Assessment of Plant Species Suitability in Green Walls Based on API, Heavy Metal Accumulation, and Particulate Matter Capture Capacity

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Abstract

Today, 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 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 the use of green walls composed primarily of plants with small leaves can significantly adsorb PM and accumulation of heavy metal.

1. 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, 2012). Traffic related-PM is known to be responsible for significant volumes of urban pollution (Pant, 2013; Ranft, 2009). Globally, it is estimated that 25% of $PM_{2.5}$ and PM_{10} are generated from road traffic (Karagulian, 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, 2005). Besides, some particles emanate from brake wear, wheel wear, clutch wear, and dust which are called non-exhaust emissions (Thorpe, 2008; Timmers, 2016; Wåhlin, 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, 2010; Hyun Cho, 2005; Maher, 2016; Pascal, 2014; Ranft, 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, 2019). The creation of green spaces structures is considered a critical way to reduce air pollution in cities. Vegetation act as a pollutant sink (Prerita Agarwal, 2019). In the process of photosynthesis, plant leaves absorb and remove air pollutants (e.g., 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, 2011; Innes, 2000; Janhall, 2015; Janhäll, 2015; Jun Yang, 2008; Mo et al., 2015; Prerita Agarwal, 2019).

Vertical greenery systems received attention because of fast installation, more 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 of 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 a variety of 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 (Rosmina A. Bustami, 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). For the implementation of these systems, more costs are required for the standard installation and maintenance of structures (Perini & Rosasco, 2013). Using living and green walls has many benefits in the urban environment include 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, 2015; Rosmina A. Bustami, 2018; UdeshikaWeerakkody 2018; Veisten, 2012).

Green infrastructure was recognized as a short solution to PM pollution remediation (Perini et al., 2011; Weerakkody et al., 2017). Recently, several studies focused on the effectiveness of vertical greenery systems for capturing PM. For example, Weerakkody et al. (Weerakkody et al., 2018a) 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. (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. (Weerakkody et al., 2017) 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 two 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.

2. Materials And Method

2.1 Materials

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.

2.2 Site description

This study was conducted in Mashhad with a longitude of 59’ 36” and a latitude of 36’ 17” in Khorasan Razavi province, located in northeastern Iran. Mashhad, with a population of 3,200,000, is the second-most populous metropolis in Iran and the ninety-fifth 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.

2.3 Active green wall design and plant materials

The green walls had dimensions of 2.09 m × 3.98 m and were made of 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. 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.

2.4 Leaf sampling

The leaf sampling was carried out after ten 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.

2.5 Air pollution tolerance index

All plant leaves samples were transferred to the laboratory immediately after sampling to conduct APTI tests. Four factors involved in APTI were analyzed together at the same time, according to the following procedure.

2.5.1 pH

The pH of plant leaves was measured based on the method of Liu and Ding (Liu & Ding, 2008). 4 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).

2.5.2 Relative Water Content (RWC)

The RWC of plant leaves was determined based on the protocol of Liu and Ding (Liu & Ding, 2008). The fresh weight (WF) 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 hours 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 hours and the dry weight (DW) was measured. The RWC was calculated with the following formula.

$$RWC = \frac{FW - DW}{TW - DW} \times 100 \quad (1)$$

2.5.3 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). 0.5 g of fresh leaves were crushed in liquid nitrogen and then homogenized in 20 ml of 80% acetone (v/v). The mixture was centrifuged for 10 minutes 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.

Chlorophyll a = [(12.7 × A_{663}) – (2.69 × A_{645})] × final volume	**(2)**
Chlorophyll b = [(22.9 × A_{645}) – (4.68 × A_{663})] × final volume	(3)
$TCC = (\text{Chlorophylla} + \text{Chlorophyllb}) \times \text{finalvolume}$	(4)

2.5.4 Ascorbic acid content (A)

The ascorbic acid content of leaves was measured using the method of Hewitt & Dickes (Hewitt & 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 dehydro-ascorbic acid. Then, 1 ml of 1% thiourea was added to two tubes (for measurement of total ascorbic acid and oxidized ascorbic acid). The samples remained stationary for 20 minutes. 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 one hour and then kept in an ice bath for 20 minutes. The absorbance of each sample was measured at 520 nm using a spectrophotometer model (UV / VIS, SP-3000 Plus, JAPAN), and then the ascorbic acid content of samples were calculated from the standard curve

2.5.5 Air pollution tolerance index calculation

APTI indicates the tolerance and tolerance of plant species 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):

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

Which, 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 (%).

