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Role of Plant Leaves in Removing Airborne Dust and Associated Metals on Beijing Roadsides

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ABSTRACT

As the capital of China, Beijing is continuously exposed to high amount of airborne dust, thus it is necessary to find improvement methods. Taking advantage of phytoremediation, an ecological and friendly way to improve air quality, this study investigates the role of urban plant leaves in removing airborne dust and its associated metals by analyzing leaf samples of 32 plant species in autumn. Results showed that leaves could remove dust from 0.510 to 23.0 g m^{-2} with an overall mean of 7.50 g m^{-2} on Beijing roadside sites. Some species removed certain metals more efficiently than others. Leaves of *Chaenomeles speciosa* accumulated the highest Cd (9.48 µg g^{-1}) and the highest Cr value (19.8 µg g^{-1}) was observed for leaves of *Sorbaria kirilowii.* Both of the highest concentrations of Cu (34.1 µg g^{-1}) and Fe (868 µg g^{-1}) appeared for leaves of *Sophora japonica*, whilst the highest values of Mn (169 µg g^{-1}) and Ni (18.7 µg g^{-1}) were found for leaves of *Rosa chinensis* and *Prunus cerasifera* f. *atropurpurea*, respectively. *Populus beijingensis* accumulated the most Pb (6.57 µg g^{-1}) and *Populus tomentos*a the most Zn (142 µg g^{-1}). For multi-metal pollution, Metal Accumulation Index (MAI) values were calculated, and the highest values were observed in unwashed leaves of *Amygdalus persica* (387), washed leaves of *Punica granatum* (105) and leaf dust of *Viburnum sargentii* (6.46). Plant species with dust accumulation rate above the mean including *Koelreuteria paniculata*, *Ulmus pumila*, *Syringa oblata*, *Malus micromalu*, *Weigela florida* cv. Red Prince, *Ailanthus altissima*, *Salix babylonica*, *Robinia pseudoacacia*, *Ligustrum* × *vicaryi*, *Euonymus japonicus*, *Prunus cerasifera* f. *atropurpurea*, *Magnolia denudata*, and species with higher MAI values including *Amygdalus persica*, *Magnolia denudata*, *Syringa oblata* are suggested to be considered in future green belt planning in Beijing.

Keywords: Phytoremediation; Urban tree; Heavy metals; Metal accumulation index; MAI.

INTRODUCTION

Most developing nations have been influenced by atmospheric pollution, in terms of human health (Anderson *et al.*, 2012), climate change (Kan *et al.*, 2012) and loss of biodiversity (Lovett *et al.*, 2009). With urban transport development, traffic-derived pollutants become an increasing problem (Walsh and Shah, 1997; Ning and Sioutas, 2010; Cao *et al.*, 2015) and have been linked to respiratory and cardiovascular disease, birth and developmental defects, cancer (Hei, 2010) and so on. According to WHO (2003), the life expectancy of urban residents in strongly polluted areas could decrease by over one year, particularly for children and people with lung and heart disease. There are 800 000 deaths annually, which could be due to urban air pollutants (WHO, 2002). Airborne particulates, used as an indicator of heavy metal pollution due to atmospheric deposition (Al-Khashman, 2004), mainly originates from fuel combustion by gasoline/diesel powered vehicles and non-combustion sources including vehicle brake and tire abrasion, gardening, household waste discharge, architectural painting and building structure erosion (Sabin *et al.*, 2006; Biasioli *et al.*, 2006; Mielke *et al.*, 2010; Kong *et al.*, 2011), and it contains a mixture of heavy metals, black carbon, polycyclic aromatic hydrocarbons and other substances suspended in the atmosphere (Bell *et al.*, 2011). Roadside soil in Beijing is significantly contaminated by heavy metals (Chen *et al.*, 2010), of which some are carcinogenic, mutagenic, teratogenic, endocrine disruptors, whereas others cause neurological and behavioral changes, especially in children (Ali *et al.*, 2013).

Vegetation has been used as an indicator of air pollution (Ram *et al.*, 2014; Norouzi *et al.*, 2015), as their leaves can effectively adsorb air particulates (Freer-Smith *et al.*, 1997; Prusty *et al.*, 2005; Nowak *et al.*, 2006; Jamil *et al.*, 2009; Qiu *et al.*, 2009) and reduce air pollutants (Nowak *et al.*,

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2006; Hofman *et al.*, 2014). Escobedo *et al.* (2008) found that planting vegetation in urban areas of Santiago City, Chile was a cost-effective measure to capture air pollutants. On an annual basis, urban trees/shrubs are estimated to remove about 215,000 tons of PM_{10} for the whole US (Nowak *et al.*, 2006) and about 234 tons of PM_{10} in Chicago alone (Nowak, 1994). In China, vegetation covering an area of 1639 ha at eight residential areas in Beijing could remove 2170 tons of dust (Zhang *et al.*, 1997), and trees in the city center could remove 772 tons of PM_{10} over a year (Yang *et al.*, 2005). Studies from other Chinese cities showed that concentrations of PM decreased by 9.1% near a forest in Shanghai (Yin *et al.*, 2011) and the amount of dust retained by trees was measured as 8600 t yr^{-1} in an area of 103 km^2 in Zhengzhou (Zhao *et al.*, 2002). A study in Huizhou, Guangdong province found that foliar dust contains appreciable amounts of Cd, Cr, Cu, Pb, Zn, and S as 0.040 t, 1.63 t, 2.70 t, 1.84 t, 5.54 t, and 19.52 t respectively from a study area (Qiu *et al.*, 2009).

Vegetation is one of the most commonly cited ecosystem methods for reducing atmospheric pollutants (Pataki *et al.*, 2011), but the ability of different taxa to accumulate particulate matter and air-borne pollutants differs (Dzierżanowski *et al.*, 2011; Escobedo *et al.*, 2011). For example, particulate accumulation on leaves of 22 trees and 25 shrubs was studied in Norway and Poland, but only *Pinus mugo* and *Pinus sylvestris*, *Taxus media* and *Taxus baccata*, *Stephanandra incisa* and *Betula pendula* were able to capture particulate matter efficiently (Sæbø *et al.*, 2012). High degrees of traffic saturation (80%–90%) (Notes: The degree of traffic saturation (%) is a ratio of demand to capacity on approaching to a junction) have been observed in the Chinese capital city of Beijing, which promote the release of heavy metals from automobile exhaust onto road surfaces and into the ecosystem (Wang *et al.*, 2012). As a result, Beijing is constantly facing high concentrations of airborne dust and there is a need to improve air quality. Previous studies mostly measured metals accumulated by plant leaves but rarely paid attention to the dust collected by leaves. In order to take advantage of the phyto-remediation method to improve air quality in urban areas of Beijing, this study investigates the role of the extant urban green plants in removing airborne dust and associated metals by their leaves. In autumn, leaf samples of 32 plant species were collected from heavy traffic roadsides, and the airborne dust collected by the leaves and its associated metals were analysed in order to identify those plant species that could well accumulate or remove dust and metals, and hence provide scientific guidance for urban vegetation planting.

MATERIALS AND METHODS

Site and Sampling

Beijing is located in the semi-humid warm temperature zone (39°90'N, 116°32'E) and has a continental monsoon climate, with cold dry winters and wet warm summers. Five high-speed roads were built up inside and around the city to satisfy traffic demand. In total, 96 leaf samples from 32 plant species (three replicates for each species) were collected at 14 sites alongside the west 3rd ring road with diurnal heavy traffic (Fig. 1, Table 1) on Oct. 28th, 2014, when there was no rain prior for 17 days to ensure that plenty of dust was deposited on leaf surfaces. Healthy intact leaves were obtained from shoots toward the street line and with height at 2.5–3.0 m above ground level for megaphanerophyte, and at 2.0 m for small trees or shrubs. Leaf samples with the same distance to traffic center were selected as possible. After collection, they were put into paper bags carefully and transported to the laboratory.

Sample Treatment and Analysis

Sample Subgroup and Leaf Area Measurement

All 96 duplicate leaf samples from 32 species were divided equally into two groups to form 192 leaf samples in total. Each of them was photographed with a ruler and the leaf area was measured under Adobe Photoshop software using the formula of leaf area = known area × leaf pixel value/target pixel.

Overall, about 300 to 500 cm^2 of leaves was measured and prepared for each group of all duplicates.

Sample Pretreatment, Digestion and Measurement

In the two groups of each duplicate sample of plant species, one group of leaves was kept unwashed and another was washed with 18.2 MΩ de-ionized water. Afterwards, both washed and unwashed leaf samples were dried in an oven at 70°C, weighed and cut into pieces, ground, and kept for further chemical analysis. Referring to Liu *et al.* (2014), about 0.2 g leaf powder of each sample was digested with a chromatographic class HNO_3-H_2O_2 solution (2 mL:1 mL) using a Microwave Digestion Instrument from CEM company. The digestion procedure was set as 3-min heating up to 80°C and kept for 15 min, then up to 190°C and kept for 15 min. After the temperature naturally dropped down to room temperature, the digested solution was diluted to 25 mL with 18.2 MΩ de-ionized water. Heavy metals (Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn) were detected by TAS-990 AAS (Beijing Puxi General Company). For sample calibration, a series of metal standards of known concentration was prepared using 1000 µg mL^{-1} stock solution, purchased from the National Center for Analysis and Testing for Nonferrous Metals and Electronic Materials. Samples of first-grade national standard material of shrubs and leaves (GBW 07603 (GSV-2)) with certified concentrations of elements from Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Science were also analysed for quality assurance check.

Calculation and Data Analysis

Calculation was conducted by three ways: (1) Dust accumulation (g m^{-2}) by plant leaves based on leaf area was calculated using unwashed leaf weight per square meter leaves minus washed leaf weight per square meter leaves. (2) Heavy metal accumulation (µg g^{-1}) in unwashed/washed leaves was calculated simply by the metal weight (µg) in unwashed/washed leaves over the unwashed/washed leaf weight (g). (3) Leaf dust metal accumulation (µg g^{-1}) based

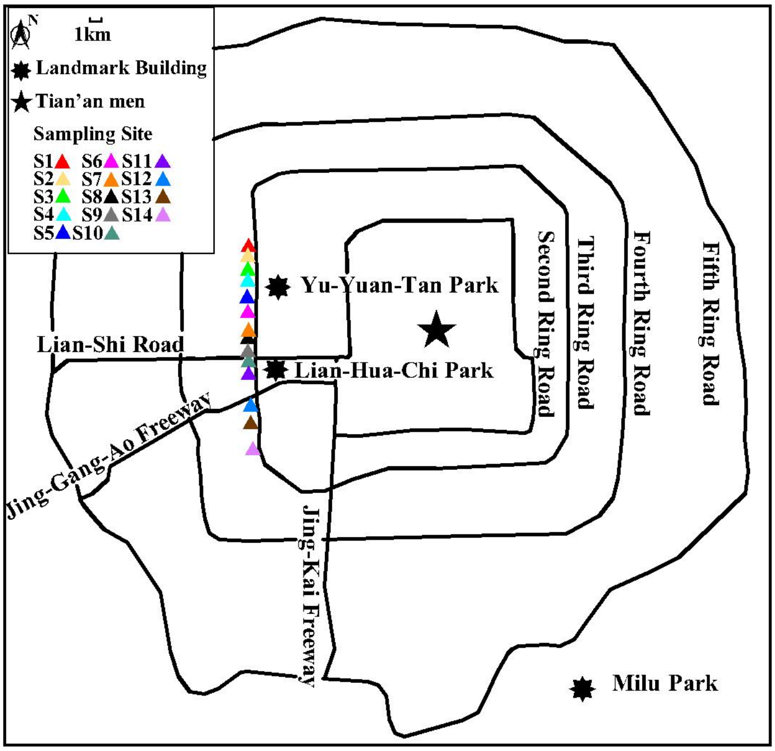

Fig. 1. Sampling sites (notes: site No. was shown in Table 1).

