumulation and storage of suspended particles (Barima et al. 2014; Räsänen et al. 2013; Weerakkody et al. 2017a, 2018b; Zhang et al. 2017a). In this study, lavender has unique morphological characteristics and many hairs, demonstrates its ability to trap and adsorb suspended particles on the leaf surface.

Figure 2 depicts the density of particles deposited in the leaves of nine plant species. As illustrated in this diagram, particulate matter accumulation capacity of plants varies. The average particle number density was 9425 mm^{-2}. The lowest density was found in *L. angustifolia* (1548 N/mm^2), while the maximum density was found in *C. edulis* (23495 N/mm^2). More than 85% of the particles accumulating on the leaf surface were in the PM_{10} range. Differences in total suspended particle accumulation between species reflect the unique properties of each leaf in PM aggregation (Aguilera Sammaritano et al. 2021; Shi et al. 2017; Weerakkody et al. 2017b, 2018c).

Elemental composition analysis

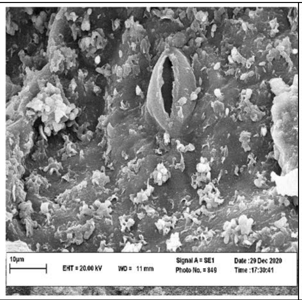
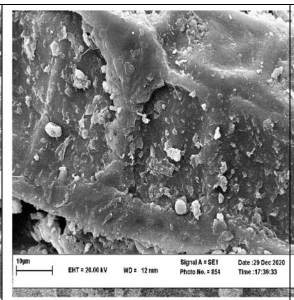
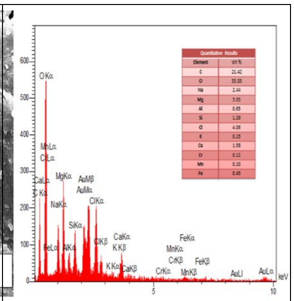
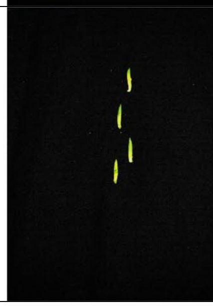
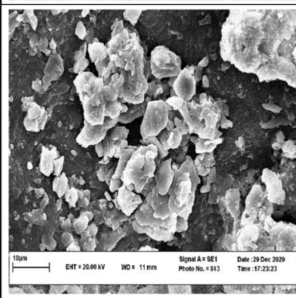
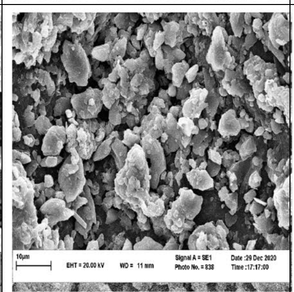
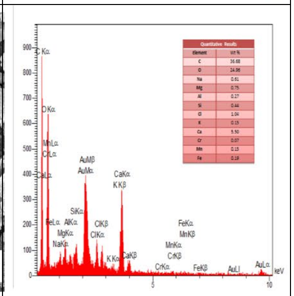
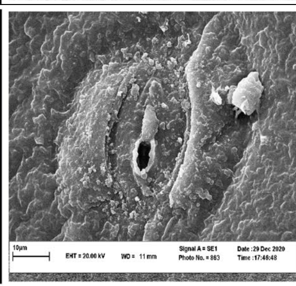
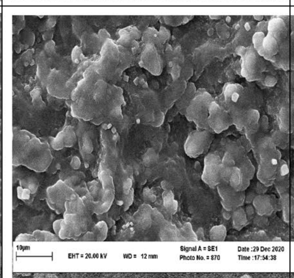
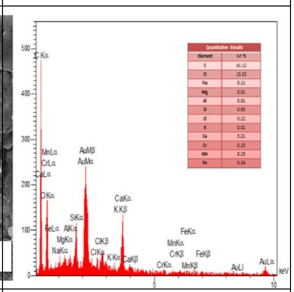
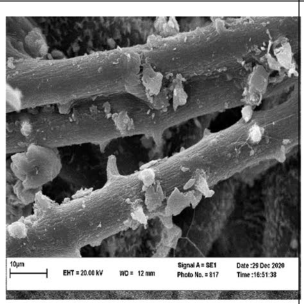
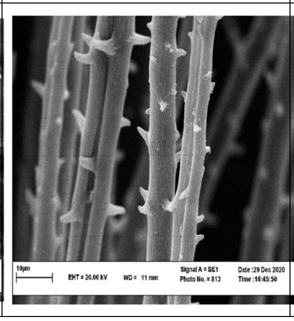
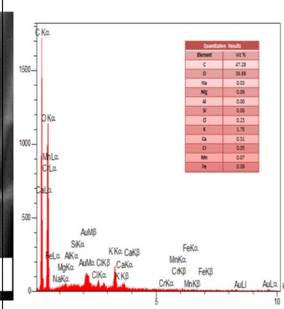
Table 6 displays the elemental composition of particulate matter deposited on plant leaves using EDX analysis. From the figures inside this table, it can be seen that all the plants had a very similar elemental composition. Carbon had the highest amount of detected metals across all species, ranging from 19 to 47%. *L. angustifolia*, *C. edulis*, *Hylotelephium* sp., and *K. Prostrata* displayed more than 40% carbon. The

