



Assessing the uptake and accumulation of heavy metals and particulate matter from ambient air by some tree species in Isfahan Metropolis, Iran

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Abstract

The main scope of this study is to evaluate the uptake and accumulation potential of heavy metals in unwashed and washed leaves and particulate matter (PM) in leaf surfaces plus waxes of different tree species in Isfahan city. The highest mean concentrations of Cd, Cr, and Ni in unwashed and washed leaves were detected in *M. nigra*, Zn and Cu in *P. fraxinifolia*, and Pb was related to *P. orientalis*. The highest and lowest mean total depositions of total particulate matter (sum of PM₁₀, PM_{2.5}, and PM_{0.2}) were found in the leaf of *M. nigra* (190.23 ± 23.5) and *S. alba* (11.9 ± 4.42 μg/cm²), respectively. The maximum bio-concentration factor (BCF) of Cd, Pb, and Ni was observed in *Morus nigra*; Cu and Zn in *Pterocarya fraxinifolia*, with the BCF of Cr found in *Acer negundo*. Comprehensive bio-concentration index (CBCI) and metal accumulation index (MAI) were applied for comparing different tree species in HMs accumulation from soil and ambient air. The highest CBCI was measured for *M. nigra* (0.86), so this tree has the potential to remediate metals from the polluted soil. Higher MAI values in washed and unwashed leaves were found in *S. alba* (6.77 and 6.98) and *M. nigra* (5.93 and 5.62), demonstrating the high capability of these trees for controlling air born-metal pollution. Based on the AOM factor, *M. nigra*, *P. fraxinifolia*, *U. umbraculifera*, *P. fraxinifolia*, *A. altissima*, and *M. alba* trees had the highest ability to capture Cd, Zn, Cu, Ni, Pb, and Cr from air. So, planting these trees would be beneficial in sensitive and critical zones such as industrial and urban areas with such atmospheric pollutants.

Keywords Heavy metal · Particulate matter · Comprehensive bio-concentration index · Tree species · Metal accumulation index

Introduction

Heavy metals (HMs) and particulate matter (PM) pollution heavily influence the ecosystem and human health. These pollutants may cause significant and serious threats in almost all urban areas (Men et al. 2018). Heavy metals are non-

biodegradable, cytotoxic, toxic, and biological accumulated, transferred from one trophic level to another through the biomagnification process (Mahapatra et al. 2019; Zhang et al. 2017a). Metal pollutants can have short- and long-term effects on the health of living things and are associated with increased risk of cancer and mortality in living creatures (Chen et al. 2020). Heavy metal pollution occurs in anthropogenic and natural pollutant form (Santos et al. 2019; Turkyilmaz et al. 2019). Natural pollution is mainly created by the wastes of all living organisms except humans along with direct wastes of humans. This source is removed by different natural mechanisms in a short period of time. However, anthropogenic pollutants are caused by human activities such as industrial activities, corrosion, fossil fuel combustion, mining, smelting, waste disposal, and agricultural practices. These types of pollutants do not degrade in the environment for long time and have serious negative consequences for human health (Alahabadi et al. 2017; Turkyilmaz et al. 2019). Toxic metals and PM can be transported into the human body and

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other living organisms through food chain or respiratory system and cause various diseases in human and animals (Simon et al. 2014; Solgi et al. 2020). With respect to the above-mentioned, detecting this class of pollutants and assessing their risk in different areas are important to protect the ecosystem and health of living organisms (Sawidis et al. 2011; Sevik et al. 2019).

In general, heavy metal and PM pollution are monitored in two forms (direct and indirect monitoring). Direct monitoring methods are expensive and provide uncertain information about the content as well as impact of metal pollutants on ecosystems (Abril et al. 2014). In addition, direct monitoring methods have been unable to provide suitable information about the effects of heavy metal and PM on living systems (Khamesi et al. 2020). On the other hand, indirect monitoring methods such as bioindicators are also extensively used as an attractive alternative to the direct methods, due to their simple, less complex instrumentation, inexpensiveness, as well as reliable and accurate data on the periodic variation of pollutants (Turdean 2011). Biological indicators are most suitable in measuring periodic changes in heavy metal pollution (Santos et al. 2019). Plant indicators uptake heavy metals from water, soil, and air and accumulate them in their tissues. Thus, these bioindicators have been used during recent years to evaluate the contamination, accumulation, and distribution of heavy metal pollutants. This is because they have relatively cheap analysis and it is easy to collect the plant materials for analysis (Hajizadeh et al. 2019). Accordingly, tree species are very important as PM and metal deposition indicators as well as bioaccumulators of air and soil pollution (El-Khatib et al. 2020). Some studies worldwide have reported the effectiveness of leaves for PM and metal absorption and biomonitoring over other parts of trees such as bark and flowers (El-Khatib et al. 2020; Matin et al. 2016). In general, the capabilities of tree leaves to deposit and absorb particles and accumulate metals from soil plus air are complex and different. Thus, assessing and identifying the capability of tree species for single and multiple heavy metal accumulation from soil as well as air and their potential for capturing and retention of particulate matters are very necessary.

Trees are also used as a suitable natural indicator to monitor the HMs pollution in urban and polluted areas (Parihar et al. 2020). Different parts of trees including needles, barks, trunks, roots, fruits, and other parts can adsorb heavy metals. Meanwhile, tree leaves are widely used due to their large surface area and their ability to absorb pollutants. They also can act as a bio-filter to absorb and remove substantial amounts of atmospheric particles and metals in polluted areas. This is because the morphology of leaf surfaces in most tree species consists of trichomes, which allow efficient absorption of some metals and liquid water directly from the atmosphere into the leaf (Abril et al. 2014; Fourati et al. 2017). Thus, trees can be applicable as suitable PM and cost-effective mitigation

tools to reduce natural and anthropogenic pollutants (Abril et al. 2014; Alahabadi et al. 2017; Fourati et al. 2017).

Different species of trees can absorb different levels of heavy metals and particulate matters. Thus, the tolerance and abilities of trees to absorb and accumulate heavy metals should be evaluated for sustainable development as urban green-space and to improve air quality around vulnerable areas such as industrial and contaminated areas as well as roadsides (Roy et al. 2020; Sæbø et al. 2012; Solgi et al. 2020). Optimizing the advantages of trees in plantation programs involves first evaluating the potential of different species to absorb and accumulate metals and PM pollutants. Then, those plants should be used as biomonitors for better results in estimation of environmental pollution. In this study, heavy metal accumulation ability has been determined in some tree species applied in polluted zones in the Isfahan city. In addition, trees can reflect the cumulative influence of heavy metals pollution on the environment because contaminants transported through their roots and leaves can be accumulated during their lifetime (Alahabadi et al. 2017; Sawidis et al. 2011). The scope of this study will be (a) evaluating the concentration of certain heavy metals (Cd, Pb, Ni, Cr, Zn, and Cu) in the washed and unwashed leaf of ten deciduous broadleaf tree species in the Isfahan city, Iran; (b) identifying the best tree species for single and multiple heavy metal accumulation in the leaf using bio-concentration factor (BCF) and comprehensive bio-concentration index (CBCI), respectively; (c) investigating the quantity of particulate matters accumulated on leaf surfaces and those trapped in waxes of ten tree species commonly cultivated in Isfahan city in terms of particle size fractions; and (d) selecting the best options of tree species for monitoring, accumulation, and remediation of PM and metals from soil and atmosphere in sensitive and critical zones such as contaminated and urban areas.