Table 1. Sites with plant species No. information.

Site No.	Locality	Latitude	Longitude	Species No.
S1	South of Zi-Zhu Bridge	39.93881–39.94011	116.30358–116.30367	01–03
S2	The East Gate of Capital Normal University	39.93597	116.30367	04
S3	Beijing Haidian Experimental Primary School	39.92594–39.92603	116.30367–116.30375	05–06
S4	North of Central Radio & Television Tower	39.91667–39.91933	116.30372–116.30375	09–10
S5	South of Central Radio & Television Tower	39.91625–39.91667	116.30356–116.30381	07–08, 12A, 12B
S6	The Overbridge on the South of Central Radio & Television Tower	39.91697	116.30436	11A
S7	North of Gong-Zhu-Fen Bridge	39.92642	116.30378	12C
S8	Under the Gong-Zhu-Fen Bridge	39.90653–39.90683	116.30208	13–14
S9	North of Lian-Hua-Chi Bridge	39.89797	116.30381	15
S10	Under the Lian-Hua-Chi Bridge	39.89711	116.30322–116.30325	16, 11B
S11	South of Lian-Hua-Chi Bridge	39.89239	116.30378–116.30389	11C, 17A
S12	South of Liu-Li Bridge	39.88097–39.88158	116.30397–116.30428	17B, 17C, 18–19
S13	Xi-Ju	39.87256–39.88633	116.30419–116.30533	20–24
S14	South of Li-Ze Bridge	39.86478–39.87236	116.30592–116.30617	25–32

on dust weight was calculated by the formula as follows: Metal concentration (μg) per gram unwashed leaves multiplied by unwashed leaves weight (g) per square meter unwashed leaves, then divided by dust weight (g) per square meter unwashed leaves. All treatments were replicated three times in the experiments and the means and standard deviations (S.D.) or standard error of mean (S.E.) were calculated with Microsoft Office Excel 2007. One-way analysis of variance was carried out with SPSS17.0. In addition, Post Hoc Multiple Comparisons were applied to obtain the significance levels of differences between plant species.

In order to estimate the overall metal accumulation ability, metals accumulation index (MAI) formula

$$\mathrm{MAI} = \left[\frac{1}{N}\right]\sum_{j=1}^{N} I_j \tag{1}$$

developed by Liu *et al.* (2007) and Monfared *et al.* (2013) was adopted to calculate MAI for each plant species including unwashed leaves, washed leaves and leaf dust, where N delegates the total number of metals analyzed and $I_j = x/\delta x$ is the sub-index for variable j, obtained by dividing the mean value (x) of each metal by its standard deviation (δx). Metal accumulation index identifies the total metal concentration in plants. In our study we have studied eight metals, therefore the value of N equals to 8 (Liu *et al.*, 2007).

RESULTS AND DISCUSSION

Dust Accumulation by Plant Leaves

Various dust retention abilities can be found for different tree species even under identical environmental conditions (Freer-Smith *et al.*, 1997; Chai and Han, 2002). Similarly, our result shows that, per square meter, leaves could remove 0.510 to 23.0 g dust with the average of 7.50 g for all 32 species (Fig. 2 and Table 2) on Beijing roadside sites. Species 24 (*Koelreuteria paniculata*) and 2 (*Ulmus pumila*) accumulated the highest amount of dust as 23.0 g m^{-2} and 22.4 g m^{-2} respectively, significantly higher than those of any other species. Leaves with surface roughness, leaf hairs, raphe, mucilage or oil, and those with short petioles absorb more dust based on previous study (Freer-Smith *et al.*, 1997), which may explain the higher leaf dust capture rates in species 24 and 2 due to mucus secretion and coarse leaf surface. The third highest dust accumulation rate (20.5 g m^{-2}) was found in species 32 (*Syringa oblata*), which is again significantly higher than those of the remaining species, except 30 (*Malus micromalu*). Species 30 accumulated dust of 15.3 g m^{-2}, which has no significant differences with dust collection rates in species 25 (*Weigela florida* cv. Red Prince, 11.9g m^{-2}), 20 (*Ailanthus altissima*, 11.1 g m^{-2}), 12 (*Salix babylonica*, 10.0g m^{-2}), 21 (*Robinia pseudoacacia*, 9.14 g m^{-2}) and 29 (*Ligustrum* × *vicaryi*, 9.10 g m^{-2}). The lowest dust accumulation of 0.510 g m^{-2} occurred in leaves of species 10 (*Amygdalus persica*). Dust accumulation of species 1 (*Sophora japonica*), 2 (*Ulmus pumila*), 11 (*Populus tomentosa*), 12 (*Salix babylonica*), 14 (*Ginkgo biloba*), 17 (*Fraxinus chinensis*) and 24 (*Koelreuteria paniculata*) in Jinan city, Shangdong province of East China (Sun *et al.*, 2015) was studied using artificial dust blowing method, and the results indicated a leaf dust accumulation sequence from high to low as for species 17, 12, 24, 11, 2, 14 and 1, which is totally different from the actual sampling results in our study, showing an order of 24 > 2 > 12 > 11 > 17 > 1 > 14. For the most common investigated species (2, 12, 17, 20, 21, 24), the leaf dust capture rates at our sites are 15.1, 13.5, 8.2, 5.2, 7.6 and 15.9 times higher than those measured from Xingxiang, a southern city of China in autumn, implying heavier airborne dust pollution at the Beijing roadside (Table 2, Zhang *et al.*, 2013), where heavy traffic always occurs.

Heavy Metal Accumulation

Heavy Metal Accumulations in Leaves of Different Plant Species

Accumulation rates of metals Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn in both washed and unwashed leaves are illustrated for all plant species in Fig. 3 and Table 3, and for individual plant species in Figs. 4(a)–4(h) and Table S1.

Cadmium (Cd)

In total 192 leaf samples from 32 plant species, including both unwashed and washed treatment, could accumulate Cd from 0.520 to 9.80 µg g^{-1} with the average of 4.71 µg g^{-1} (Table 3, Fig. 3), which is higher than the Cd normal value of 2 µg g^{-1} in plants (Hajar *et al.*, 2014). The accumulation

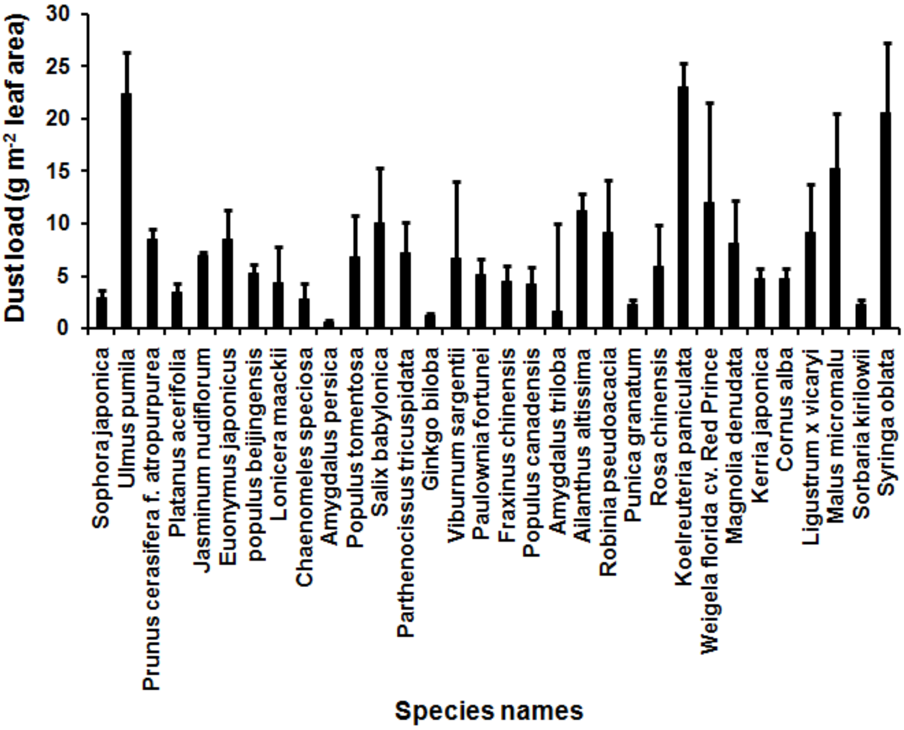

Fig. 2. Dust accumulations by leaves of different plant species (Note: error bar means standard deviation).

Table 2. Dust accumulations by leaves of different plant species (g m^{-2} leaf).