Table 6 SEM photomicrographs of adaxial and abaxial surfaces of plant leaves and their EDX results in magnification of 5000

Plant	Leaf shape	Adaxial part	Abaxial part	EDX Analysis
Rosmarinus officinalis				
Lavandula angustifolia				
Carpobrotus edulis				
Malephora crocea				
Vinca minor				

second most abundant element observed in the DEX of all species was oxygen, with a value in the range of 9–36%. *K. prostrata*, *F. thymifolia*, and *L. angustifolia* had the maximum quantity (more than 30%). Ca, K, Mg, Si, and Al were found in the EDX of all plant species with values less than 3%. It is good to mention that three plants have higher Ca contents of 3% (*L. angustifolia*; 7%, *S. reflexum*; 5%, and *Hylotelephium* sp.; 3%). The elemental composition of trapped particulates is classified into three categories: (1) mineral particles, (2) metallic particles, and (3) biogenic particles. The minerals particles comprised Al, Si, O, Ca, Fe, K, Mg, which originated from various kinds of aluminum silicates of soil. Pollen is the central part of biogenic particles. The central elements of pollen are C, O, Si (Heredia

Table 6 (continued)

Frankenia thymifolia				
Sedum reflexum				
Hylotelephium sp				
Kochia Prostrata				

Rivera and Gerardo Rodriguez 2016). Thus, it can be concluded that the particles containing Si, Al, K, Mg, and Ca originated from dust. As shown in Table 6, Fe, Mn, and Cr concentrations in plant leaves ranged from 0.07 to 0.5%. The metal elements such as Fe, Mn, and Cr formed the metallic particles derived from industrial additives (Heredia Rivera and Gerardo Rodriguez 2016). These metals on the leaf surface are result from air pollution from motor vehicles.

Road traffic exhaust (elemental carbon), ammonium (NH_3), nitrate (oxidation of NO_2), sulfate (oxidation of SO_2), organic matter (wood smoke, coal smoke, etc.), and dust and soil (Si, Al, Ca) are significant PM groups together with their main chemical components, and principal sources (Harrison 2020). In many urban areas, elemental carbon in atmospheric PM comes from a various sources (Schauer 2003). The majority of the material in vehicle exhaust particles is elemental carbon, often known as black carbon, which comes from both unburned fuel and lubricating oil vaporized within the engine (Shi et al. 2000). Diesel exhaust is the primary source of elemental carbon in London, but coal combustion is the primary source of elemental carbon particles in Beijing (Harrison 2020). In this research, green wall plants were planted in a high-traffic area of the city that had been designated as a contaminated site by local air pollution monitoring data (EPMC 2021). It is reasonable to presume that the carbon originated from the combustion of fossil fuels in vehicles. It is worth noting that elemental carbon is not the only tracer for vehicular emissions, and further research is needed to figure out what the other significant sources are.