Materials and methods

Sampling and determining particulate matter and heavy metal concentration

The study was performed on samples collected from Isfahan city. Isfahan city is located in the central part of Iran (Fig. 1). This city has important features; it is the economic and cultural center of Iran with the highest industrial (second largest industrial city in Iran), population, and traffic density. The population of the Isfahan city is 5,346,518 according to the 2019 census. Today, Isfahan is one of the most populated and crowded cities in Iran (third most populated city in the country), with a dry climate and hot summers congested by heavy traffic as well as polluted air, and is frequently exposed to dust events during the year (Norouzi et al. 2015). The land use pattern of this city is dominated by residential as well as

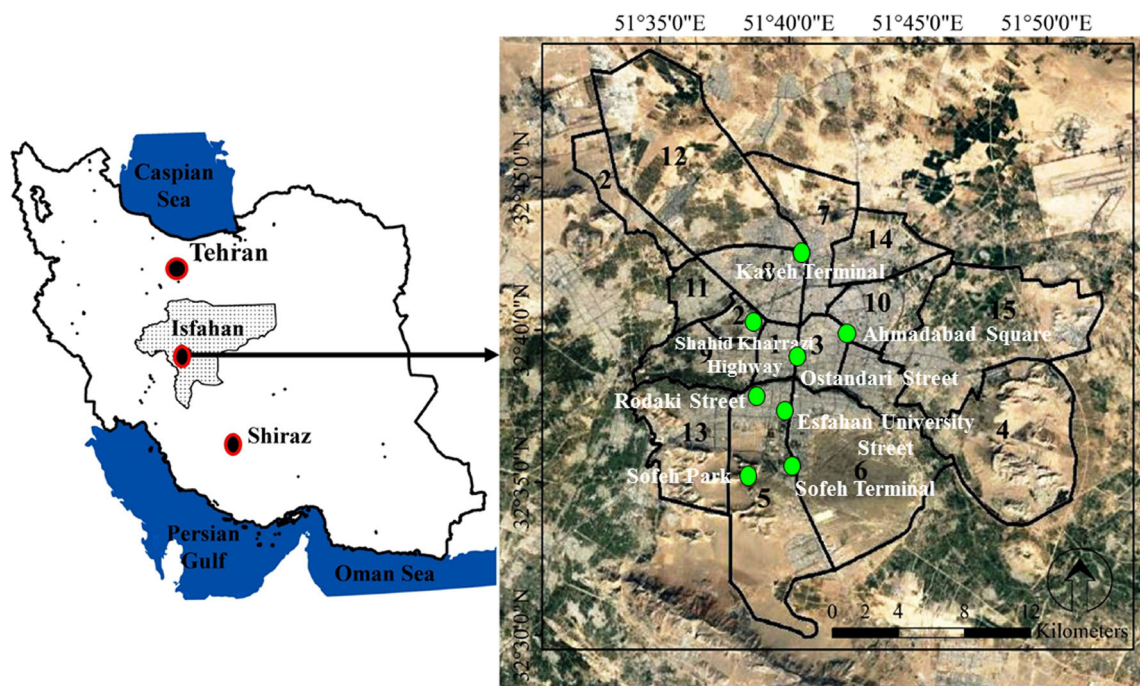


Fig. 1 The distribution of the sampling stations within the case study

industrial areas (such as biggest steel and melting plant in the country, petrochemical and chemical processing industries, oil refinery, traditional and architecture industry), parks (such as Charbagh Khajoo and Nazhvan Park), and a petrochemical plant along with many other major and minor plants in and around the city; all of which contribute to its polluted air. Indeed, over the recent years, it has been the center of attention and high density of population due to the concentration of cultural and historical attractions, human and economic activities such as different kinds of industries, transportation, cultural, housing, business, and educational services. In the case study area, ten dominant tree species including (*Platanus orientalis* L. (*P. a*); *Robinia pseudoacacia* L. (*R. p*); *Ulmus umbraculifera* Trautv. (*U. u*); *Salix alba* L. (*S. a*); *Morus alba* L.; *Morus nigra* L. (black mulberry) (*M. n*); *Acer negundo* L. (box elder) (*A. n*); *Fraxinus excelsior* L. (*F. e*); *Ailanthus altissima* (Mill.) Swingle (*A. a*) and *Pterocarya fraxinifolia* (Poir.) Spach (*P. f*) were identified throughout the city. Then, in order to compare the capability of those tree species in accumulating particulate matters and heavy metals from the environment (soil and air), 8 stations were selected for sampling, 7 stations in highly polluted zones with high traffic density and crowded population (including Kaveh terminal, Sofeh terminal, Ahmadabad Square, Shahid Kharazi Highway, Isfahan university street, Ostandari street, Rodaki street) and one control or unpolluted station (Sofeh). Two trees were selected in each station from every species as a sample. Figure 1 displays the distribution of the sampling stations within the case study. Leaf samples of all species were cut and collected in September 2019. The samples were taken

on all four sides of the plant at 1.0–2.5-m height above the ground level. In this regard, a total of 131 leaf samples were collected. Samples of leaves were placed in paper bags, labeled, and transported to the laboratory, with the samples then divided into two sections (one part unwashed and other part washed with deionized water). They were dried at room temperature (25 °C) for 12 days. Next, to dry the leaf samples completely, they were placed in oven at 60 °C for 24 h. The dried leaves were mechanically ground into powder using mill blades. One gram of each powdered sample was poured into polytetrafluoroethylene (digestive tubes) to which 10 ml of 65% HNO₃ (Merck, Germany) and 70% HClO₄ (Merck, Germany) were added with a 1:4 ratio. PTFE tubes were placed on a heater at 40 °C for 1 h and then the temperature increased to 140 °C for 3 h. The contents of each tube were cooled and then transferred to 25-ml volumetric flasks, with the final volumes completed with deionized water (Yap et al. 2002). To perform the quality control, five blank samples were placed along with leaf samples. Finally, the metal concentrations in the digest samples were determined using atomic absorption spectroscopy (AAS) device 797 VA Computrace, manufactured by Metrohm, Switzerland, with a flame or graphite furnace nebulizer (Perkin-Elmer).

Comparing indices

Bio-concentration factor (BCF)

Bio-concentration factors (BCF) are known as the ratios of total heavy metal values in the aerial tissue (leaves or barks)

to their concentration in soil sample in which the plant has been grown. The BCF has been applied to assess the potential of plants to accumulate metal from soil sample (Alahabadi et al. 2017; Shi et al. 2011). BCF was calculated as follow Eq. 1:

$$\text{BCF} = \frac{C_{\text{aerial tissue}}}{C_{\text{soil}}} \quad (1)$$

where $C_{\text{aerial tissue}}$ is the metal values in aerial tissues and C_{soil} is the metal values in soil.