Species No.	Species names	Mean ± stdev in Beijing	Mean in Jinan	Mean ± stdev in autumn of Xingxiang	Mean ± stdev in Xingxiang roadside
1	*Sophora japonica*	2.83 ± 0.78	5.98	2.74 ± 0.23	NA
2	*Ulmus pumila*	22.4 ± 3.9	7.78	1.48 ± 0.18	1.31 ± 0.21
3	*Prunus cerasifera* f. *atropurpurea*	8.41 ± 1.04	NA	NA	NA
4	*Platanus acerifolia*	3.40 ± 0.89	NA	NA	NA
5	*Jasminum nudiflorum*	6.88 ± 0.32	NA	NA	NA
6	*Euonymus japonicus*	8.49 ± 2.82	NA	NA	NA
7	*Populus beijingensis*	5.25 ± 0.88	NA	NA	NA
8	*Lonicera maackii*	4.29 ± 3.47	NA	1.54 ± 0.06	NA
9	*Chaenomeles speciosa*	2.79 ± 1.46	NA	NA	NA
10	*Amygdalus persica*	0.510 ± 0.220	NA	1.45 ± 0.06	2.15 ± 0.16
11	*Populus tomentosa*	6.78 ± 3.99	7.97	2.27 ± 0.28	NA
12	*Salix babylonica*	10.0 ± 5.2	9.54	0.74 ± 0.04	NA
13	*Parthenocissus tricuspidata*	7.15 ± 2.97	NA	NA	NA
14	*Ginkgo biloba*	1.19 ± 0.14	6.25	1.21 ± 0.12	1.49 ± 0.04
15	*Viburnum sargentii*	6.68 ± 7.31	NA	NA	NA
16	*Paulownia fortunei*	5.11 ± 1.44	NA	NA	NA
17	*Fraxinus chinensis*	4.35 ± 1.53	10.47	0.53 ± 0.03	1.07 ± 0.03
18	*Populus canadensis*	4.16 ± 1.60	NA	NA	NA
19	*Amygdalus triloba*	1.57 ± 8.41	NA	NA	NA
20	*Ailanthus altissima*	11.1 ± 1.7	NA	2.12+0.13	3.97 ± 0.06
21	*Robinia pseudoacacia*	9.14 ± 4.96	NA	1.21 ± 0.10	1.64+0.14
22	*Punica granatum*	2.19 ± 0.53	NA	NA	NA
23	*Rosa chinensis*	5.86 ± 3.95	NA	NA	NA
24	*Koelreuteria paniculata*	23.0 ± 2.3	8.0187	1.45 ± 0.15	2.07 ± 0.33
25	*Weigela florida* cv. Red Prince	11.9 ± 9.6	NA	NA	NA
26	*Magnolia denudata*	8.11 ± 4.05	NA	NA	NA
27	*Kerria japonica*	4.63 ± 1.05	NA	NA	NA
28	*Cornus alba*	4.69 ± 0.95	NA	NA	NA
29	*Ligustrum* x *vicaryi*	9.10 ± 4.66	NA	NA	NA
30	*Malus micromalu*	15.3 ± 5.2	NA	NA	NA
31	*Sorbaria kirilowii*	2.26 ± 0.45	NA	NA	NA
32	*Syringa oblata*	20.5 ± 6.8	NA	NA	NA
Data origins		This study	Sun *et al.*, 2015	Zhang *et al.*, 2013	Zhang *et al.*, 2013

Note: NA: not available.

rates of Cd from this study are also higher than that in plants sampled from Yan'an, a small city in western China, with a range of 0.14–3.52 µg g^{-1} (Hu *et al.*, 2014) and from the roadside of Florence, Italy with mean Cd values of 0.09–0.12 µg g^{-1} in *Quercus ilex* leaves (Ugolini *et al.*, 2013).

In this study, species 9 (*Chaenomeles speciosa*) accumulated the highest Cd of 9.48 µg g^{-1} in its unwashed leaves, which is significantly higher than that of any other plant species (Table S1, Figs. 4(a)), presumably due to its rich leaf oleanolic and other organic acid contents, as previous study showed that the contents of acetic and citric acids were significantly correlated with the content of Cd in leaves (Sun *et al.*, 2006). Species 32 (*Syringa oblata*) had the second highest Cd accumulation rate of 8.74 µg g^{-1}, which is again significantly higher than those of other plant species. Leaves of species 31 (*Sorbaria kirilowii*) and 29 (*Ligustrum* × *vicaryi*) also accumulated a significantly higher amount of Cd (8.14 and 8.06 µg g^{-1}), in comparison with those in leaves of the remaining species excluding species 28 (*Cornus alba*, 7.80 µg g^{-1}). The accumulation rates for species 30 (*Malus micromalu*), 27 (*Kerria japonica*) and 26 (*Magnolia denudata*) were 7.42, 7.41, 6.81 µg g^{-1} respectively, and they are all significantly higher than those in the remaining 81.2% species (Table S1, Figs. 4(a)). For same species, the differences of metal Cd accumulation rates between unwashed and washed leaves were various, and were only significant for species 1 (*Sophora japonica*), 3 (*Prunus cerasifera* f. *atropurpurea*), 7 (*Populus beijingensis*) and 24 (*Koelreuteria paniculata*).

Metal concentrations in leaves from this study were compared with results from previous studies in Table 4. The Cd concentrations in all investigated species at our sites were lower than the general levels of Cd (> 10 µg g^{-1}) in plants (Markert, 1993), but exceeded the plant food toxic maximum limit of 0.5 µg g^{-1} in China (MPHPRC, 2012), suggesting that roadside leaves are unfit for human

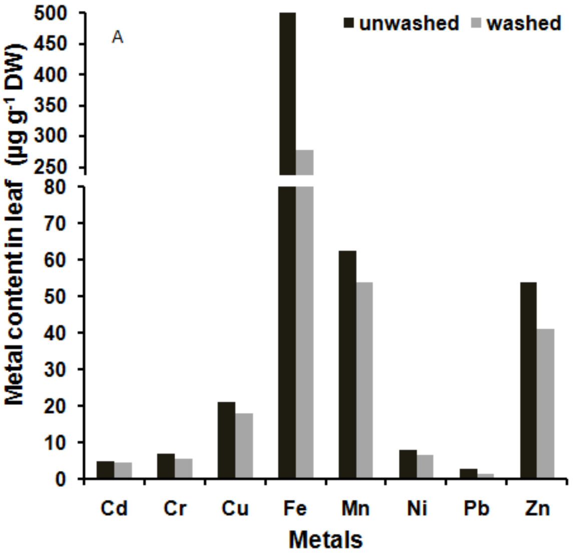

Fig. 3. Mean metal accumulation in plant leaves.

food or medicine usage. Cd concentration in leaves of *Robinia pseudoacacia* (species 21) from an industrial city Denizli, Turkey was 3.70 µg g^{-1} (Çelik *et al.*, 2005), which is lower than the 5.73 µg g^{-1} measured in this study. Species of *Ailanthus altissima* (20), *Ligustrum* × *vicaryi* (29), *Sophora japonica* (1), *Fraxinus chinensis* (17), *Robinia pseudoacacia* (21) and *Ulmus pumila* (2) accumulated Cd of 5.45, 8.06, 3.18, 3.79, 5.73 and 3.08 µg g^{-1} in unwashed leaves and 4.83, 7.70, 2.93, 3.40, 5.50 and 2.66 µg g^{-1} in washed leaves respectively from this study. They are all much higher than those of 2.28, 1.96, 1.59, 1.59, 1.10, 1.36 µg g^{-1} in the same species leaves from the Yan'an city (Hu *et al.*, 2014), indicating heavier Cd pollution in the capital city with frequent heavy traffic. Combustion of fossil fuels (coal and petroleum), incineration of municipal solid waste, vehicle tire wear, and combustion of vehicle lubricating oil can all contribute to airborne Cd in urban area.

In addition, Cd accumulation rates in washed leaves for species *Sophora japonica* (1), *Platanus acerifolia* (4), *Populus tomentosa* (11), *Ginkgo biloba* (14) and *Koelreuteria paniculata* (24) at our sites were 2.93, 2.12, 2.76, 4.11 and 5.93 µg g^{-1} respectively, which were higher than those collected at other non-main roadside sites of Beijing from a previous study, measured as 0.191, 0.045, 0.587, 0.045 and 0.063 µg g^{-1} respectively (Liu *et al.*, 2007), implying that the 3rd ring road of Beijing suffered heavier or increasing Cd pollution than other non-main traffic roads.

Cr

All 192 plant leaf samples, including both unwashed and washed treatments from 32 species, showed accumulation rates for Cr ranged from 2.01 to 22.7 µg g^{-1} with an average of 6.35 µg g^{-1} (Table 3, Fig. 3). The current results were very similar to the Cr normal range of 0.006–18 µg g^{-1} in plants (Hajar *et al.*, 2014), but much higher than those in the investigated plants leaves from Yan'an where Cr ranged as 0.021–0.952 µg g^{-1} with averages from 0.097 to 0.365 µg g^{-1} (Hu *et al.*, 2014). At the roadside of Florence Italy, the mean Cr values of 1.3–3.1 µg g^{-1} in *Quercus ilex* leaves (Ugolini *et al.*, 2013) fall within the range of this study but towards the lower end.

Similar to Cd, the ability of Cr accumulation varied for individual plant species. *Sorbaria kirilowii* (31) accumulated the highest Cr of 19.8 µg g^{-1} in their unwashed leaves and the second highest Cr accumulation was found in *Syringa oblata* (32) with a collection rate of 12.5 µg g^{-1}. *Sophora japonica* (1) also showed significantly higher collection rate as 10.6 µg g^{-1}, in comparison with those of other 81.2% species (Table S1, Figs. 4(b)). Leaf Cr concentions in *Sophora japonica* (1), *Ulmus pumila* (2), *Prunus cerasifera* f. *atropurpurea* (3), *Euonymus japonicus*(6), *Chaenomeles speciosa* (9), *Viburnum sargentii* (15), *Populus canadensis* (18), *Ailanthus altissima* (20), *Rosa chinensis* (23) and *Koelreuteria paniculata* (24) were significantly different between unwashed and washed leaves.

The Cr concentrations in all species leaves exceeded the Chinese plant food toxic maximum limit of 1.0 µg g^{-1} (Table 4; MPHPRC, 2012), implying that roadside leaves cannot be consumed by animals or people. In comparison, the Cr concentrations measured at our sites for species *Ailanthus altissima* (20), *Ligustrum* × *vicaryi* (29), *Sophora japonica* (1), *Fraxinus chinensis* (17), *Robinia pseudoacacia* (21) and *Ulmus pumila* (2) in both unwashed leaves (6.03, 6.97, 10.6, 5.32, 4.53 and 9.15 µg g^{-1}) and washed leaves (5.05, 5.98, 7.54, 4.40, 4.07 and 5.49 µg g^{-1}) (Table S1, Figs. 4(b)) were much higher than that from the same species in the Yan'an city (0.243, 0.195, 0.268, 0.365, 0.097 and 0.125 µg g^{-1}) (Hu *et al.*, 2014), indicating heavier Cr pollution at the current studied sites. Motor vehicles are considered

Table 3. Heavy metal accumulation in all plant leaves.

Treatment	Metal type	Unwashed Leaf				Washed Leaf			
		N	Ave.	Min.	Max.	N	Ave.	Min.	Max.
Metal concentrations of plant leaves based on leaf dry weight (µg g^{-1} DW)	Cd	96	4.88	1.04	9.67	96	4.53	0.520	9.80
	Cr	96	7.02	2.01	22.7	96	5.68	2.79	21.6
	Cu	96	21.1	11. 7	47.3	96	17.9	10.6	30.8
	Fe	96	500. 0	122	926	96	279	116	594
	Mn	96	62.5	24.0	195	96	53.7	16.7	177
	Ni	96	7.98	2.90	25.4	96	6.77	2.49	15.2
	Pb	96	2.66	0.240	11.0	96	1.51	BDL	3.48
	Zn	96	53.8	19.9	246	96	41.0	13.7	162

Note: BDL refers to figures below detection limit.

as the main source of Cr^{6+} in air particulate in the urban area of Beijing (Di *et al.*, 2014), although weathering of parent rock and waste water are regarded as the major sources of Cr enrichment in plants (Hu *et al.*, 2014).