Heavy metal analysis

Figure 3 depicts the accumulation of heavy metals in the leaves of plants grown on the green walls. As shown in Fig. 3, the highest chromium (Cr) accumulation was found the *S. reflexum* (5.38 mg/kg) followed by *F. thymifolia* (4.21 mg/kg), while the lowest was found in the *C. edulis* (1.61 mg/kg). The Cr content of air ranges from 1 to 40 ng/m^3 (Puxbaum 1991), but in industrial areas, it can reach 20 to 70 ng/m^3 (Mandiwana et al. 2006). Cr content in plants ranges from 0.02–0.2 mg/kg with phytotoxicity at concentrations greater than 10 mg/kg (Pais and Benton 1997). Cr concentrations in green wall plants were higher than in those grown under controlled conditions (control sample). This increase was in the 1 to 60 (for *M. crocea*) percent range.

From Fig. 3, *S. reflexum* had the highest iron (Fe) accumulation (307,000 mg/kg) followed by *F. thymifolia* (160,000 mg/kg), while *R. officinalis* had the lowest (2277 mg/kg). Plants have iron levels ranging from 10 to 1000 mg/kg dry matter. Iron is the critical constituent of plants, aiding stabilizing of N_2 and acting as a catalyst in forming chlorophylls (Caselles et al. 2002). Iron concentrations in green wall plants were much higher than in control sample plants in this study. This increase ranged from 8 to 95% (for the *M. crocea*).

Zinc (Zn) accumulation was most outstanding in the *M. crocea* (425.37 mg/kg) and lowest in the *R. officinalis* plant (16.41 ppm). *K. prostrata* (56.87 mh/kg) and stone crop (41.62 mg/kg) ranked second and third in zinc accumulation, respectively. Zinc concentrations in green wall plants were higher than in control plants. This increase ranged between 15 and 70% (for *M. crocea*).

As evidenced in Fig. 3, The highest accumulation of Pb was found in the *S. reflexum* (2.21 mg/kg), while the lowest accumulation was found in the *V. minor* (0.3 mg/kg). The second and third ranks belonged to the *F. thymifolia* (1.69 mg/kg) and *Hylotelephium* sp. (1.02 mg/kg). Pb concentration in green wall plants was much higher than controlled plants. The increment percentage change was between 4 and 76% (for *M. crocea*).

As proved in Fig. 3, the highest Cd accumulation was in the *Hylotelephium* sp. (0.65 mg/kg), followed by *S. reflexum* (0.36 mg/kg), and the lowest accumulation was in the *M. crocea* (0.03 mg/kg). Cadmium levels in plants are permitted to range between 0.2 and 0.8 mg/kg, with toxic accumulation estimated to range between 5 and 30 mg/kg (Kabata-Pendias 1992). Cadmium is involved in the absorption, transport, and utilization of several elements, including potassium, calcium, magnesium, and phosphorus, by plants. Besides, Cd concentrations were higher in green wall plants than in control plants. Accumulation increased by between 33 and 100% (for *L. angustifolia*, *R. officinalis*, *S. reflexum*).

As seen in Fig. 3, accumulation was most remarkable in *S. reflexum* (1.39 mg/kg) and *F. thymifolia* (1.02 mg/kg). The *R. officinalis* had the most minor accumulation (0.27 mg/kg). Arsenic is an unnecessary and generally toxic element that prevents root spread and mass production in plants. The concentration of as in all plants grown in the wall was higher than in control plants. The increase was between 5 and 100% (for *R. officinalis*).