Comprehensive bio-concentration index (CBCI)

Comprehensive bio-concentration index (CBCI) approach was first proposed by Zhao et al. (2014). CBCI is known as the capability of tree species for comprehensive accumulation of multiple metals. In general, to compute the CBCI index the membership function of fuzzy synthetic evaluation is required. First step, the fuzzy set or the factor set U , $U = (u_1, u_2, u_3 \dots u_i)$ was estimated. Where U is the level of comprehensive accumulation ability for each tree, and u_i are various heavy metal pollution factors (Zhao et al. 2014). In the second step, the amount of fuzzy membership function for trees' accumulation ability of each metal pollution factor was estimated using the following formula Eq. 2:

$$\mu(x) = \frac{X - X_{\min}}{X_{\max} - C_{\min}} \quad (2)$$

Here X is the BCF of a given metal pollution factor, X_{\min} and X_{\max} are the minimum and maximum amounts of the BCF for the certain heavy metal, respectively. The maximum $\mu(x)$ minimum and are denoted as the fuzzy membership values one and zero, respectively, which reflect the highest and lowest comprehensive accumulation factors for heavy metals. Finally, CBCI can be estimated from Eq. 3.

$$\text{CBCI} = \frac{1}{N} \sum_{i=1}^N \mu_i \quad (3)$$

where N is the total number of heavy metals analyzed, and μ_i is $\mu(x)$ of metal i .

Metal accumulation index (MAI)

MAI factor was used to evaluate and compare the ability of tree species to accumulate efficiencies of the atmospheric metals. Tree species with high amount of MAI are very effective to be applied as barriers between vulnerable and polluted zones (Levei et al. 2018). The MAI factor was computed according to the standard Eq. 4.

$$\text{MAI} = \left(\frac{1}{N} \right) \sum_{j=1}^N I_j \quad (4)$$

where the MAI factor shown the metal accumulation, N is the total number of metals measurement, and I_j is the sub-index for variable j . I_j was gained by the ratio of mean concentration of each heavy metal (X) in tree leafs and their standard deviation (Δx) as follows (Liu et al. 2007) Eq. 5:

$$I_j = \frac{X}{\Delta X} \quad (5)$$

Air-originated metals (AOM)

In many previous research, AOM has been used to evaluate the contribution ratio of the metals derived from the atmosphere source (Safari et al. 2018). The AOM factor was calculated using Eq. 6:

$$(\text{AOM})\% = \frac{[C]_{\text{unwashed}} - [C]_{\text{washed}}}{[C]_{\text{unwashed}}} \times 100 \quad (6)$$

where $[C]_{\text{washed}}$ and $[C]_{\text{unwashed}}$ are the heavy metal contents in the washed and unwashed leaf samples, respectively.

Accumulation particulate matter leaf surface and in waxes

After the collection of leaves from the plants in the field, the samples were carefully handled with plastic gloves, enclosed in plastic bags, and immediately brought to the laboratory. The samples were stored in paper bags at room temperature in a clean storage facility until analysis of PM. Particulate matter fractions sizes (PM_{0.2}, PM_{2.5}, and PM₁₀) were calculated on leaf surfaces and in waxy layers using the method proposed by Dzierżanowski et al. (2011).

Results

PM contents

The mean concentration of PM on leaf surfaces and epicuticular waxes ($\mu\text{g}/\text{cm}^2$) of different tree species are obtainable in Table 1. The results showed that in leaf surface the best PM-retention performing of species in PM_{0.2}, PM_{2.5}, and PM₁₀ capture 18.13_(±0.5), 46.13_(±9.5) and 128.5_(±13.5) were in *M. nigra* (for PM_{0.2} and PM_{2.5}) and *P. orientalis* (for PM₁₀), respectively. In epicuticular waxes, the best PM-retention performing of species in PM_{0.2} PM_{2.5} and PM₁₀ capture were in *M. nigra* (0.46_(±0.09)), *Pterocarya fraxinifolia* (41.92_(±3.49)), and *U. umbraculifera* (85.64_(±15.23)). In addition, the trend of accumulation of total particulate matter on the leaf surface

Table 1 Accumulation of particulate matter (PM₁₀, PM_{2.5}, PM_{0.2}, and total) on leaves leaf surfaces and waxes of different tree species

Tree species	Leaf surfaces				Leaf waxes			
	PM ₁₀	PM _{2.5}	PM _{0.2}	Total	PM ₁₀	PM _{2.5}	PM _{0.2}	Total
<i>F. excelsior</i>	26.49	10.98	2.40	39.86	5.63	2.86	1.33	9.92
<i>A. altissima</i>	44.50	31.33	3.40	79.23	25.33	5.53	2.83	33.68
<i>M. nigra</i>	126.89	46.09	18.50	190.31	68.33	42.92	15.13	132.56
<i>R. pseudoacacia</i>	18.67	7.30	1.05	27.02	14.00	5.11	0.77	19.88
<i>A. negundo</i>	49.18	10.04	5.01	64.23	45.49	7.66	3.68	56.83
<i>S. alba</i>	8.39	3.14	0.46	11.90	2.72	1.58	0.42	4.75
<i>U. umbraculifera</i>	92.60	40.61	10.96	141.56	85.64	34.26	4.86	124.76
<i>P. orientalis</i>	128.50	35.80	12.72	176.02	67.67	32.77	11.50	111.94
<i>M. alba</i>	59.00	24.92	14.00	87.93	39.00	15.25	8.67	62.92
<i>P. fraxinifolia</i>	8.48	2.78	0.77	12.03	3.57	1.33	0.52	4.92

from the highest to the lowest was as follows: *M. nigra* > *P. orientalis* > *U. umbraculifera* > *M. alba* > *A. altissima* > *A. negundo* > *F. excelsior* > *R. pseudoacacia* > *P. fraxinifolia* > *S. alba*. In epicuticular waxes, from the highest to the lowest it has been *M. nigra*, *U. umbraculifera*, *P. orientalis*, *M. alba*, *A. negundo*, *A. altissima*, *R. pseudoacacia*, *F. excelsior*, *P. fraxinifolia*, and *S. alba*.

Heavy metals contents

Mean_(with standard deviations) and range of heavy metal concentrations (mg/kg dry weight) in the unwashed and washed leaf samples were depicted in Table 2. The amount of heavy metal concentration differs among species and is related to metal types and the potential of tree species to absorb and accumulate heavy metals. As a result of Cd, Zn, Cu, Ni, Pb, and Cr, the highest mean quantities were detected in *M. nigra*, *P. fraxinifolia*, *M. nigra*, *P. orientalis*, *P. orientalis*, and *P. orientalis*, respectively (Table 2). In fact, the results demonstrated that depending on tree species there was an obvious difference between accumulated amounts of metals in their leaves. The trend of heavy metal accumulation in the unwashed and washed leaves was similar and in this order of magnitude (Zn > Cu > Ni > Pb > Cr > Cd) in all trees.