Cu

For all 192 unwashed and washed leaf samples, Cu ranged from 10.6 to 47.3 µg g^{-1} with the mean of 19.5 µg g^{-1} (Table 3, Figs. 3), which is roughly within the Cu normal range of 0.4–45.8 µg g^{-1} in plants from Malacca of Malaysia (Hajar *et al.*, 2014) but towards the higher end. The copper concentrations in plants from Yan'an ranged as 0. 58–9.97 µg g^{-1} with averages of 2.94–7.38 µg g^{-1} (Hu *et al.*, 2014), which were much lower than those in leaves from this study. In addition, the mean Cu values of 15.3–19.8 µg g^{-1} in *Quercus ilex* leaves from the roadside site of Florence, Italy (Ugolini *et al.*, 2013) were close to the mean value in this study.

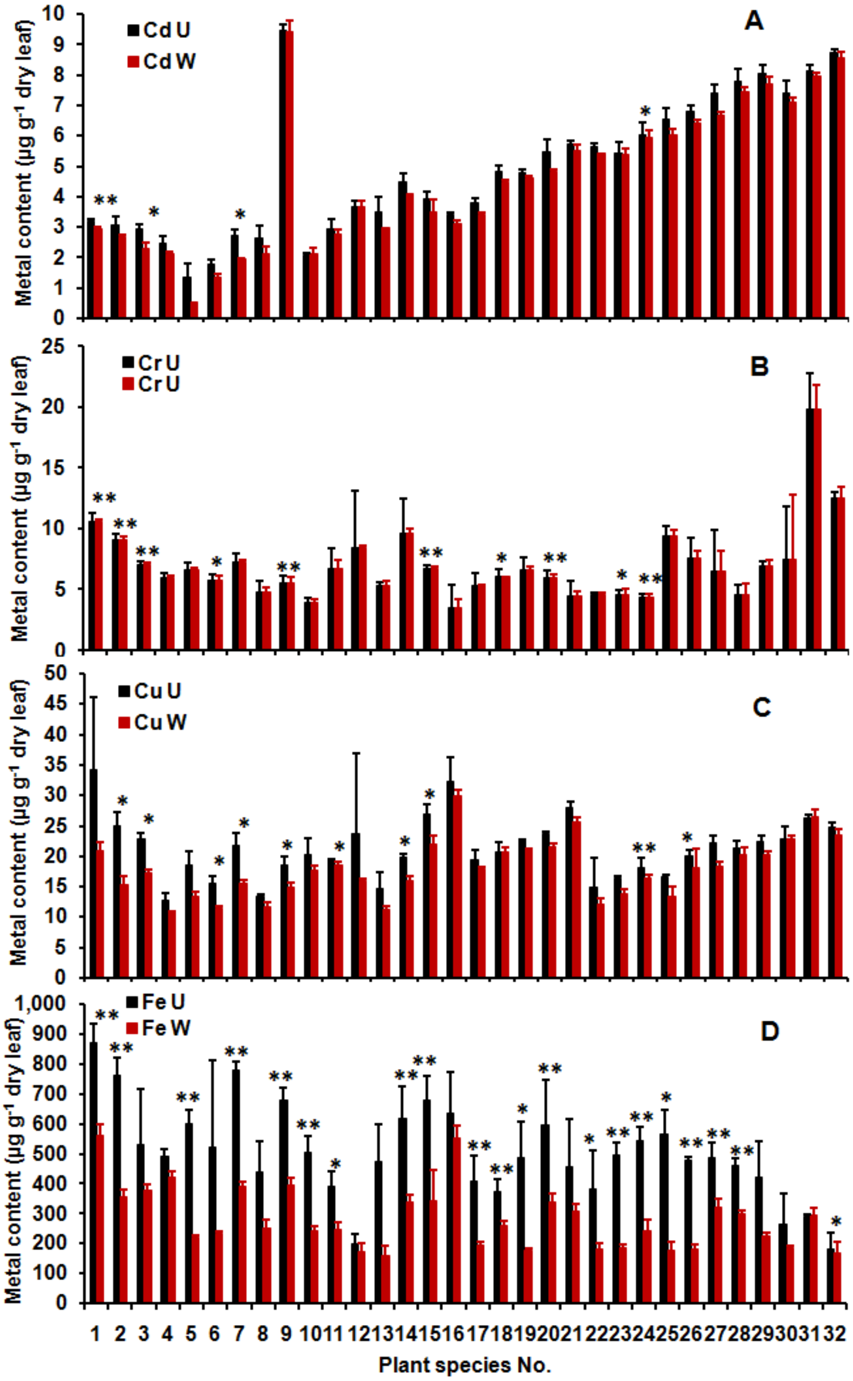

Fig. 4. Heavy metal accumulations in unwashed and washed leaves of different plant species (Notes: **: Refers to significant difference between metal concentration in unwashed and washed leaves for same plant species at 0.01 level. *: Refers to significant difference between metal concentration in unwashed and washed leaves for same plant species at 0.05 level).

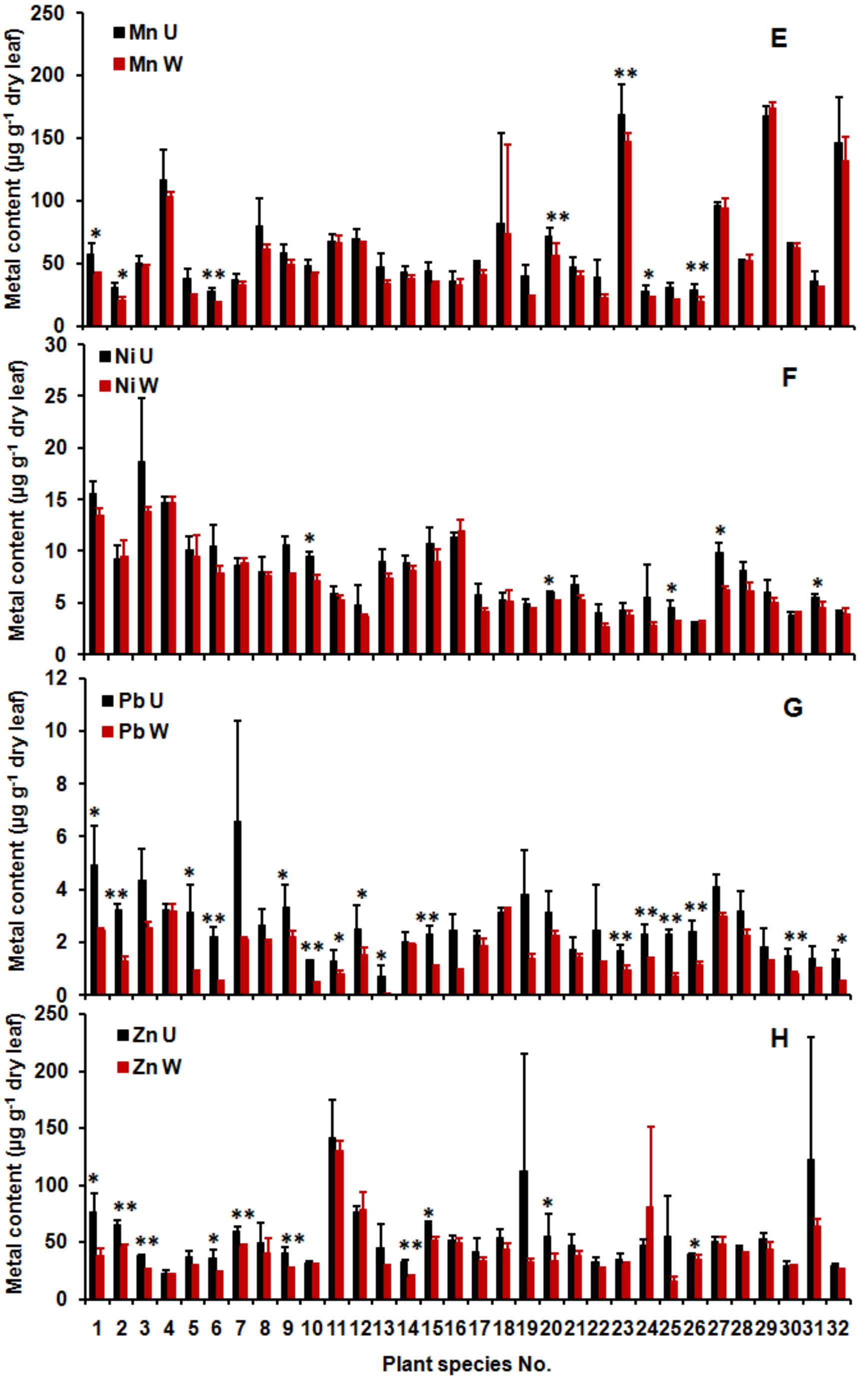

Fig. 4. (*continued*).

In regard to individual plants, species 1 (*Sophora japonica*) accumulated the highest Cu of 34.1 µg g^{-1} in its unwashed leaves, which was significantly higher than those from any other plant species. Species 16 (*Paulownia fortunei*) and 21 (*Robinia pseudoacacia*) also collected higher amounts of Cu as 32.1 and 27.8 µg g^{-1} respectively, and each was significantly higher than those in the leaves of other 87.5% and 59.4% species. *Ulmus pumila* (2), *Prunus cerasifera* f. *atropurpurea* (3), *Euonymus japonicus* (6), *Populus beijingensis* (7), *Chaenomeles speciosa* (9), *Populus tomentosa* (11), *Ginkgo biloba* (14), *Viburnum sargentii* (15), *Koelreuteria paniculata* (24) and *Magnolia denudata* (26) showed significantly higher Cu values in unwashed leaves than that in washed ones as expected.

Again species *Ailanthus altissima* (20), *Ligustrum* × *vicaryi* (29), *Sophora japonica* (1), *Fraxinus chinensis* (17), *Robinia pseudoacacia* (21) *and Ulmus pumila* (2) accumulated much larger amounts of Cu at our sites in both unwashed leaves (23.5, 22.3, 34.1, 19.3, 27.8 and 24.9 µg g^{-1}) and washed leaves (21.5, 20.1, 20.8, 17.8, 25.5 and 15.2 µg g^{-1}) in comparison with the Cu concentrations of 7.38, 7.04, 6.83, 6.02, 3.88 and 2.94 µg g^{-1} measured

Table 4. Metal concentrations in leaves of this study and previous studies (μg g^{-1} leaf).