2.5.6 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. Table 2 shows the assigned grades (+ or −) for each property based on various criteria related to plants. Scoring of plant species was performed according to their multifaceted traits (Mondal, 2011; Rai, 2019). The maximum score assigned to each plant is 16 based on the number of positive points (+). The score is converted to percentages using the following equation to indicate the API quantity of a particular species (Kaur & Nagpal, 2017). API values classify the plant species into various levels of performance (Table 3).

$$\%score = \frac{Gradesobtainedbyplantspecies}{Maximumpossiblegradesforanyplantspecies} \times 100 \quad (6)$$

2.6 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.

2.7 EDX analysis

The elemental composition of captured PM was determined while the leaves were scanned with SEM for their PM characteristics (Section 2.6). 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.

2.8 Heavy metal analysis

The heavy metal contents of the plant were measured by the acid digestion method described by Uddin et al. (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 hours. 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).

2.9 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.

3. Results And Discussions

2.10 APTI analysis

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

2.10.1 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; Pandey et al., 2016; Scholz & 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, 2000). This reduction rate is much higher in susceptible plants than tolerant plant species (Scholz & 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).

2.10.2 RWC

The RWC of the green wall plants was summarized in Table 4. Their average values vary significantly from 30 to 90%. *Malephora crocea* and *Hylotelephium sp* (85%) had the highest amounts (86 and 85%), and *K. Prostrata* had the lowest (38%). 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 & Jaya, 2010; Singh et al., 1991).

2.10.3 Ascorbic acid

Ascorbic acid contents of plants located in the green wall were summarized in Table 4, displaying a range of 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 *Malephora crocea* (0.878 mg/g) and *Hylotelephium s*p (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 & 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 & 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).

2.10.4 Chlorophyll content

Table 4 shows the total chlorophyll content of the studied plants, which ranges 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 & Chauhan, 2008; Prajapati & 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 & 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 & Tripathi, 2008). However, the chlorophyll content of plants varies based on the level of contamination in their environment and their tolerance or susceptibility (Rai & Panda, 2015).

2.10.5 Linear regression analysis

Figure 2 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 & Nagpal, 2017), which reported the significant strong positive impact of ascorbic acid on APTI.

2.10.6 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 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 & Nagpal, 2017; Prajapati & 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 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* s and R. officinalis are tolerant to air pollution, while K. Prostrata is sensitive species.

2.10.7 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, lavender and *R. officinalis* were assessed as very good plants, while *M. crocea* and *S. reflexum* were considered as good plants. *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 bioaccumulation 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 & Nagpal, 2017).

2.10.8 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. (Ram et al., 2014), Ottel´e et al. (Ottelé et al., 2010), and Weerakkody et al. (Weerakkody et al., 2017; Weerakkody et al., 2018b), proved that the highest accumulation 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, non-smooth surfaces have been identified as auxiliaries in the accumulation and storage of suspended particles (Barima et al., 2014; Räsänen et al., 2013; Weerakkody et al., 2018a; Weerakkody, 2017; Zhang, 2017). Besides, the grooves and their properties, such as deep or shallow, play a key 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 retenting 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 accumulated 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., 2018a; Weerakkody, 2017; Zhang, 2017). In this study, lavender has unique morphological characteristics and many hairs, which demonstrating its ability to trap and adsorb suspended particles on the leaf surface.

2.10.9 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 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%). PM is composed of inorganic such as nitrates, sulfides, carbon black, and organic matter [1]. 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 major part of biogenic particles. The central elements of pollen are C, O, Si (Heredia Rivera & Gerardo Rodriguez, 2016). Thus, it can be concluded that this particle originated from dust. Moreover, as shown in Table 6, Fe, Mn, and Cr concentrations in plant leaves ranged from 0.07 to 0.5 percent. The metal elements such as Fe, Mn, Cr formed the metallic particles derived from industrial additives (Heredia Rivera & Gerardo Rodriguez, 2016). These metals on the leaf surface are the result of air pollution from motor vehicles.