From Fig. 3, the highest accumulation of Ni was found in *S. reflexum* (7.34 mg/kg), followed by *F. thymifolia* (4.52 mg/kg), and *R. officinalis* had the lowest accumulation (1.45 mg/kg). The concentration of Ni in green wall plants was much higher than in plants grown under controlled conditions in this study but much lower than the standard. The increase ranged from 5 to 70% (for *C. edulis*).

The use of ornamental plants in phytoremediation is not well documented, and the effects of heavy metals on these plants have not been thoroughly researched. Heavy metals remediation mediated by ornamental plants can eliminate toxins while also improving the appearance of the place (Khan et al. 2021). For example, *L. anqustifolia* has been subjected to soil heavy metals remediation. Angelova et al. (2015) concluded that *L. anqustifolia* is a plant which the hyperaccumulators of lead and accumulates of cadmium and zinc. The uptake of Ni by *L. anqustifolia* rises linearly with increasing Ni levels, according to Barouchas et al. (2019). In this research, similar results were obtained for accumulating Pb, Cd, Zn, and Ni by *L. angustifolia*.

Lavender has traditionally been utilized in cosmetics, hygiene products, and traditional medicine as aqueous extracts, essential oils, and dried components worldwide. Their pleasant flavor and scent, as well as their antibacterial, antifungal, insect repellant, insecticidal, and antioxidant capabilities, make them popular as food ingredients (Erland and Mahmoud 2016). Besides, rosemary is used in various items across the world, including food, medicine, health care, and cosmetics. Rosemary extracts were shown to contain high antioxidants like terpenoids and phenolic acids, which provide them with antioxidant, antibacterial, and antiviral effects (Dai and Liu 2021; Xie et al. 2017). Consequently, the heavy metal concentrations in these two plants were compared to the FAO standards. According to FAO, the maximum allowable limit for Cr, Zn, Ni, Fe concentration in plants is 5, 60, 67, and 450 mg/kg, respectively (Session 2007). In this study, the amount of these heavy metals in these plant species was almost below the standard. Besides, the levels of As and Pb in both plants were higher than the FAO standards. FAO has determined that the maximum acceptable concentration of As and Pb in all plant parts is 0.1 and 0.3 mg/kg (Session 2007).