Sample type (species no)	locality	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn	references
32 species of leaves (min.–max.)	Traffic Beijing	0.520–9.80	2.01–22.7	10.6–47.3	116–926	16.7–195	2.47–4066	BDL–11.0	13.7–246	This study
Plant food toxic maximum limit	NA	0.5	1.0	NA	NA	NA	1.0 (oil)	1.0	NA	MPHPRC, 2012
Toxic levels in leaves generally	NA	> 10	NA	NA	NA	NA	> 20	3–20	> 200	Markert, 1993
Acer pseudoplatanus (mean)	Urban Vienna	0.12	NA	5.1	165	211	NA	NA	65	Simon *et al.*, 2011
Vegetables (range min.–max.)	sewage-irrigated area	0.03–0.73	0.83–11.8	3.58–18.59	NA	NA	NA	1.97–3.81	32.01–69.26	Liu *et al.*, 2005
Normal in plants (range)	NA	2	0.006–18	0.4–45.8	640–2486	15–100	0.1–3.7	3	1–160	Hajar *et al.*, 2014
Stevia rebaudiana (mean)	Malacca, Malaysia	0.3515	5.0103	6.9411	623	6.0358	1.6737	0.5233	44.4235	
Metal ranges for all species (min. –max.)	Yan'an, China (industrial region, main road and residential area)	0.86–2.28	0.097–0.385	1.53–7.38	NA	NA	NA	2.83–12.57	4.21–19.21	Hu *et al.*, 2014
Ailanthus altissima (mean ± stdev) (20)		2.28 ± 0.88	0.243 ± 0.111	7.38 ± 1.50	NA	NA	NA	11.92 ± 6.71	5.68 ± 1.49	
Ligustrum vicaryi (mean ± stdev) (29)		1.96 ± 0.84	0.195 ± 0.159	7.04 ± 1.64	NA	NA	NA	12.57 ± 7.61	7.86 ± 1.56	
Sophora japonica (mean ± stdev) (1)		1.59 ± 0.59	0.268 ± 0.135	6.83 ± 2.02	NA	NA	NA	10.93 ± 9.85	6.06 ± 1.70	
Fraxinus chinensis (mean ± stdev) (17)		1.59 ± 0.97	0.365 ± 0.258	6.02 ± 2.28	NA	NA	NA	8.81 ± 6.56	4.38 ± 1.16	
Robinia pseudoacacia (mean ± stdev) (21)		1.10 ± 0.64	0.097 ± 0.082	3.88 ± 2.22	NA	NA	NA	4.55 ± 4.15	5.18 ± 2.55	
Ulmus pumila (mean ± stdev) (2)		1.36 ± 1.07	0.125 ± 0.059	2.94 ± 2.04	NA	NA	NA	3.09 ± 2.27	5.18 ± 4.22	
Robinia pseudoacacia (unwashed) (mean ± stdev) (21)	Industry, Denizli, Turkey	3.70 ± 1.45	NA	16.92 ± 2.01	3087.0 ± 70.4	349.2 ± 1.38	NA	206.2 ± 17.2	89.91 ± 5.88	Çelik *et al.*, 2005
Robinia pseudoacacia (washed) (mean ± stdev)		1.99 ± 0.82	NA	8.46 ± 0.83	89.91 ± 5.88	229.2 ± 12.28	NA	NA	43.49 ± 2.03	
Robinia pseudoacacia (unwashed) (mean ± stdev)	Urban roadside Denizli, Turkey	1.33 ± 0.17	NA	20.81 ± 1.39	414.4 ± 11.2	221.3 ± 9.47	NA	72.69 ± 4.05	139.0 ± 11.4	
Robinia pseudoacacia (washed) (mean ± stdev)		0.756 ± 0.09	NA	10.15 ± 1.26	139.0 ± 11.4	175.3 ± 4.89	NA	NA	53.05 ± 7.44	
Robinia pseudoacacia (unwashed) (mean ± stdev)	Suburban, Denizli, Turkey	0.805 ± 0.09	NA	12.22 ± 1.63	255.01 ± 3.76	147.8 ± 3.29	NA	21.84 ± 1.34	33.20 ± 2.30	
Robinia pseudoacacia (washed) (mean ± stdev)		0.570 ± 0.03	NA	8.125 ± 0.65	33.20 ± 2.30	95.4 ± 3.27	NA	NA	21.01 ± 2.16	
Robinia pseudoacacia (unwashed) (mean ± stdev)	Control, Denizli, Turkey	0.365 ± 0.01	NA	5.64 ± 0.08	100.2 ± 11.4	53.6 ± 3.01	NA	15.11 ± 0.11	13.02 ± 0.11	
Robinia pseudoacacia (washed) (mean ± stdev)		0.325 ± 0.01	NA	5.28 ± 0.09	13.02 ± 0.11	43.3 ± 2.18	NA	NA	11.53 ± 0.34	

Table 4. (*continued*).

Sample type (species no)	locality	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn	references
Koelreuteria paniculata (mean ± stdev) (24)	Mn mine site, Xiangtan, Hunan, China	0.51	NA	9.97	NA	1037.10	3.11	2.66	22.74	Tian *et al.*, 2009
Elaeocarpus decipens (mean ± stdev)		0.92	NA	9.67	NA	1389.18	3.50	2.64	36.08	
Ginkgo biloba (mean ± stdev) (14)	Street sides, Beijing	0.045 ± 0.008	NA	NA	NA	NA	NA	3.92 ± 0.88	NA	Liu *et al.*, 2007
Populus tomentosa (mean ± stdev) (11)		2.91 ± 0.33	NA	NA	NA	NA	NA	0.587 ± 0.111	NA	
Sophora japonica (mean ± stdev) (1)		0.191 ± 0.025	NA	NA	NA	NA	NA	5.69 ± 0.55	NA	
Koelreuteria paniculata (mean ± stdev) (24)		0.063 ± 0.020	NA	NA	NA	NA	NA	3.49 ± 1.38	NA	
Platanus acerifolia (mean ± stdev) (4)		0.045 ± 0.016	NA	NA	NA	NA	NA	2.65 ± 1.08	NA	
Quercus ilex (unwashed) (mean ± stdev)	Roadside, Florence, Italy	0.12 ± 0.01	3.1 ± 0.03	19.8 ± 0.16	534.5 ± 6.5	405.4 ± 1.6	NA	3.7 ± 0.15	42.8 ± 0.50	Ugolini *et al.*, 2013
Quercus ilex (washed) (mean ± stdev)		0.09 ± 0.01	1.3 ± 0.03	15.3 ± 0.22	376.8 ± 3.7	333.9 ± 4.7	NA	3.3 ± 0.04	40.8 ± 0.43	Ugolini *et al.*, 2013
Platanus orientalis (unwashed) (range)	Isfahan, Central Iran, Oct.–Nov.	NA	NA	16.6–27.0	627.9–1461.2	124.9–176.2	9.3–12.7	865.5–1510.9	40.6–68.8	Norouzi *et al.*, 2015
Platanus orientalis (washed) (range)		NA	NA	11.3–12.3	228.9–222.3	100.5–102.0	5.8–5.9	344.8–88.9	28.0–28.2	Norouzi *et al.*, 2015

Note: NA: not available; BDL: below detection limit.

from sites in the Yan'an city (Table 4; Hu *et al.*, 2014). Atmospheric Cu pollution is normally related to traffic pollution and coal combustion emissions (Zang *et al.*, 2016), which explains the above results. In addition, Cu concentrations in both unwashed and washed leaves of *Robinia pseudoacacia* (21) from this study were observed as 27.8 and 25.5 µg g^{-1} respectively, which were also higher than those of 5.58–20.81 µg g^{-1} from any sites in Denizli, Turkey (Table 4; Çelik *et al.*, 2005).

Fe

Metal Fe concentrations in this study ranged from 116 to 926 µg g^{-1} (Table 3, Fig. 3) for all washed and unwashed leaf samples, which were lower than and mostly fell outside the typical range of 640–2486 µg g^{-1} in plants (Hajar *et al.*, 2014), but the mean value of 389 µg g^{-1} is similar to the mean values of 376.8–534.5 µg g^{-1} in *Quercus ilex* leaves from the roadside of Florence, Italy (Ugolini *et al.*, 2013).

The highest Fe accumulation rate occurred in unwashed leaves of species 1 (*Sophora japonica*, 868 µg g^{-1}), which is significantly higher than those in leaves of other species except 7 (*Populus beijingensis*, 776 µg g^{-1}) and 2 (*Ulmus pumila*, 762 µg g^{-1}), although the latter two showed significantly higher Fe values than that from other 81.2% and 75.0% species respectively. Species 9 (*Chaenomeles speciosa*) and 15 (*Viburnum sargentii*) gave a collection rate of 676 and 675 µg g^{-1} respectively, and they were significantly higher than those in leaves of other 62.5% species (Table S1, Figs. 4(d)). Iron concentrations, measured in a previous study in leaves of *Avicennia schaueriana* (up to 332.7 µg g^{-1}) and *Laguncularia racemosa* (up to 300.9 µg g^{-1}) collected from mangrove areas with high particulate iron pollution (Arrivabene *et al.*, 2015), were still lower than those obtained at the current roadside sites. There are various inorganic elements in atmospheric aerosols, among which iron is one of the highest content (Li *et al.*, 2005). As one of the principal elements in the Earth crust, the high iron values detected in this study may be partly due to atmospheric contamination from fossil fuel combustion, apart from soil dust.

Significantly higher Fe values were found in unwashed leaves than in washed leaves for most species 1, 2, 5, 7, 9–11, 14, 15, 17–20, 22–28 and 32. Fe concentrations in unwashed and washed leaves of *Robinia pseudoacacia* (21) were observed as 454 and 305 µg g^{-1} respectively, which were slightly higher than that of 414 µg g^{-1} in unwashed leaves and 139 µg g^{-1} in washed leaves of same species from urban roadside site of Denizli, Turkey (Çelik *et al.*, 2005).

Mn

The results for Mn from all 192 plant leaf samples revealed a range of 16.7–195 µg g^{-1} and a mean of 58.1 µg g^{-1} (Table 3, Fig. 3), which well covered the normal range of 15–100 µg g^{-1} in plants (Hajar *et al.*, 2014), but were much lower than the mean values of 333.9–405.4 µg g^{-1} in *Quercus ilex* leaves at the roadside site of Florence, Italy (Ugolini *et al.*, 2013).