2.10.10 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. 1, The highest chromium (Cr) accumulation was found in 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). Cr content in plants ranges from 0.02–0.2 mg/kg with phytotoxicity at concentrations greater than 10 mg/kg (Pais, 1997). According to FAO, The maximum allowable limit for Cr concentration in plants is 5 mg/kg (WHO/FAO, 2007). In this study, the amount of Cr in all plant species except *S. reflexum* was almost below the standard. The Cr content of air ranges from 0.001 to 1 mg/m^3, but in industrial areas, it can reach 30 to 50 mg/m^3. 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 (307000 mg/kg) followed by *F. thymifolia* (160000 mg/kg), while *R. officinalis* had the lowest (2277 mg/kg). Plants have iron levels ranging from 10 to 1000 mg/kg dry matter. Besides, the maximum permissible limit for iron-based on FAO is 450 mg/kg (WHO/FAO, 2007). Iron is the critical constituent of plants, aiding in the stabilization of N_2 and acting as a catalyst in forming chlorophylls (Caselles, 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 mg/kg) and Stone crop (41.62 mg/kg) ranked second and third in zinc accumulation, respectively. The maximum permissible limit for Zn concentration in plants is 60 mg/kg (WHO/FAO, 2007). Zinc concentrations in green wall plants were higher than in control plants. The amount of this increase ranged between 15 and 70 (for *M. crocea*) percent.

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). FAO has determined that the maximum acceptable concentration of Pb in all plant parts is 0.3 mg/kg (WHO/FAO, 2007). 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 A, 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 percent (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 negligible accumulation (0.27 mg/kg). Arsenic is an unnecessary and generally toxic element that prevents root spread and mass production in plants. According to FAO, the maximum acceptable concentration of As in all plant parts is 0.1 mg/kg (WHO/FAO, 2007). All of the plants had higher arsenic levels than that. 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). FAO has established a nickel permissible level of 67 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 5–70% (for *C. edulis*).

4. 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.

Declarations

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Consent for publication: “Not applicable”

Availability of data and materials: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Authors' contributions:

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Ava Heidari:	Conceptualization, Methodology, Software, Validation, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Funding acquisition, Project administration.
Zahra Karimian:	Methodology, Validation, Software,Writing - Review & Editing.
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Tables

Due to technical limitations, Tables are only available as a download in the Supplemental Files section.