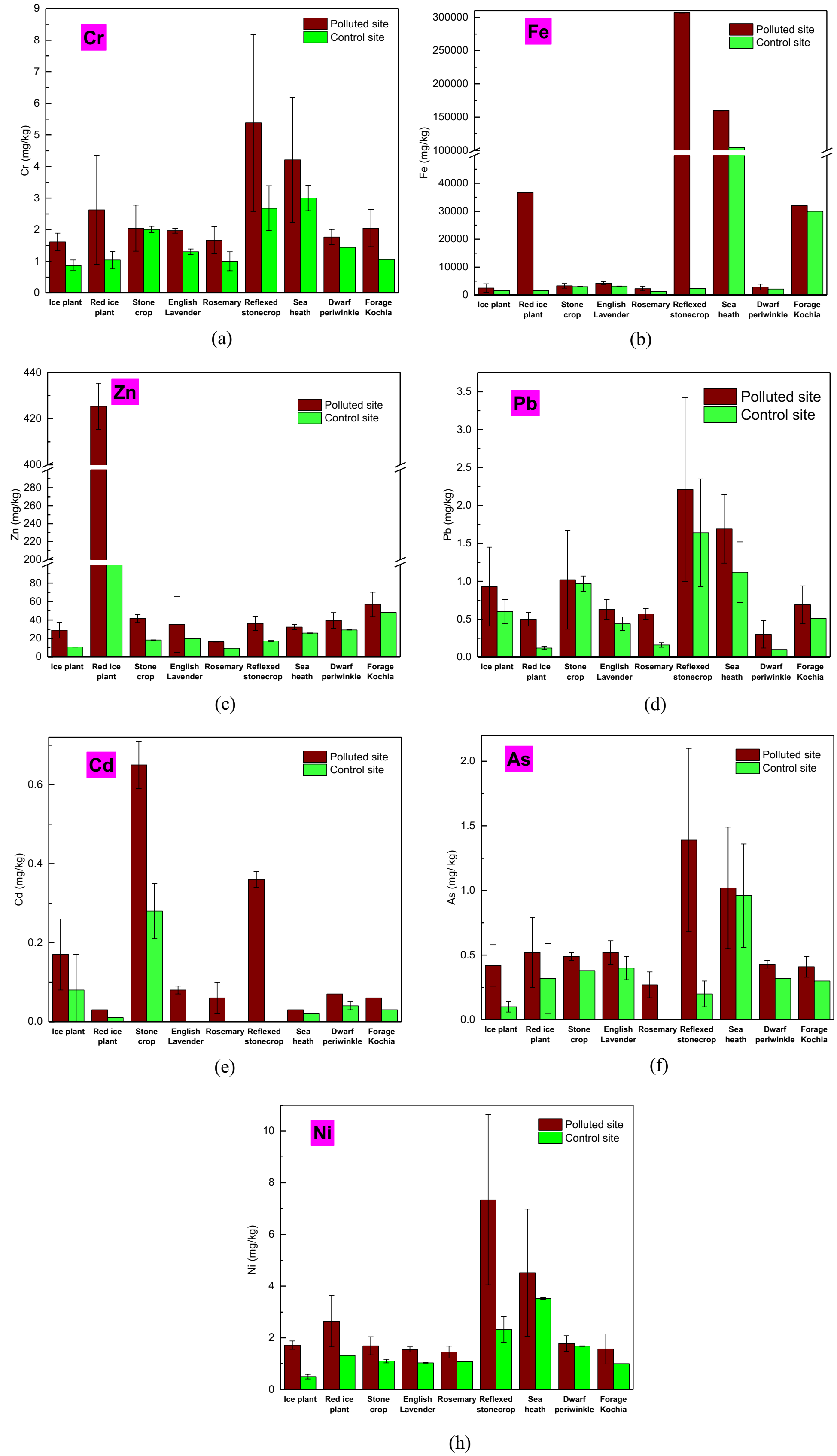


Fig. 3 Heavy metal accumulation in the leaves of plant species found in living green wall; **a** Cr; **b** Fe; **c** Zn; **d** Pb; **e** Cd; **f** As ; **h** Ni

Conclusion

This study assessed the ability of nine plant species, including *R. officinalis*, *L. angustifolia*, *C. edulis*, *M. crocea*, *V. minor*, *F. thymifolia*, *S. reflexum*, *Hylotelephium* sp., and *K. prostrata*, to grow along a busy road in Mashhad, Iran. The APTI findings revealed that *C. edulis* and *R. officinalis* had the highest tolerance to air pollution, while *K. prostrata* had the lowest. There was also a significant positive relationship between APTI and RWC and ascorbic acid. SEM images of the adaxial and the abaxial leave surfaces of all species showed that all had trapped suspended particles. *L. angustifolia*, *M. crocea*, *Hylotelephium* sp., and *K. prostrata* displayed more than 40% carbon. According to EDX analysis, more than 40% elemental composition of particulate matter deposited on leaves of *L. angustifolia*, *M. crocea*, *Hylotelephium* sp., and *K. prostrata* was carbon. The second most element (more than 30%) observed in the DEX of *K. prostrata*, *F. thymifolia*, and *L. angustifolia* was oxygen. The high percentage of these two elements in the composition of PM indicates that they originated from dust. The *S. reflexum* accumulated the most Cr, Fe, Pb, and As. The concentration of heavy metals in all species in the green wall was significantly higher than in the control sample. The *M. crocea* is showed the most significant increase (more than 60%) for Cr, Fe, Zn, and Pb. According to API results, the *C. edulis* is the best option for planting in air-polluted areas of the city. *L. angustifolia* and *R. officinalis* were ranked second and third, respectively.

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Declarations

Competing interests The authors declare no competing interests.

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