Mn collection rates in unwashed leaves followed the order as 23 (*Rosa chinensis*, 169µg g^{-1}) > 29 (*Ligustrum* × *vicaryi*, 168 µg g^{-1}) > 32 (*Syringa oblata*, 147 µg g^{-1}) > 4 (*Platanus acerifolia*, 117 µg g^{-1}) > 27 (*Kerria japonica*, 96.0 µg g^{-1}) > the values (28.0–82.2 µg g^{-1}) of the rest 75% species (Table S1, Fig. 4(e)), although the difference between species 4 and 27 was not statistically significant. Comparison between Mn concentrations in unwashed and washed leaves for same species showed that *Sophora japonica* (1), *Ulmus pumila* (2), *Euonymus japonicus* (6), *Ailanthus altissima* (20), *Rosa chinensis* (23), *Koelreuteria paniculata* (24) and *Magnolia denudata* (26) collected significantly higher Mn concentrations in unwashed leaves than in washed leaves. Mn concentrations in unwashed and washed leaves of *Robinia pseudoacacia* (21) were observed as 47.6 and 40.0 µg g^{-1} respectively at our site and they were significantly lower than those of 43.3–349.2 µg g^{-1} measured from sites in Denizli, Turkey (Table 4; Çelik *et al.*, 2005) where heavier Mn pollution sources may exist.

Ni

Ni concentrations measured from all leaf samples including both unwashed and washed treatment ranged as 2.49–25.4 µg g^{-1} with an average of 7.38 µg g^{-1} (Table 3, Fig. 3), and most species showed higher values in comparison with the Ni normal range of 0.1–3.7 µg g^{-1} in plants (Hajar *et al.*, 2014).

Comparison between different species showed that species 3 (*Prunus cerasifera* f. *atropurpurea*) accumulated the highest Ni concentration of 18.7 µg g^{-1} in its unwashed leaves, which is significantly higher than those in other species but remarkably lower than that collected by leaves of hyperaccumulating plants (plants with adaptations that allow them to take up and tolerate immense quantities of metals), with up to 3700 and 8100 µg g^{-1} Ni from Marivan of Iran, where high Ni concentration (1350 µg g^{-1}) was also observed in soil (Ghaderian *et al.*, 2007). Species 1 (*Sophora japonica*) and 4 (*Platanus acerifolia*) also showed significantly higher Ni concentrations (15.6 and 14.8 µg g^{-1}) than those in leaves of the remaining species. In addition, Ni concentrations in species 16 (*Paulownia fortunei*, 11.4 µg g^{-1}) and 15 (*Viburnum sargentii*, 10.8 µg g^{-1}), ranked after 4, were also significantly higher than those in leaves of other remaining 62.5% and 59.4% species respectively.

Significantly higher Ni concentrations were observed in unwashed leaves than in washed leaves for species 10 (*Amygdalus persica*), 20 (*Ailanthus altissima*), 25 (*Weigela florida* cv.Red Prince), 27 (*Kerria japonica*), 31 (*Sorbaria kirilowii*), though most species showed higher mean Ni values in unwashed leaves.

Pb

Lead accumulation rate for all leaf samples ranged from as little as below detection limit (0.0540 µg g^{-1} DW) to 11.0 µg g^{-1} with a mean of 2.09 µg g^{-1} (Table 3, Fig. 3), which were close to the normal value of 3 µg g^{-1} (Hajar *et al.*, 2014) and the typical concentrations of less than 10 µg g^{-1} (Kabata-Pendias and Pendias, 2001; Padmavathiamma and Li, 2007). Similarly, the Pb mean values of 3.3–3.7 µg g^{-1} in *Quercus ilex* leaves at the roadside site of Florence, Italy (Ugolini *et al.*, 2013) were falling within the range of our study.

Pb concentrations contained in all unwashed leaf samples exceeded the Chinese plant food toxic maximum limit of 1.0 µg g^{-1} (Table S1 and 5; MPHPRC, 2012). Further analysis found that unwashed leaves of species 7 (*Populus beijingensis*) collected the highest amount of Pb as 6.57 µg g^{-1}. Species 1 (*Sophora japonica*), 3 (*Prunus cerasifera* f. *atropurpurea*) and 27 (*Kerria japonica*) also accumulated higher Pb concentrations (4.94, 4.33 and 4.11 µg g^{-1}), and they were significantly higher than those in unwashed leaves of other 84.4%, 68.7% and 59.4% species respectively. Almost half of the species including 1, 2, 5, 6, 9, 10, 12, 13, 15, 23–26, 30 and 32 showed significantly higher Pb concentration in unwashed leaves than in washed ones. Different orders of lead accumulation appeared for washed leaf samples, for which species 18 (*Populus canadensis*), 4 (*Platanus acerifolia*) and 27 (*Kerria japonica*) showed the highest Pb values of 3.25, 3.19 and 3.00 µg g^{-1}. Significantly higher Pb concentrations were also found in washed leaves of species 3 (*Prunus cerasifera* f. *atropurpurea*), 1 (*Sophora japonica*), 20(*Ailanthus altissima*) and 28 (*Cornus alba*) (2.56, 2.46, 2.26 and 2.24 µg g^{-1}).

Much lower Pb concentrations were observed at our sites for the same species *Ailanthus altissima* (20), *Ligustrum* × *vicaryi* (29), *Sophora japonica* (1), *Fraxinus chinensis* (17), *Robinia pseudoacacia* (21) *and Ulmus pumila* (2) in both unwashed (3.13, 1.82, 4.94, 2.28, 1.77 and 3.23 µg g^{-1}) and washed leaves (2.26, 1.25, 2.46, 1.85, 1.46 and 1.28 µg g^{-1}) (Table S1, Figs. 4(g)), comparing with those measured from the Yan'an city (7.38, 7.04, 6.83, 6.02, 3.88, 2.94 µg g^{-1}) (Hu *et al.*, 2014), implying that heavier particular Pb pollution sources may exist in the Yan'an city. Also, the values of species 21 (*Robinia pseudoacacia*, 1.77 and 1.46 µg g^{-1}) from this study were far lower than those at sites in Denizli, Turkey, where Pb concentrations varied from 11.53 to 139.0 µg g^{-1} (Table 4; Çelik *et al.*, 2005), indicative of much less Pb pollution at the roadside of Beijing.

Similarly, species *Sophora japonica* (1), *Platanus acerifolia* (4), *Populus tomentosa* (11), *Ginkgo biloba* (14) and *Koelreuteria paniculata* (24) accumulated Pb of 2.46, 3.19, 0.823, 1.90 and 1.33 µg g^{-1} respectively, which were slightly lower than those measured previously at other roadside sites of Beijing for the same species as 5.69, 2.65, 2.91, 3.92 and 3.49 µg g^{-1} respectively (Liu *et al.*, 2007). It may indicate that either there is less Pb pollution at the 3rd ring road than those at other sites, or the government policy for eliminating for Pb in gasoline since 2000 has worked in reducing Pb pollution.

Zn

The accumulation rates of Zn for all leaf samples ranged from 13.7 to 246 µg g^{-1} with a mean of 47.4 µg g^{-1} (Table 3, Fig. 3), which is similar to the Zn normal range of 1–160 µg g^{-1} in plants (Table 4; Hajar *et al.*, 2014), but much higher than that found in Yan'an city, which showed a range of 2.83–12.57 µg g^{-1} for all investigated plant species (Hu *et al.*, 2014). Mean Zn values of 40.8–42.8 µg g^{-1} in *Quercus ilex* leaves at the roadside site of Florence, Italy were more or less the same as the mean of this study (Table 4; Ugolini *et al.*, 2013).

Species 11 (*Populus tomentosa*) collected the highest amount of Zn as 142 µg g^{-1} in its unwashed leaves, which is significantly higher than those in leaves of any other species, except species *Sorbaria kirilowii* (31) and *Amygdalus triloba* (19). The latter two species accumulated Zn of 123 and 113 µg g^{-1}, which were significantly higher than those in leaves of other remaining 90.6% and 87.5% species. Moreover, Zn concentrations of plant species 1, 2, 3, 6, 7, 9, 14, 15, 20 and 26 were significantly higher in unwashed leaves than washed leaves (Table S1, Fig. 4(h)). The highest Zn level was also observed in washed leaves of species 11 (131 µg g^{-1}), but the subsequent higher values occurred in species 24 (*Koelreuteria paniculata*) and 12 (*Salix babylonica*) with accumulation rates of 80.7 and 78.8 µg g^{-1}, which were significantly higher than those in leaves of all other species except species 31 (*Sorbaria kirilowii*, 64.2 µg g^{-1}).

Inter-site comparison for same species indicate that metal Zn accumulation rates from this study were much higher in species *Ailanthus altissima* (20), *Ligustrum* × *vicaryi* (29), *Sophora japonica* (1), *Fraxinus chinensis* (17), *Robinia pseudoacacia* (21) and *Ulmus pumila* (2) in both unwashed/washed leaves (55.7/34.0, 53.0/43. 7, 76.8/37.8, 41.5/33.4, 47.5/38.8 and 65.0/46.4 µg g^{-1}), comparing with that measured in the Yan'an city (5.68, 7.86, 6.06, 4.38, 5.18 and 5.18 µg g^{-1}) (Table 4; Hu *et al.*, 2014). However, the Zn concentrations observed in unwashed and washed leaves of *Robinia pseudoacacia* (47.5 and 38.8 µg g^{-1}) were far lower than the Zn values of unwashed leaves (89.91–139.0 µg g^{-1}) and washed leaves (43.49–53.05 µg g^{-1}) at sites in Denizli, Turkey (Table 4; Çelik *et al.*, 2005).

Heavy Metal Accumulation Based on Leaf Dust for Different Plant Species

Metal contents based on per gram dust collected on leaves were calculated for the 96 pairs of leaf samples, and the results were illustrated in Table 5 for the values of maximum and mean of all plant samples and in Table 6 for the averages of individual species. Comparison was also made with previous studies at both national and international sites in Table 5.

In Huizhou of Guangdong province, a southern city of China, similar Cd concentrations (6.2–12.8 µg g^{-1}) but higher Pb values (434.0–512.0 µg g^{-1}) (Table 5; Qiu *et al.*, 2009) were observed comparing with the results from this study, where levels of Cd and Pb were ranged as BDL-37.1 µg g^{-1} and BDL-237 µg g^{-1}. Concentrations of most metals investigated in this study are higher than that measured in previous studies for Cu, Fe, Pb, Zn from Urban Vienna, Cu, Fe, Mn, Ni, Pb, Zn in Debrecen (Hungary) and Cu, Ni, Pb, Zn from Belgrade, Serbia & Montenegro.

Metal concentrations in leaf dust were also compared with metal contents in soil samples. The results show that much higher mean levels of Cd (9.45 µg g^{-1}), Cu (88.0 µg g^{-1}) and Zn (308 µg g^{-1}) were found in our leaf dust than those detected in the roadside soil (Chen *et al.*, 2010). On the contrary, the mean values of Cr, Ni and Pb were lower in the leaf dust than in the soil (Table 5). The above results may indicate that leaf dust accumulation is much more efficient

Table 5. Comparison between metal concentration of leaf dust in this study and those of leaf dust and soil in previous studies (µg g^{-1} dust or soil).