Figures

Figure 1

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

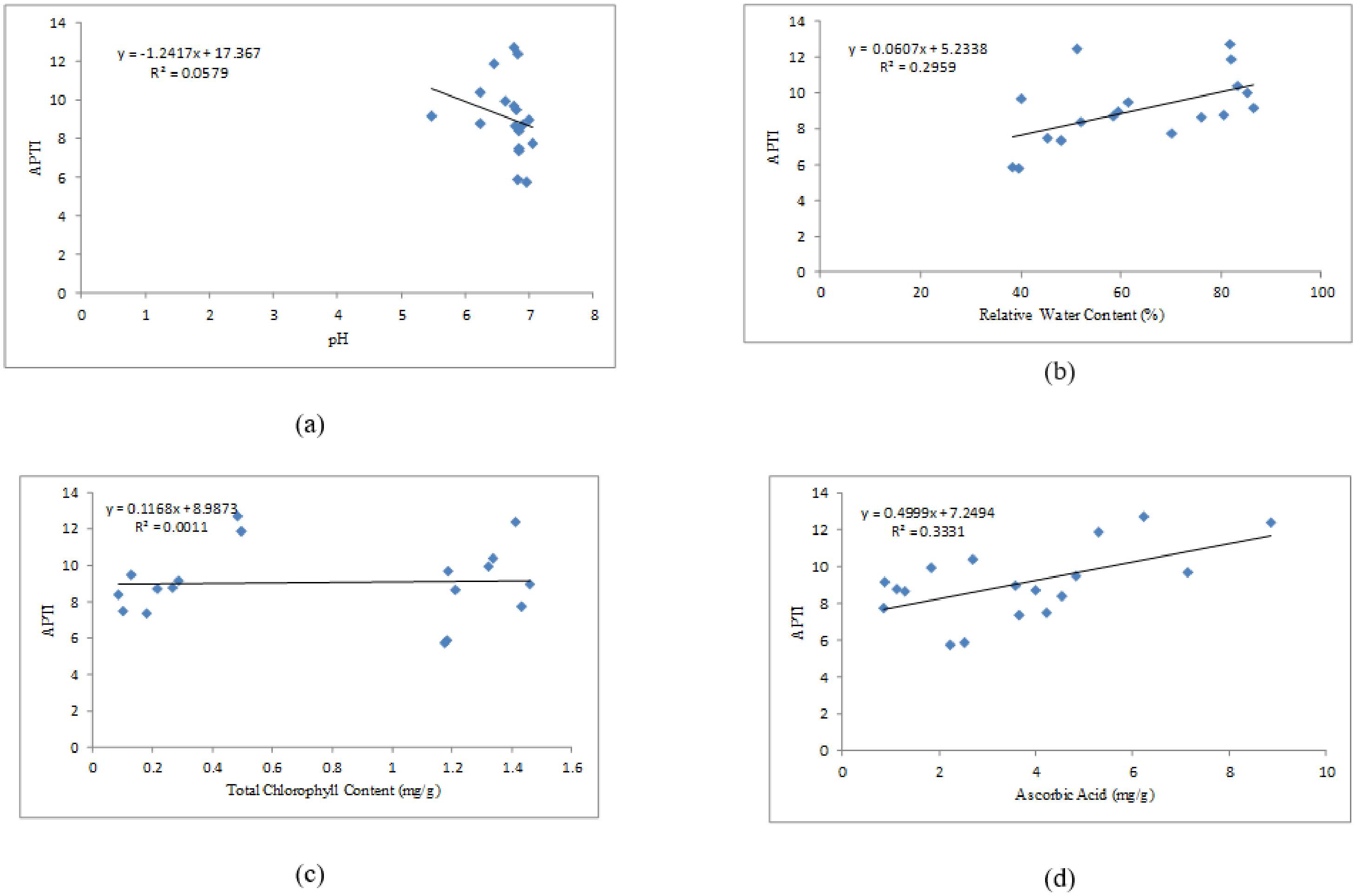

Figure 2

Linear regression analysis of biochemical parameters with APTI values, (a) pH, (b) Relative water content (c) Total chlorophyll content, and (d) ascorbic acid.

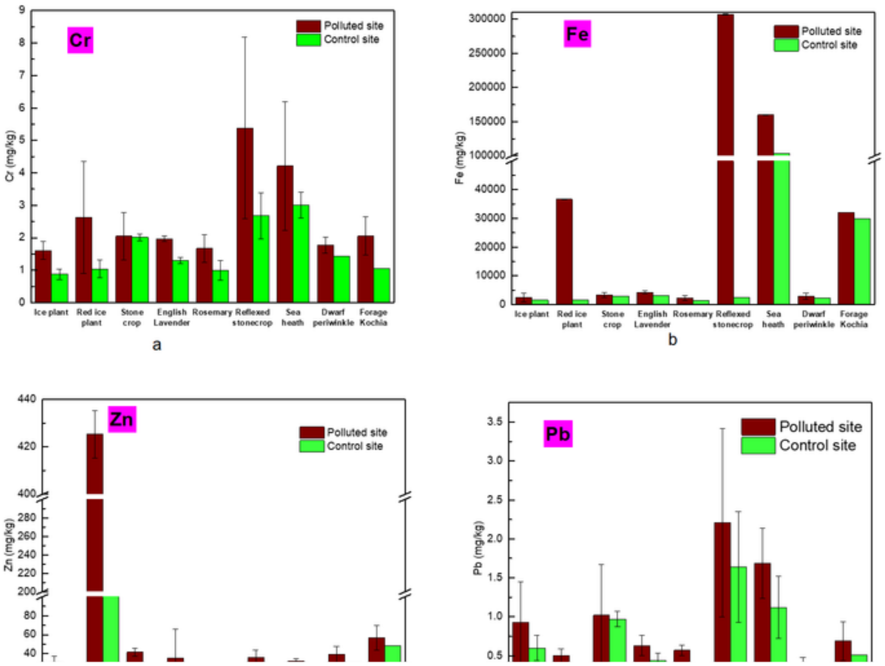

Figure 3

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.

Supplementary Files

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