In the present study, the concentration of Cd was obtained between 0.73 and 1.05 mg/kg. The highest accumulation of Cd in unwashed leaves was seen in the *M. nigra* with values of 1.05_(± 0.05) and followed by *P. orientalis* > *A. negundo* > *A. altissima* > *U. umbraculifera* > *M. alba* > *P. fraxinifolia* > *F. excelsior* > *R. pseudoacacia* > *S. alba* and the lowest uptake of Cd was observed *S. alba* with values of 0.73_(± 0.04). In washed leaves, from the highest to the lowest it has been *M. nigra* > *P. orientalis* > *A. negundo* > *U. umbraculifera* > *M. alba* > *P. fraxinifolia* > *A. altissima* > *F. excelsior* > *R. pseudoacacia* > *S. alba*. The accumulation of Zn was recorded between

27.99_(6.50) (in washed leaves of *U. umbraculifera*) and 39.90_(6.24) mg/kg (in unwashed leaves of *P. fraxinifolia*). The arrangement of trees according to Zn uptake in washed and unwashed leaves was similar: *P. fraxinifolia* > *M. nigra* > *P. orientalis* > *M. alba* > *R. pseudoacacia* > *U. umbraculifera* > *F. excelsior* > *S. alba* > *A. negundo* > *A. altissima*.

The lowest and highest Ni accumulation were recorded in the *S. alba* and *M. nigra* with values 3.55_(1.69) and 7.16_(2.52) in unwashed and 6.47_(1.51) and 3.35_(1.70) mg/kg in washed leaves, respectively. The arrangement of trees according to Ni uptake in washed and unwashed leaves were similar: *M. nigra* > *P. orientalis* > *R. pseudoacacia* > *A. altissima* > *A. negundo* > *P. fraxinifolia* > *M. alba* > *U. umbraculifera* > *F. excelsior* > *S. alba*. The lowest and highest Cu accumulation were recorded in the *R. pseudoacacia* and *P. fraxinifolia* with values 9.82_(1.48) and 15.28_(4.62) in unwashed and 8.85_(1.48) and 14.60_(2.24) mg/kg in washed leaves, respectively. The arrangement of trees according to Cu uptake in washed and unwashed leaves were similar. *P. fraxinifolia* > *A. altissima* > *P. orientalis* > *M. nigra* > *U. umbraculifera* > *F. excelsior* > *A. negundo* > *M. alba* > *S. alba* > *R. pseudoacacia*. Concentrations of Pb in tree species varied from 1.44_(0.34) to 3.33_(1.31) mg/kg in unwashed and from 1.28_(0.39) to 3.03_(0.33) in washed leaves in *R. pseudoacacia* and *P. orientalis*, respectively. The arrangement of trees according to Pb uptake in washed leaves was *P. orientalis* > *M. nigra* > *U. umbraculifera* > *A. negundo* > *A. altissima* > *S. alba* > *M. alba* > *F. excelsior* = *P. fraxinifolia* > *R. pseudoacacia*. As well as in washed leaves the arrangement of trees was *P. orientalis* > *M. nigra* > *U. umbraculifera* > *A. negundo* > *S. alba* > *A. altissima* > *F. excelsior* > *M. alba* > *P. fraxinifolia* > *R. pseudoacacia*.

The mean concentration values of Cr in tree species were varied from 1.44_(0.43) to 2.38_(0.52) mg/kg in unwashed leaves and from 1.34_(0.33) to 2.19_(0.53) mg/kg for washed leaves in

Table 2 Mean_(standard deviation) and value range of heavy metal concentration in the unwashed and washed leaf of different tree species

Tree species	Cd		Zn		Ni		Cu		Pb		Cr	
	Unwashed	Washed	Unwashed	Washed	Unwashed	Washed	Unwashed	Washed	Unwashed	Washed	Unwashed	Washed
<i>F. excelsior</i>	0.82 _(0.09) 0.68–0.98	0.78 _(0.05) 0.62–0.95	30.41 _(6.29) 19.97–42.47	29.02 _(5.02) 18.92–41.37	4.20 _(1.15) 1.81–8.09	3.95 _(1.07) 1.72–7.77	11.74 _(5.80) 6.65–26.62	10.64 _(1.43) 5.94–24.27	2.13 _(0.77) 0.6–3.06	1.98 _(0.77) 0.54–2.94	1.44 _(0.43) 1.01–2.37	1.34 _(0.33) 0.97–2.24
<i>A. altissima</i>	0.86 _(0.07) 0.92–0.73	0.79 _(0.07) 0.68–90	29.69 _(5.71) 23.73–39.12	28.49 _(4.22) 23.1–38.98	6.81 _(2.41) 3.67–9.62	6.35 _(2.58) 3.11–9.51	13.66 _(2.03) 10.34–15.73	12.96 _(1.87) 10.11–15.26	2.28 _(0.90) 1.04–2.82	2.00 _(0.67) 0.97–2.31	1.94 _(0.99) 0.81–3.53	1.82 _(0.47) 0.74–3.38
<i>M. nigra</i>	1.05_(0.05) 0.74–1.37	0.96 _(0.05) 0.71–1.24	35.70 _(3.56) 27.72–44.97	33.11 _(4.44) 26.35–41.67	7.16_(2.52) 2.54–10.11	6.47 _(1.51) 2.21–9.66	11.96 _(3.31) 6.30–18.95	10.94 _(2.07) 6.06–17.73	3.17 _(0.32) 0.83–7.5	2.91 _(1.08) 0.77–6.51	2.28 _(0.52) 1.06–2.91	2.03 _(0.53) 1.01–2.84
<i>R. pseudoacacia</i>	0.76 _(0.06) 0.54–0.92	0.72 _(0.07) 0.51–0.89	30.82 _(5.66) 98.20–36.07	29.02 _(5.79) 19.08–35.21	6.85 _(1.45) 4.83–8.55	6.37 _(1.53) 4.07–8.12	9.82 _(1.30) 8.42–12.10	8.85 _(1.48) 8.02–11.63	1.44 _(0.34) 0.88–1.81	1.28 _(0.39) 0.65–1.63	1.61 _(1.0) 0.33–2.77	1.50 _(0.23) 0.25–2.71
<i>A. negundo</i>	0.89 _(0.08) 0.79–1.01	0.83 _(0.07) 0.76–0.95	30.28 _(2.23) 24.12–40.06	28.80 _(4.98) 23.75–38.39	6.37 _(2.01) 3.11–10.04	6.11 _(1.94) 3.27–9.81	11.57 _(3.86) 5.40–13.73	10.56 _(1.96) 5.12–13.42	2.48 _(1.17) 1.19–4.08	2.07 _(0.71) 1.08–3.81	2.30 _(0.85) 1.75–4.12	2.15 _(0.53) 1.66–3.94
<i>S. alba</i>	0.73 _(0.04) 0.47–0.88	0.71 _(0.04) 0.42–0.87	30.39 _(2.53) 26.78–34.83	29.56 _(2.59) 25.63–34.06	3.56 _(1.69) 0.78–6.15	3.35 _(1.70) 0.68–5.97	10.78 _(2.93) 6.87–15.13	9.85 _(1.01) 6.08–14.37	2.24 _(0.58) 1.48–3.35	2.06 _(0.63) 1.26–3.21	1.78 _(0.76) 0.95–3.10	1.63 _(0.37) 0.89–2.70
<i>U. umbraculifera</i>	0.85 _(0.05) 0.74–0.93	0.81 _(0.04) 0.68–0.90	30.49 _(4.40) 23.73–39.12	27.99 _(6.50) 23.10–38.98	4.46 _(2.95) 3.67–9.62	4.08 _(2.92) 3.11–9.47	11.82 _(2.71) 10.34–15.74	10.65 _(1.72) 10.11–15.26	2.79 _(0.86) 0.74–2.94	2.41 _(0.6) 0.61–2.31	1.88 _(0.56) 0.81–3.53	1.72 _(0.44) 0.74–3.38
<i>P. orientalis</i>	0.97 _(0.15) 0.64–1.18	0.91 _(0.13) 0.61–1.08	32.18 _(5.54) 24.35–40.43	31.09 _(5.33) 24.01–39.31	7.02 _(3.84) 1.72–13.61	6.41 _(3.45) 1.64–12.25	12.75 _(5.95) 7.2–24.55	11.56 _(0.96) 7.14–23.60	3.33_(1.31) 1.54–5.97	3.03 _(0.33) 1.22–5.76	1.95 _(0.40) 1.23–2.47	1.82 _(0.41) 0.97–2.28
<i>M. alba</i>	0.84 _(0.07) 0.71–0.97	0.80 _(0.06) 0.68–0.91	32.01 _(6.91) 14.28–35.62	31.03 _(3.56) 14.17–34.53	5.26 _(1.82) 2.73–8.67	4.90 _(1.77) 2.27–8.23	10.94 _(2.28) 7.75–14.25	9.94 _(1.97) 7.11–13.14	2.17 _(1.14) 1.07–4.31	1.89 _(0.34) 1.02–4.12	1.93 _(0.59) 1.27–3.32	1.70 _(0.23) 1.17–2.95
<i>P. fraxinifolia</i>	0.83 _(0.05) 0.76–0.93	0.80 _(0.06) 0.73–0.90	39.90 _(6.24) 31.34–46.03	38.53 _(2.35) 29.62–45.65	5.90 _(1.03) 4.61–7.13	5.28 _(1.24) 4.27–7.02	15.28_(4.62) 11.22–21.74	14.60 _(2.24) 10.12–20.89	2.13 _(0.51) 1.27–2.64	1.82 _(0.51) 1.08–2.37	2.23 _(0.49) 1.43–2.64	2.00 _(0.32) 1.31–2.37
Soil samples	0.91 _(0.14)		58.35 _(5.55)		78.79 _(9.80)		38.22 _(4.78)		24.29 _(2.06)		25.14 _(2.7)	