Sample type	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn	references
Leaf dust at 3-ring-road, Beijing (max., mean)	37.1, 9.45	399, 35.7	614,88.0	6.79×10^3, 5.80×10^3	2750, 272	702, 41.1	237, 25.7	4.06×10^3, 308	This study
Leaf dust in Huizhou, Guangdong province (min.–max.)	6.2–12.8	NA	NA	NA	NA	NA	434.0–512.0	NA	Qiu *et al.*, 2009
Leaf dust in Urban Vienna (mean)	NA	NA	30	2136	NA	NA	18	311	Simon *et al.*, 2011
Leaf dust in Debrecen, Hungary (min.–max.)	NA	NA	7–70	2–2009	46–828	1–120	1–43	30–385	Simon *et al.*, 2014
Leaf dust 1 in Belgrade, Serbia & Montenegro (mean)	NA	NA	5.14	NA	NA	NA	16.2	16.9,	Tomašević *et al.*, 2005
Leaf dust 2 in Belgrade, Serbia & Montenegro (mean)	NA	NA	5.14	NA	NA	NA	7.34	11.84	Tomašević *et al.*, 2005
roadside soil in Beijing (mean)	0.215	61.9	29.7	NA	NA	26.7	35.4	92.1	Chen *et al.*, 2010
China soil guideline (1, 2 and 3 classes)	0.2, 0.3, 1.0	90, 200, 300	NA, 200, 400	NA	NA	40, 50, 200	35, 300, 500	100, 250, 500	EPAC & SAQSIQ, 2008
Soil in agricultural suburb in Beijing (mean ± stdev)	0.136 ± 0.061	NA	22.4 ± 6.31	NA	NA	NA	20.4 ± 5.2	69.8 ± 16.5	Lu *et al.*, 2012
Dust in Isfahan city in Nov. to Dec. (min.–max.)	NA	NA	141–172	14865–18855	295–341	72–102	1316–1930	125–171	Norouzi *et al.*, 2015
Soil in Daxing, Beijing	0.16	NA	NA	NA	NA	NA	NA	NA	Tan *et al.*, 2006

Note: NA: not available.

Table 6. Heavy metal concentrations in leaf dust for individual species (mean ± Std. Error of Mean).

Species	Heavy metal concentration (μg g^{-1} dust)							
No.	Cd	Cr	Cu (× 10)	Fe (× 10^{3})	Mn (× 10^{2})	Ni	Pb	Zn (× 10^{2})
1	7.88 ± 0.46	69.2 ± 15.0	29.9 ± 15.8	6.84 ± 1.72	3.45 ± 0.57	57.9 ± 23.7	52.6 ± 21.5	7.65 ± 1.21
2	4.63 ± 0.75	22.4 ± 2.1	6.07 ± 1.10	2.26 ± 0.36	0.678 ± 0.109	8.36 ± 2.33	10.2 ± 0.7	1.36 ± 0.25
3	7.82 ± 0.27	20.9 ± 1.1	6.53 ± 0.45	1.67 ± 1.00	0.730 ± 0.254	56.2 ± 28.0	18.2 ± 5.4	1.33 ± 0.03
4	13.0 ± 6.1	29.8 ± 4.4	5.97 ± 1.50	2.17 ± 0.52	4.57 ± 3.72	16.2 ± 8.0	4.04 ± 2.48	0.172 ± 0.245
5	15.6 ± 5.1	37.4 ± 8.4	11.0 ± 2.2	7.34 ± 0.72	2.84 ± 1.01	22.3 ± 7.5	43.7 ± 12.0	1.56 ± 0.53
6	7.58 ± 1.36	20.4 ± 2.3	6.90 ± 1.47	3.77 ± 2.57	1.58 ± 0.20	35.5 ± 10.9	24.9 ± 5.8	1.75 ± 0.67
7	10.2 ± 1.8	20.0 ± 5.6	8.10 ± 1.20	4.42 ± 0.37	0.900 ± 0.485	7.48 ± 2.82	47.5 ± 21.8	1.81 ± 0.07
8	14.1 ± 3.5	47.5 ± 31.0	7.38 ± 3.87	6.62 ± 3.98	7.77 ± 5.84	37.9 ± 20.0	27.8 ± 20.6	3.59 ± 2.07
9	11.5 ± 2.0	29.9 ± 8.9	9.69 ± 0.70	7.66 ± 1.86	2.53 ± 0.18	91.6 ± 35. 6	35.1 ± 15.7	3.73 ± 0.83
10	7.26 ± 3.77	73.8 ± 25.5	39.6 ± 13.6	42.1 ± 12.9	13.0 ± 7.4	406 ± 150	138 ± 50	7.04 ± 5.85
11	4.33 ± 2.15	10.3 ± 14.4	3.15 ± 0.30	3.38 ± 1.14	0.768 ± 0.499	12.9 ± 4.4	8.99 ± 1.65	1.84 ± 2.34
12	3.71 ± 0.70	25.5 ± 10.5	5.34 ± 3.42	0.462 ± 0.131	0.852 ± 0.388	9.45 ± 4.79	8.91 ± 2.13	0.227 ± 0.721
13	8.06 ± 2.91	20.3 ± 1.8	4.36 ± 1.51	3.47 ± 0.23	1.63 ± 0.40	24.3 ± 4.7	7.90 ± 3.46	1.96 ± 0.96
14	26.3 ± 9.0	213 ± 96	27.5 ± 2.9	18.4 ± 1.7	4.05 ± 0.58	73.2 ± 28.4	7.68 ± 13.80	9.55 ± 0.89
15	10.2 ± 3.3	72.2 ± 31.9	17.3 ± 7.1	9.80 ± 3.63	2.59 ± 0.62	56.9 ± 26.8	44.5 ± 21.1	4.29 ± 1.44
16	8.56 ± 1.54	15.1 ± 21.2	8.41 ± 5.15	2.16 ± 1.32	1.13 ± 0.89	14.8 ± 5.8	27.7 ± 8.7	0.954 ± 0.444
17	13.0 ± 5.4	25.3 ± 15.5	4.93 ± 2.44	4.58 ± 1.76	2.17 ± 0.32	41.1 ± 19.5	8.22 ± 2.31	2.13 ± 1.35
18	11.1 ± 2.8	23.0 ± 10.2	2.23 ± 1.75	2.66 ± 1.03	2.27 ± 0.62	7.88 ± 4.87	1.15 ± 2.78	2.66 ± 1.08
19	9.84 ± 5.19	29.8 ± 21.5	4.05 ± 2.86	6.22 ± 7.56	2.67 ± 3.89	24.6 ± 21.3	67.1 ± 72.0	7.45 ± 4.84
20	9.51 ± 2.01	11.9 ± 1.9	3.63 ± 0.40	2.17 ± 0.60	1.68 ± 0.14	11.1 ± 1.0	8.78 ± 2.86	1.89 ± 0.64
21	8.18 ± 1.39	11.2 ± 7.7	4.71 ± 0.51	2.13 ± 0.96	1.25 ± 0.47	20.9 ± 6.4	5.32 ± 2.73	1.37 ± 0.62
22	15.3 ± 2.1	58.8 ± 13.9	13.3 ± 13.2	10.7 ± 4.1	7.28 ± 2.94	70.6 ± 13. 6	62.7 ± 39.4	3.19 ± 1.42
23	6.13 ± 1.50	15.8 ± 1.6	8.56 ± 4.75	7.71 ± 4.31	9.11 ± 6.47	15.9 ± 6.0	22.9 ± 15.9	1.65 ± 1.05
24	6.37 ± 0.75	6.95 ± 0.81	2.28 ± 0.30	1.42 ± 0.03	0.469 ± 0.053	12.8 ± 6.5	5.16 ± 0.77	0.417 ± 0.217
25	5.89 ± 3.98	94.1 ± 70.7	13.1 ± 10.5	13.6 ± 11.4	3.35 ± 2.50	41.8 ± 30.1	57.6 ± 49.2	11.2 ± 8.4
26	11.1 ± 1.5	18.5 ± 8.4	4.73 ± 1.57	3.66 ± 0.80	1.25 ± 0.30	2.47 ± 0.70	15.4 ± 3.4	0.952 ± 0.368
27	17.4 ± 3.8	31.6 ± 18.3	7.45 ± 1.75	2.78 ± 0.72	1.29 ± 0.73	55.4 ± 4.4	18.7 ± 3.4	0.780 ± 0.425
28	12.4 ± 4.0	15.6 ± 13.0	3.49 ± 1.20	2.38 ± 0.15	0.337 ± 0.279	32.9 ± 11.0	14.1 ± 4.8	1.17 ± 0.14
29	10.7 ± 1.1	18.5 ± 5.3	4.57 ± 0.72	1.95 ± 0.42	0.735 ± 0.907	13.8 ± 2.4	4.75 ± 4.15	1.22 ± 0.47
30	8.91 ± 1.77	9.87 ± 12.80	2.08 ± 0.74	0.649 ± 0.382	0.724 ± 0.125	3.12 ± 1.22	6.24 ± 1.74	0.247 ± 0.136
31	12.3 ± 3.7	30.6 ± 50.1	2.16 ± 1.27	0.281 ± 0.323	1.41 ± 0.98	23.1 ± 2.0	9.78 ± 5.47	13.7 ± 13.6
32	9.55 ± 0.45	14.4 ± 5.1	3.00 ± 2.37	0.255 ± 0.087	2.07 ± 0.55	6.14 ± 2.67	6.00 ± 2.23	0.459 ± 6.360

for metals Cd, Cu and Zn than for Cr, Ni and Pb. Another study on the surrounding soil of Daxing district, a suburb of Beijing, measured Cd concentration as 0.16 μg g^{-1} (Tan *et al.*, 2006), which is lower than those in both leaf dust in this study and in the roadside soil of Beijing in the previous study, presumably due to less traffic in the suburban area. Heavier Cd pollution in traffic area of Beijing was also reported in previous study, in which 127 urban soil samples collected from six areas in Beijing, indicating that Cd was mainly from traffic sources (Xia *et al.*, 2011). Meanwhile, Cr and Pb values of 68.94 and 36.81 μg g^{-1} measured in the suburban Daxing were higher than those in the leaf dust from this study and the roadside soil from the previous study. According to the soil guideline values of China, over 50% Beijing roadside soil was polluted by Cd and slightly polluted by Cu, Pb and Zn (Chen *et al.*, 2010). The mean concentrations of Cd and Zn in our leaf dust exceeded the third class value (1.0 μg g^{-1}) and the second class value (250 μg g^{-1}) of the soil guidelines respectively (Table 5; EPAC & SAQSIQ, 2008).