M. nigra and *F. excelsior*, respectively. The highest mean accumulation of Cr in washed and unwashed leaves was similar and detected in *M. nigra*, followed by *A. negundo*, *P. fraxinifolia*, *P. orientalis*, *A. altissima*, *M. alba*, *U. umbraculifera*, *S. alba*, *R. pseudoacacia*, while the lowest concentration was in *F. excelsior*.

BCF, CBCI, MAI, and AOM values

The results of bioconcentration factor (BCF) for washed-leaf trees samples are shown in Fig. 2. The mean BCF of Cd were in the range of 0.78 to 1.05 for washed leaves, the maximum BCF was found in *M. nigra* while the minimum concentration was found in *S. alba*. For Ni, *M. nigra* had the highest BCF value (0.09) and followed by *P. orientalis* = *R. pseudoacacia* = *A. negundo* = *A. altissima* (0.08), *P. fraxinifolia* (0.07), *M. alba* (0.06), *F. excelsior* = *U. umbraculifera* (0.05), and *S. alba* (0.04). The maximum mean BCF of Zn were observed in *P. fraxinifolia* (0.66) and followed by *Morus nigra* (0.62), *P. orientalis* = *M. alba* (0.56), *S. alba* (0.53), *F. excelsior* = *R. pseudoacacia* = *A. negundo* (0.52), and *U. umbraculifera* = *A. altissima* (0.51). For Cu, the amount of average of bioconcentration factors varied from 0.21 to 0.38, the highest values were observed in *P. fraxinifolia* (0.38) and followed by *A. altissima* (0.34), *P. orientalis* (0.3), *M. nigra* (0.29), *F. excelsior* = *A. negundo* = *U. umbraculifera* (0.28), *M. alba* = *S. alba* (0.26), and *R. pseudoacacia* (0.23). For Pb, the average of BCF varied from 0.05 to 0.12, the highest values of BCF was observed in *M. nigra* = *P. orientalis* (0.12) and followed by *U. umbraculifera* (0.1), *A. negundo* (0.09), *F. excelsior* = *S. alba* (0.08), *A. altissima* (0.08) = *M. alba* = *P. fraxinifolia* (0.07), and *R. pseudoacacia* (0.05). The highest bio-concentration factors (BCF) of Cr in tree species were found in *A. negundo* (0.09) and followed by *M. nigra* = *P. fraxinifolia* (0.08), *A. altissima* = *P. orientalis* =

U. umbraculifera = *M. alba* (0.07), *R. pseudoacacia* = *S. alba* (0.06), and *F. excelsior* (0.05).

Results of CBCI, MAI, and AOM (%) index in the leaves (washed) of different tree species have been given in Table 3. The CBCI results showed that in washed leaves *M. nigra* with the values equal to 0.89 had the highest capacity for multi-metal accumulation as compared with other trees and followed by *P. orientalis* (0.77), *P. fraxinifolia* (0.72), *A. negundo* (0.65), *A. altissima* (0.58), *U. umbraculifera* (0.45), *M. alba* (0.44), *R. pseudoacacia* (0.32), *F. excelsior* (0.31), and *S. alba* (0.29). In unwashed leaves, *M. nigra* (0.86), *P. orientalis* (0.74) = *P. fraxinifolia* (0.74), *A. negundo* (0.63), *A. altissima* (0.60), *U. umbraculifera* (0.47), *M. alba* (0.46), *R. pseudoacacia* (0.33), *F. excelsior* (0.31), and *S. alba* (0.28) were the highest to lowest CBCI valued. The MAI results indicated that the highest values of Cd, Cr, and Ni metals detected in *M. nigra*, while the highest values of Zn and Cu were observed in *P. fraxinifolia* species and for Pb the maximum MAI values were observed in *P. orientalis*. A general trend for MAI values for the leaves in this order of magnitude: *S. alba* > *M. nigra* > *R. pseudoacacia* > *P. fraxinifolia* > *U. umbraculifera* > *A. altissima* > *M. alba* > *A. negundo* > *P. orientalis* = *F. excelsior*. The results showed that the highest AOM values for Cd was observed in *M. nigra* (8.92%). Highest and lowest AOM for Zn were seen in *U. umbraculifera* (8.18%) and *S. alba* (2.74%). For Ni, the highest and lowest AOM values were obtained in *P. fraxinifolia* (10.40%) and *A. negundo* (4.10%). Highest and lowest AOM for Cu were seen in *U. umbraculifera* (10.42%) and *P. fraxinifolia* (4.46%). For Pb, the highest and lowest AOM values were observed in *P. fraxinifolia* (15.26%) and *F. excelsior* (7.08%). Highest and lowest AOM for Cu were seen in *M. alba* (11.59%) and *A. altissima* (6.03%).

Fig. 2 Values of BCF of heavy metal in the leaf (washed) of studied tree species

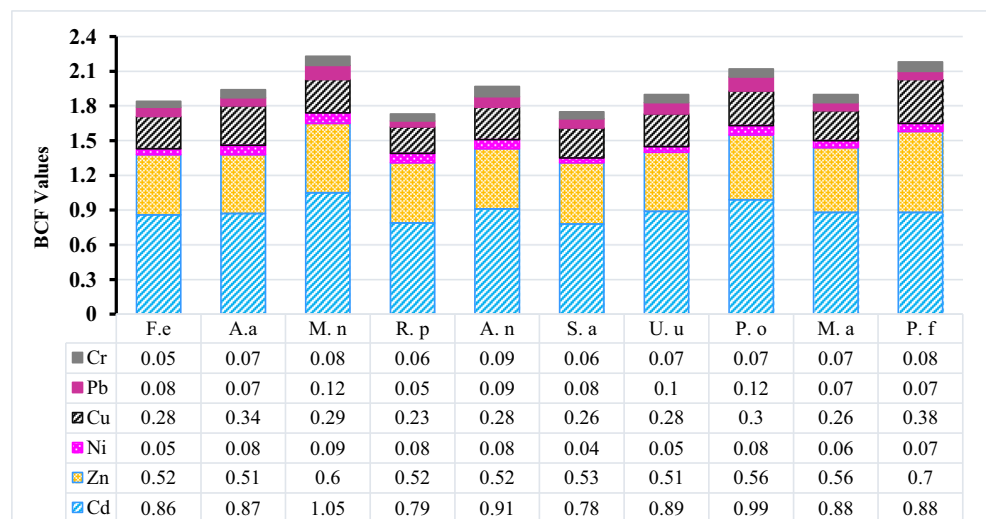


Table 3 Values of BCF, AOM (%), CBCI, and MAI heavy metal indexes in the leaf of different tree species

Tree species	AOM (%)						CBCI		MAI	
	Cd	Zn	Ni	Cu	Pb	Cr	Unwashed	Washed	Unwashed	Washed
<i>F. excelsior</i>	5.33	4.58	6.10	9.39	7.08	7.00	0.31	0.31	4.94	4.89
<i>A. altissima</i>	7.43	4.03	6.68	5.10	12.37	6.03	0.60	0.58	5.17	4.88
<i>M. nigra</i>	8.92	7.25	5.68	8.55	8.08	6.77	0.86	0.89	5.93	5.62
<i>R. pseudoacacia</i>	5.83	5.83	6.98	9.81	11.34	6.55	0.33	0.32	5.87	5.12
<i>A. negundo</i>	6.63	4.88	4.10	6.15	16.66	6.62	0.63	0.65	4.65	4.79
<i>S. alba</i>	2.71	2.74	5.53	8.55	8.19	8.49	0.28	0.29	6.98	6.77
<i>U. umbraulifera</i>	5.45	8.18	8.37	10.42	13.54	8.54	0.47	0.45	5.84	5.50
<i>P. orientalis</i>	6.39	3.38	8.64	9.33	8.79	6.31	0.74	0.77	3.94	3.86
<i>M. alba</i>	5.20	3.08	6.75	9.09	13.18	11.59	0.46	0.44	4.72	4.94
<i>P. fraxinifolia</i>	5.20	3.43	10.40	4.46	15.26	10.70	0.74	0.72	5.85	5.63

Discussion

PM

Significant differences in the amount of particulate matter accumulation in different plant species have been confirmed by many studies. According to the results, the amount of particulate matters deposited on the leaf surface and epicuticular waxes would differ from species to species based on the PM fraction and the potential of tree species to capture particulate matters. Higher capacity of PM deposition occurred in the leaf surface and epicuticular waxes of *M. nigra*. These observations could be attributed to its leaf traits such as size (large leaves), roughness, and small petioles on leaf surface that are suitable for PM capture. PM capture and its deposition potential in different plant species are influenced by various factors, including physiological, morphological, and anatomical leaf characteristics (size and shape, trichome density, length of petioles, surface roughness, texture, leaf hairiness, stomatal index (such as diameter, density, and conductance), wettability, epicuticular wax composition, etc.), foliage and branch configuration, climate and environmental factors, human activities, weather conditions (such as relative humidity and air temperature), topography, direction and speed of wind, as well as sources and amount of pollutants in the environment (Bajpai et al. 2019; Gajbhiye et al. 2019; Hassanen et al. 2016; Räsänen et al. 2013). For instance, the plants with growing high and large leaves can be more exposed to air pollutant deposition on the leaves as compared with trees growing low or small leaves, particularly trees (Dzierżanowski et al. 2011). The presence/absence of hairs, abundance of trichomes, and roughness of leaf surface could contribute to enhancing their capacity to trap atmospheric PMs. Overall, leaf surface structures as well as foliage and branch configuration are very effective factors influencing the amount of PM capture and

deposition on leaves. Thus, diverse leaf structures may be responsible for the heterogeneity of PM accumulation potential within and across different plant species (Rao and Dubey 1992; Zhang et al. 2017b). Tomašević et al. (2005) reported that the values of PM trapped and collected by plant leaves were dependent on the type of plant species given the different characteristics of the leaf surface structures, epidermis, foliage, and branch configuration (Tomašević et al. 2005). Generally, tree species assessment differed significantly in their potential for particulate matter, as also found by Dzierżanowski et al. (2011), Zhang et al. (2020), and Sgrigna et al. (2020).

Heavy metals

The average heavy metal concentrations (mg/kg dry weight) in the unwashed and washed leaf samples revealed that the amount of heavy metal concentration differs from species to species given the metal types, as well as the potential of tree species to absorb and accumulate heavy metals without showing any external damage. The difference between amount of heavy metals in the polluted/control sites and washed/unwashed of tree leaves (washed < unwashed) indicated that these species can be used as suitable tools for biomonitoring of atmospheric pollution. Trees studied differed significantly in their ability to absorb and accumulate heavy metals. *M. nigra* was most effective for the uptake and accumulation of Cd and Cu, *P. fraxinifolia* for Zn, and *P. orientalis* for Ni, Pb, and Cr, while the least effective was found in *S. alba* (for Cd and Ni), *P. orientalis* (for Zn), *R. pseudoacacia* (for Cu and Pb), and *F. excelsior* (for Cr), respectively. Indeed, the findings indicated that some tree species uptake and concentrate heavy metals in their tissues (leaves) at higher levels as compared to others. These achievements are similar to previous researchers' findings (Hajizadeh et al. 2019; Salih and

Aziz 2019; Turkyilmaz et al. 2020; Turkyilmaz et al. 2018). Studies have shown that heavy metal accumulation in plants varies depending on different factors including the plant species, various organelles of the same plant, and plant anatomical structure such as size and structure of the stomata (Tošić et al. 2016; Turkyilmaz et al. 2020), air and soil pollution, source of pollution, traffic density, along with microclimate and environmental conditions (Monfared et al. 2013; Solgi et al. 2020; Turkyilmaz et al. 2019). The levels of Zn, Ni, Cu, Ni, Cr, and Cd in leaves were not well associated with their concentrations in the soil. The availability of heavy metals in soil would be influenced by the soil characteristics such as organic-matter values, pH, redox conditions, chemical speciation, soil texture, and clay content which can interact with the heavy metals and the chemical forms of metals in soil solutions (Pajak et al. 2017).