Mean metal concentrations in leaf dust of each species are detailed in Table 6. Comparison between species indicated that there were significant concentration differences for all measured metals. The highest Cd was observed in species 14 (*Ginkgo biloba*, 26.3 μg g^{-1} dust), which is significantly higher than those of other species except 27 (*Kerria japonica*). Significantly higher metal concentrations were observed for Cr in leaf dust of species 14 (213 μg g^{-1} dust) and for Cu in species 10 (*Amygdalus persica*), 1 (*Sophora japonica*), and 14 (396, 299 and 275 μg g^{-1} dust). Species 10 collected the highest Fe content of 42.1 × 10^{3} μg g^{-1} dust, whilst *Ginkgo biloba* (14) also showed significantly higher Fe concentration (18.4 × 10^{3} μg g^{-1} dust) than those in the remaining species except 26 (*Magnolia denudata*, 3.66 × 10^{3} μg g^{-1} dust), 25 (*Weigela florida* cv. Red Prince), 22 (*Punica granatum*) and 15(*Viburnum sargentii*). Similar as Cu and Fe, the highest Pb value also occurred in species 10 (138 μg g^{-1} dust). Mn concentration in species 10 was also the highest (13.0 × 10^{2} μg g^{-1} dust), and it is significantly higher than those in other species excluding *Lonicera maackii* (8), *Punica granatum* (22) and *Rosa chinensis* (23). *Amygdalus persica* (10) was found to contain the highest Ni value (406 μg g^{-1} dust), which is significantly higher than those of remaining species. The second highest Ni value was observed in species 9 (*Chaenomeles speciosa*, 91.6 μg g^{-1} dust), but it is not significantly different from those of other remaining species. *Sorbaria kirilowii* (31) contained the highest Zn (13.7 × 10^2 μg g^{-1} dust) level, and it is significantly higher than those of any other species, except 1, 10, 14, 19, and 25. *Weigela florida* cv. Red Prince (25) was also found to contain significantly higher Zn value (11.2 × 10^2 μg g^{-1} dust) than those of remaining 65.6% species, except 1, 8, 9, 10, 11, 14, 15, 18, 19, 22.

Metal Accumulation Index (MAI) of Different Species

To estimate the overall metal accumulation ability of individual plant species, metal accumulation index (MAI) was separately calculated for unwashed leaves, washed leaves and leaf dust. The results were shown in Fig. 5 and Table 7, with the MAI values listed in decreasing order in the table. For unwashed leaves, species 10 (*Amygdalus persica*) showed the highest MAI value of 387, followed by species 26 (*Magnolia denudata*, 35.2) and 32 (*Syringa oblata*, 28.1), whilst species 13 (*Parthenocissus tricuspidata*) exhibited the lowest MAI value of 6.35. It implies that *Amygdalus persica* (10) is the best multi-metal removing species. Regarding to the washed leaves, plant *Punica granatum* (22) had the highest level of MAI (105), followed by species 18 (*Populus canadensis*, 59.8) and 30 (*Malus micromalu*, 50.3), and the lowest value occurred in species 25 (*Weigela florida* cv. Red Prince, 13.0), which indicate that leaves in species 22 were most toxic and in species 25 were the safest for consumption. In addition, *Viburnum sargentii* (15) showed the highest MAI value of 6.46 in the dust per gram leaves, followed by species 10 (*Amygdalus persica*, 5.94) and 2 (*Ulmus pumila*, 5.72), whereas the lowest value was found in species 30 (*Malus micromalu*, 0.450).

CONCLUSIONS

This study suggests that some plant species are suitable for planting at heavy traffic roadside of urban areas in Beijing, based on the investigation of 32 plant species for their ability to accumulate airborne dust and associated heavy metals.

Plant species, that could remove atmospheric dust efficiently, were identified from high to low as *Koelreuteria paniculata* (24), *Ulmus pumila* (2), *Syringa oblata* (32), *Malus micromalu* (30), *Weigela florida* cv. Red Prince (25), *Ailanthus altissima* (20), *Salix babylonica* (12), *Robinia*

Table 7. MAI in unwashed leaves, washed leaves and leaf dust for different plant species (Ranked high to low).

Species No.	unwashed leaves MAI	Species No.	washed leaves MAI	Species No.	leaf dust MAI
10	387	22	105	15	6.46
26	35.2	18	59.8	10	5.94
32	28.1	30	50.3	2	5.72
11	23.5	19	46.1	3	5.34
31	22.0	14	41.4	26	5.32
19	18.0	3	34.0	24	4.44
3	17.1	17	32.6	25	4.04
20	16.6	4	32.1	9	4.02
14	16.0	7	31.6	6	3.35
28	15.6	1	27.3	1	3.00
15	15.4	20	26.0	7	2.77
23	15.4	13	23.3	13	2.61
29	15.0	9	23.0	14	2.46
30	15.0	5	22.8	5	2.43
9	15.0	27	22.3	20	2.40
27	14.5	29	22.1	28	2.06
4	14.1	6	22.0	27	1.92
21	14.1	31	21.5	23	1.91
16	13.7	32	20.7	17	1.79
17	13. 6	12	20.7	19	1.77
2	13.5	26	18.9	21	1.76
1	12.9	28	18.9	22	1.59
7	12.8	2	17.9	29	1.48
25	12.7	10	16.8	16	1.33
22	12.5	21	16.7	11	1.29
18	10.7	8	15.6	8	1.29
24	10.2	24	15.6	32	1.29
8	10.0	23	15.1	18	1.18
6	8.52	11	14.9	4	1.11
12	7.35	16	14.0	31	0.900
5	7.21	15	13.4	12	0.820
13	6.35	25	13.0	30	0.450

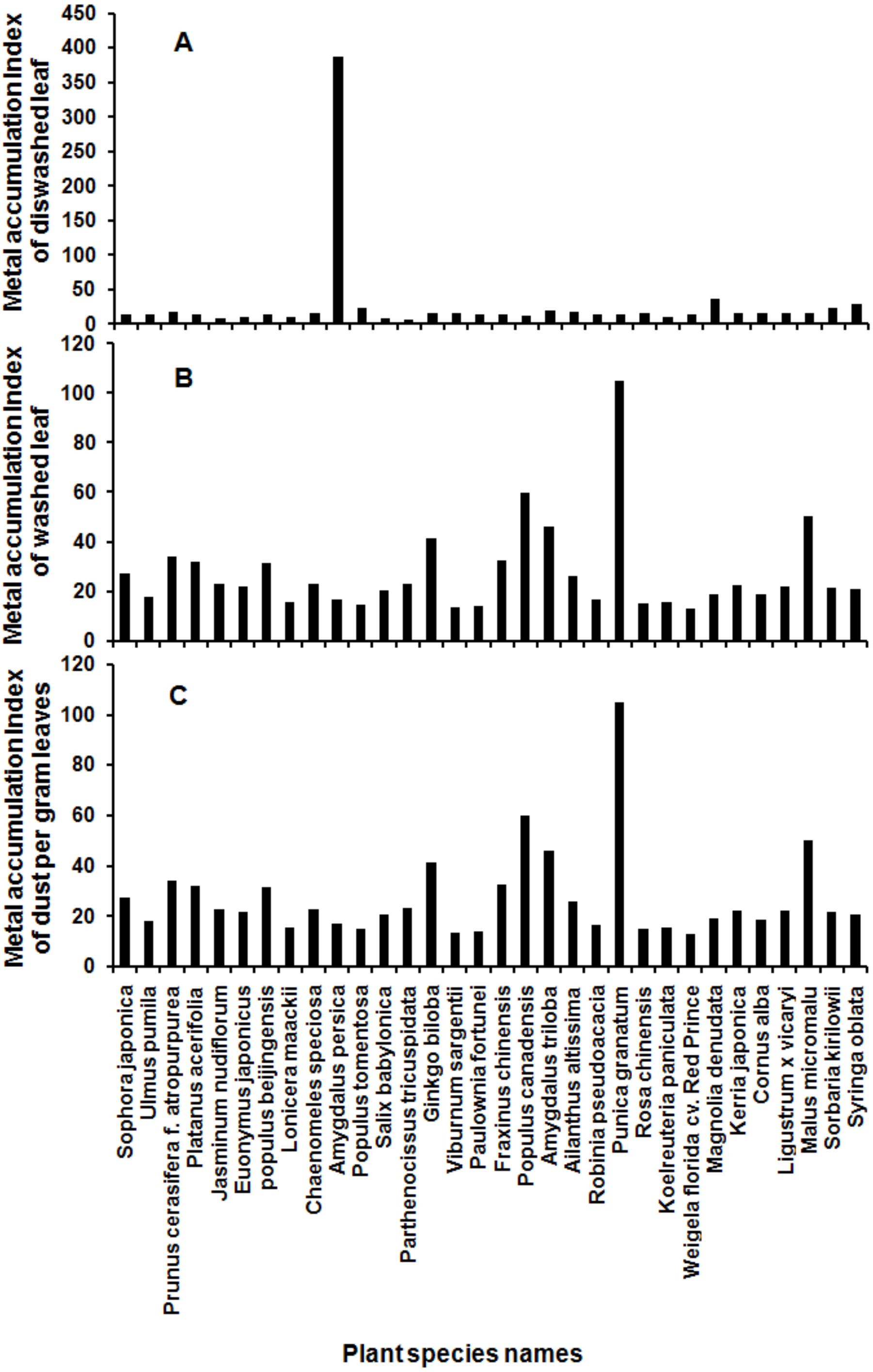

Fig. 5. Metal Accumulation Index in unwashed, washed leaves and dust per gram leaves for different plant species.

pseudoacacia (21), *Ligustrum* x *vicaryi* (29), *Euonymus japonicus* (6), etc.

Plant species can also be considered for the reduction of single metal pollution in airborne dust at special situations. The first choice for metal Cd phytoremediation is *Chaenomeles speciosa* (9), and species *Syringa oblata* (32), *Sorbaria kirilowii* (31), *Ligustrum* × *vicaryi* (29) and *Cornus alba* (28) can also be considered. *Sorbaria kirilowii* (31) and *Syringa oblata* (32) are the best species for Cr pollution remedy, whilst best species identified for other metals are *Sophora japonica* (1) for both Cu and Fe, *Ligustrum* × *vicaryi* (29) and *Rosa chinensis* (23) for Mn, *Prunus cerasifera* f. *atropurpurea* (3) for Ni, *Populus beijingensis* (7) for Pb, and *Populus tomentos*a (11) for Zn.

To target multiple metal pollution problems such as urban roadside site, MAI value can be a better choice for selecting efficient metal removing plant species. Species *Amygdalus persica* (10), with the highest MAI value in unwashed leaves and the second highest value in leaf dust, was found to be the best choice for mutiple metal accumulation. Species

Magnolia denudata (26) and *Syringa oblata* (32) can also be selected due to their higher than average MAI values in unwashed leaves. Plants *Punica granatum* (22), *Populus canadensis* (18) and *Malus micromalu* (30) can be used based on metal reduction in washed leaves, whilst species *Viburnum sargentii* (15), *Amygdalus persica* (10), *Ulmus pumila* (2), *Prunus cerasifera* f. *atropurpurea* (3) and *Magnolia denudata* (26) may be considered based on MAI values for leaf dust.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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