In present study, the concentration of Cd was recorded between 0.71 (in washed leaves of *S. alba*) and 1.05 mg/kg (in unwashed leaves of *M. nigra*). Differences were observed in the Cd absorption and accumulation in leaves with regard to studied tree species. Alatou and Sahli (2019) recorded a Cd concentration of 0.20 and 0.48 mg/kg, respectively, for washed and unwashed *E. cladocalyx* F. Muell leaves from contaminated and uncontaminated urban areas. Sert et al. (2019) recorded a Cd concentration of 0.39 mg/kg in leaves of *R. officinalis* (Sert et al. 2019). Comparison of findings with these results illustrated that Cd accumulation above pollution levels was recorded for all samples. Meanwhile, the Cd levels in leaf samples were found to be lower than the levels in *R. pseudoacacia*, *A. altissima*, *F. chinensis*, *S. matsudana*, and *U. pumila* (Hu et al. 2014) and *P. orientalis*, *R. pseudoacacia*, and *F. rotundifolia* (Monfared et al. 2013), as well as Alatou and Sahli (2019) who recorded Cd concentrations of 0.81 and 1.19 mg/kg, respectively, for washed and unwashed *C. sempervirens* var. *fastigiata* leaves from contaminated and uncontaminated urban areas (Alatou and Sahli 2019). Fossil fuel combustion (coal and petroleum), tire rubber, iron and steel plants, combustion of vehicle lubricating oils, incineration of municipal solid waste, roadside dust, and vehicular exhaust emissions of tire abrasion are considered to be the main anthropogenic sources of Cd enrichment in plants in polluted urban areas (Alatou and Sahli 2019; Cowan et al. 2020; Hu et al. 2014). In addition, according to Kabata-Pendias (2010), the toxic level of Cd in plant species is above the 20 mg/kg (Kabata-Pendias 2010) while its normal level is lower than 10 mg/kg (Tomašević et al. 2005). Thus, the Cd concentrations measured in the leaves of all tree studied were under the toxic level. The comparison of mean values of Cd accumulation levels determined in all investigated species showed that *M. nigra*, *P. orientalis*, and *A. negundo* are the best biological indicators of Cd contamination in the polluted sites and can be used as suitable tools for analyzing the spatial distribution or monitoring this metal in polluted areas.

The accumulation of Zn was recorded between 27.99_(6.50) (in washed leaves of *U. umbraculifera*) and 39.90_(6.24) mg/kg (in unwashed leaves of *P. fraxinifolia*). Alatou and Sahli (2019) recorded the mean Zn accumulation of 43.58 and 48.94 mg/kg, respectively, for washed and unwashed *E. cladocalyx* F. Muell leaves from contaminated and uncontaminated urban areas. Sevik et al. (2019) recorded the zinc accumulation ranging from 41.84 to 160.04 mg/kg in *R. pulchrum* leaves. Comparison of findings with these results showed that Zn accumulation above pollution levels was recorded for all samples. However, the levels of Zn in leaf samples were found to be lower than the levels in *Ailanthus altissima*, *Salix matsudana* var. *matsudana*, *Sophora japonica*, *Salix matsudana*, *P. asperata*, *F. chinensis*, *Prunus cerasifera* cv. *Pissardii*, *R. pseudoacacia*, and *U. pumila* (Hu et al. 2014). According to Kabata-Pendias (2000), the toxic level of Zn in plant species is above the 400 mg/kg (Kabata-Pendias 2010) while its normal level ranges from 10 to 150 mg/kg (Padmavathiamma and Li 2007). Thus, the Zn accumulation measured in the leaves of all trees studied all lied within the safe and normal range levels. In polluted areas, the highest Zn values were obtained in *P. fraxinifolia*, *M. nigra*, and *P. orientalis*. So these species are the best biological indicators for Zn in assessing and its monitoring in polluted areas.

The lowest and highest Ni accumulation were recorded between 3.55_(1.70) (in washed leaves of *S. alba*) and 7.16_(2.52) mg/kg (in unwashed leaves of *M. nigra*). The results revealed that Ni accumulation in all studied species in the research sites were below the toxic level (30 ppm) (Kabata-Pendias 2000). According to the obtained data, the mean nickel accumulation in all investigated species was higher than its concentration in *R. officinalis* (2.26–3.49 ppm) (Sert et al. 2019). However, the level of Ni in leaf samples was found to be lower than its level in *N. oleander* (27.96 ppm) (Aslam et al. 2012). Thus, the Ni measured in polluted areas showed that the highest values of Ni were obtained in *M. nigra*, *P. orientalis*, and *R. pseudoacacia*; thus, these species can be used as indicator for Ni monitoring in polluted areas. Fossil fuel combustion (coal and petroleum), atmospheric and roadside dust exhaust gasses, and municipal waste incineration are considered to be the major sources of Zn in polluted urban areas (Dogan et al. 2010; Farhan et al. 2012; Norouzi et al. 2015).

The lowest and highest Cu accumulation were recorded in the *R. pseudoacacia* and *P. fraxinifolia* with values 9.82_(1.48) and 15.28_(4.62) in unwashed, as well as 8.85_(1.48) and 14.60_(2.24) mg/kg in washed leaves, respectively. According to Serbula et al. (2012) results, most species can uptake considerable levels of copper in their tissues under different conditions (natural and anthropogenic) (Serbula et al. 2012). Although Cu is an important component of enzymes involved in oxidation-reduction reactions, it is a very toxic metal

(Alatou and Sahli 2019). In this study, in all investigated species Cu accumulation levels were higher than its accumulation in *A. altissima*, *S. matsudana* var. *matsudana*, *S. japonica*, *S. matsudana*, *P. asperata*, *F. chinensis*, *P. cerasifera* cv. *Pissardii*, *R. pseudoacacia*, and *U. pumila* (Hu et al. 2014). Alatou and Sahli (2019) recorded the mean concentration of Cu as 7.41 and 7.92 mg/kg, respectively, for washed and unwashed *E. cladocalyx* F. Muell leaves from contaminated and uncontaminated urban areas. However, the levels of Cu in leaf samples were found to be higher than its level in *R. officinalis* (27 ppm) (Affholder et al. 2013). The phytotoxic range of Cu in the plant species is 20–100 mg/kg values (Padmavathamma and Li 2007) while its safe concentration is 3–30 mg/kg (Kabata-Pendias 2000). So, the Cu accumulation was in the normal range in all investigated species. In addition, the accumulation of Cu in all trees in polluted areas showed that the highest values of Cu accumulated in *P. fraxinifolia*, *A. altissima*, and *P. orientalis*; so, these species can be used as a bioindicator of Cu pollution in contaminated zones.

The concentration of Pb in all species varied from 1.28_(0.39) (in washed leaves of *R. pseudoacacia*) to 3.33_(1.31) mg/kg (in unwashed leaves of *P. orientalis*). The results demonstrated that the Pb accumulation level (in all leaf samples) was lower than the toxic level (from 30 to 300 mg/kg) (Kabata-Pendias 2000), while its safe concentrations in the plants can range within 5–10 mg/kg. Alatou and Sahli (2019) recorded the average Pb concentration of 7.50 and 10.83 mg/kg, respectively, for washed and unwashed *E. cladocalyx* F. Muell leaves from urban areas. Monfared et al. (2013) measurement above of Pb (higher than 3.33 mg/kg) in leaves in some trees such as *P. orientalis*, *R. pseudoacacia*, and *F. rotundifolia* (Monfared et al. 2013). However, the level of Pb in leaf samples was found to be higher than its level in *A. glutinosa* (0.96 ppm), *R. pseudoacacia* (0.71 ppm), and *F. excelsior* (0.126 ppm) (Alahabadi et al. 2017). Fossil fuel combustion (gasoline, coal, and petroleum), incineration of municipal solid waste, roadside dust, open-air burning, abrasion of tire, and automobile exhaust emissions are regarded as the main origins of Pb in polluted areas (Mukherjee et al. 2016). In addition, the accumulation of Pb in all trees at polluted areas showed that the highest values of Pb accumulated in *P. orientalis*, *M. nigra*, and *U. Umbraculifera*; hence, these species can be used as bioindicators and beneficial species for remediation and monitoring this metal from contaminated areas.

Cr concentrations measured from all investigated leaf samples including both unwashed and washed treatment varied from 1.34_(0.33) (in washed leaves of *F. excelsior*) to 2.38_(0.52) mg/kg (in unwashed leaves of *M. nigra*). The amount of Cr accumulation in leaf samples was under the toxic level (10 ppm) (Kabata-Pendias 2010). Liu et al. (2017) recorded the Cr concentration for species *U. pumila*, *R. pseudoacacia*,

F. chinensis, *S. japonica*, *Ligustrum* × *vicaryi*, and *A. altissima* in both washed leaves (5.49, 4.07, 4.40, 7.54, 5.98, and 5.05 mg/kg) and unwashed leaves (9.15, 4.53, 5.32, 10.6, 6.97, and 6.03 mg/kg). Hu et al. (2014) detected a 4.17 mg/kg of Cr in leaves of *R. officinalis*. However, the level of Cr in leaf samples was found to be lower than its level in *A. altissima*, *S. japonica*, *S. matsudana*, *P. asperata*, *F. chinensis*, and *R. pseudoacacia* (Hu et al. 2014). Combustion sources such as fossil fuel, power plant, industry dumping areas, steel works, industrial lubricants, metal plating, cement industry, motor vehicles, roadside dust, and vehicular exhaust emissions are considered as the main sources of Cr enrichment in plants in polluted urban zones (Abbasi et al. 2017; Liu et al. 2017; Norouzi et al. 2015). In addition, the accumulation of Cr in all investigated species in polluted areas showed that the highest values of Cr accumulation were found in *M. nigra*, *A. negundo*, and *P. fraxinifolia*; so these species can be used as bioindicator and beneficial species for remediation and monitoring of this metal from contaminated areas.

MAI

MAI reveals the ability of diverse plant species in terms of uptake and accumulation of airborne heavy metals. According to the MAI calculated in washed and unwashed leaves, the highest MAI values were detected in *S. alba* (6.77 and 6.98) and *M. nigra* (5.93 and 5.62) while the lowest were found in *P. orientalis* (3.94 and 3.86). Comparison of results with findings reported in other places such as Karaj city (in Iran) (Monfared et al. 2013), Yan'an city (in China) (Hu et al. 2014), Olkusz city (in southern Poland) (Hu et al. 2014; Monfared et al. 2013; Pająk et al. 2017), gas and petrochemical zone Asaluyeh area (in Iran) (Safari et al. 2018) showed that the MAI levels may vary given the tree species and local atmospheric chemistry, the amount and type of anthropogenic activities, main polluted sources, atmospheric changes, wind effect, and meteorology. In addition, other factors such as leaf tree properties, plant growth rate, sampling time period, and height also influence the potentials of removal of atmospheric pollutants by urban plants from air. For instance, the plants with growing high and large leaves can be more exposed to air pollutant deposition and collect airborne heavy metals in leaves as compared to trees growing low or small leaves. Indeed, the detected value of MAI index in different tree leaves indicated that the responses of trees to heavy metal are different. Also, the plants with the greatest MAI values can be applied as barriers in vulnerable, densely populated areas and contaminated zones for metal contamination (Zhai et al. 2016). So, in this study, the recorded MAI levels suggest that *S. alba*, *M. nigra*, *R. pseudoacacia*, *P. fraxinifolia*, *U. umbraculifera*, *Platycladus orientalis*,

and *A. altissima* are the best species to be cultivated in populated and urban areas.

AOM

AOM index reveals the discrepancy between the values of heavy metal uptake by plant tissues and the airborne particles on the leaf surface (Alfani et al. 2000; Safari et al. 2018). Observations showed that among all investigated trees, the AOM factor for *M. nigra* and *U. umbraculifera* was larger than for other species. This can be related to their leaf traits such as size (large), roughness of leaves, density, and the existence of a mucus layer on the surface of leaf which may have a significant impact on more dust and air particles' capture. In this regard, the results showed that the highest total particulate matter deposition (sum of PM₁₀, PM_{2.5}, and PM_{0.2}) was observed on *M. nigra* leaves. AOM assessment in previous studies indicated that many factors such as environmental and climatic conditions, leaf characteristics, atmospheric changes, speed and direction of wind, and contents and chemical composition of epicuticular waxes play important roles in the amount of airborne particles captured from the atmosphere. It is related to the values of heavy metals detected in the leaf samples (Liang et al. 2017; Sawidis et al. 2011; Simon et al. 2014).

Conclusion

In this study, we aimed to analyze the potential uptake and accumulation of heavy metals (Zn, Cu, Pb, Ni, Cd, and Cr) in unwashed and washed leaves along with PM in leaf surfaces and waxes of different tree species in Isfahan city (Iran). The results revealed that the urban trees differed in uptake and accumulation of heavy metals and total particulate matter. In this regard, the highest absorber for Cd, Cr, and Ni (in unwashed and washed leaves) was the *M. nigra*, while for Zn and Cu (*P. fraxinifolia*) and Pb it was the *P. orientalis*. The highest and lowest capacity for total particulate matter removal belonged to the *M. nigra* and *S. alba*, respectively. Trees such as *M. nigra* with large leaves and their roughness surface proved to be the most efficient in capturing and retaining particulate matter and heavy metals. The trees' potential to accumulate certain heavy metal from the soil depends on the metal and plant species. The differences in the heavy metal uptake and accumulation from soil and air with regard to plant species could highlight the need for assessing the capability of trees in controlling pollution in polluted areas. Accordingly, the CBCI and MAI indices results showed *M. nigra* and *S. alba* had the greatest performance to accumulate and remediate the multi-metals from the soil and ambient air, respectively. As such, these species could be used as a simple and beneficial way of remediation and monitoring the polluted sites in Isfahan.

Generally, we conclude that selection and plantation of suitable plant species could be effective for modification of the environment quality, monitoring as well as the remediation of the contaminated areas, since plant organs (especially leaves) are the main absorbers and monitoring tools of heavy metals plus air pollutants.

Author contribution All authors contributed to the study conception and design. Masoud Hatamimanesh: conceptualization, visualization, writing, and editing. Samar Mortazavi: formal analysis, investigation, editing, and revising. Eisa Solgi contributed in statistical analysis and conclusion. Ahmad Mohtadi: supervision and review.

Data Availability In this manuscript, all data and material methods are available.

Declarations

Ethics approval This manuscript complies with ethical standards.

Consent for publication The authors consent to publish the manuscript.

Conflict of interest The authors declare no competing interests.

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