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Atmospheric Particle Distribution on Tree Leaves in Different Urban Areas of Aksu City, Northwest China

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ABSTRACT

Residents in arid regions of northwest China, where dust storms are more common, are continually exposed to air pollution particularly fine particles of $PM_{2.5}$ and PM_{10}, causing health hazards to residents. Urban greening species have a strong dust retention capacity which is also available in arid conditions and should be chosen to reduce the impact of air pollution on people and the urban environment. In this paper, three common tree species in four different functional areas: Transportation area (TA), Residential area (RA), Industrial area (IA), and Clean area (CA) of Aksu City were selected to measure their foliar dust to select the matching trees for appropriate sites. The dust particle size distribution for $PM_{2.5}$ and PM_{10} was analyzed to explore the particle size difference between foliar dust and natural landing dust. The largest particle size was recorded in IA (168.56 μm), while the smallest was found in CA (43.25 μm). Furthermore, *Salix babylonica* (*S. babylonica*) absorbed the highest $PM_{2.5}$ and PM_{10}, 0.15% and 1.39% respectively; while *Ulmus densa* (*U. densa*) absorbed the least $PM_{2.5}$ and PM_{10}, 0.08% and 0.37%. *Platanus acerifolia* (*P. acerifolia*) foliar dust particle density was the highest, and has stable dust retention capacity, while, *S. babylonica* foliar dust particulate density is the lowest under the same conditions (height/location, pollution exposition, weather). Our findings concluded that the average values of dust diameters in the four areas differed significantly. It is concluded that *P. acerifolia* is the best performer in removing dust in different functional urban areas and *S. babylonica* was more suitable for CA because of having the capacity to remove fine particle matter.

INTRODUCTION

Air pollution has multiple adverse effects on human health. Fine particles in the urban environment are a public health concern because of respiratory diseases and allergic reactions. It may also trigger asthma symptoms such as wheezing, coughing, tightness in the chest, and shortness of breath (Olmo et al. 2011, Brook 2007). Urban airborne particle matters (PMs) are the most pressing environmental challenges around the world, especially in rapidly developing countries like PR China (Chen et al. 2015a, 2015b). There is compelling evidence that particle size distribution controls where particles end up in human lungs and cause severe health risks and toxicity (Anderson et al. 2001, Amorim et al. 2013). Cities frequently experience elevated amounts of air particle matter pollution due to high traffic volumes (Kumar & Foster 2009, Pattinson et al. 2014).

Particles with an aerodynamic diameter (10-100 µm) are easily excreted by sneezing and coughing, coarse particles (2.5-10 µm) are usually deposited in the upper respiratory tract, whereas fine (0.1-2.5 µm) and ultrafine (≤0.1 µm) particles can reach the lungs and also the alveolar regions (Popek et al. 2013, Nemmar et al. 2002). The impact on health depends on the content of toxic substances, their physical properties, and exposure time (Gavett et al. 1997, Laden et al. 2000, Ghio & Devlin 2001). Owing to exposure to PM, it is estimated that the average life span of Europeans is decreased by approximately nine months, while in heavy air-pollution areas, the average shortening of life is nearly three years (Cliff et al. 2005).

Epidemiological and toxicological studies have highlighted a link between an increase in PM concentration and an increase in childhood and adult morbidity and mortality due to cardiopulmonary disease (Pope et al. 2002, Al-Dabbous & Kumar 2014). To mitigate air pollution, the use of urban vegetation is often regarded as an effective counter-measure (Wang et al. 2012, Vos et al. 2013). Particles in the air are deposited on the vegetation, and leaves absorb gaseous contaminants through their stomata (Baumgardner et al. 2012, Szkop 2016). Landscape plants have a large leaf surface area that allows contaminants to accumulate and impinge. Each chloroplast comprises 600 million chlorophyll molecules, and the average leaf size contains 70 million cells with 5 × 1010 chloroplasts (Shah et al. 2018).

Various studies have assessed the deposition rate and the rate at which pollutants are taken up by the urban vegetation (Freer-Smith et al. 2005, Brantley et al. 2014, Hagemann et al. 2014). Vegetation density affects both deposition and dispersion of airborne particles (Gromke 2011, Langner et al. 2011, Belan et al. 2015). For deposition, the vegetation area is either described as leaf area index (LAI); leaf area/ground area, dimensionless) or as leaf area density (LAD); leaf area/unit volume, m^2m^{-3} or m^2m^{-1}) (Chen et al. 2016). For dispersion, the porosity, drag force, or pressure drop are measured (Wagener et al. 2012). Many different measures are used in the literature (Tiwary et al. 2006, Roupsard et al. 2013, Wolch et al. 2014, Xia et al. 2014, Liu et al. 2018), thereby reducing comparability. Furthermore, either deposition or dispersion is commonly estimated based on measurements of the other, generating a significant error. (Janhäll 2015).

Plants growing in urban areas contribute significantly to improving air quality. Using samples from more than 40 species Sæbø et al. (2012) found a positive correlation between particle deposition and hairy leaves and the wax content of the leaves (Sæbø et al. 2012). Thick leaves showed lower deposition for all particle sizes, apart from 0.2-2.5 µm particles (Yang et al. 2015). There was a 10 to 20-times difference between different vegetation species in terms of particle deposition (Mao et al. 2013, Salmond et al. 2013, Gheorghe & Lon 2011). Even for the same particle size range, different vegetation species have different deposition rates, but the existing data cannot yet provide a parameterized description. (Guerrero-Leiva et al. 2016, Baidourela et al. 2015, Nurmamat et al. 2017).

This work aims to measure how much dust could be deposited in the leaves of main urban tree species such as *Platanus acerifolia*, *Ulmus densa,* and *Salix babylonica* and to determine the distribution of dust particle sizes as well as their relationship with natural landing dust.

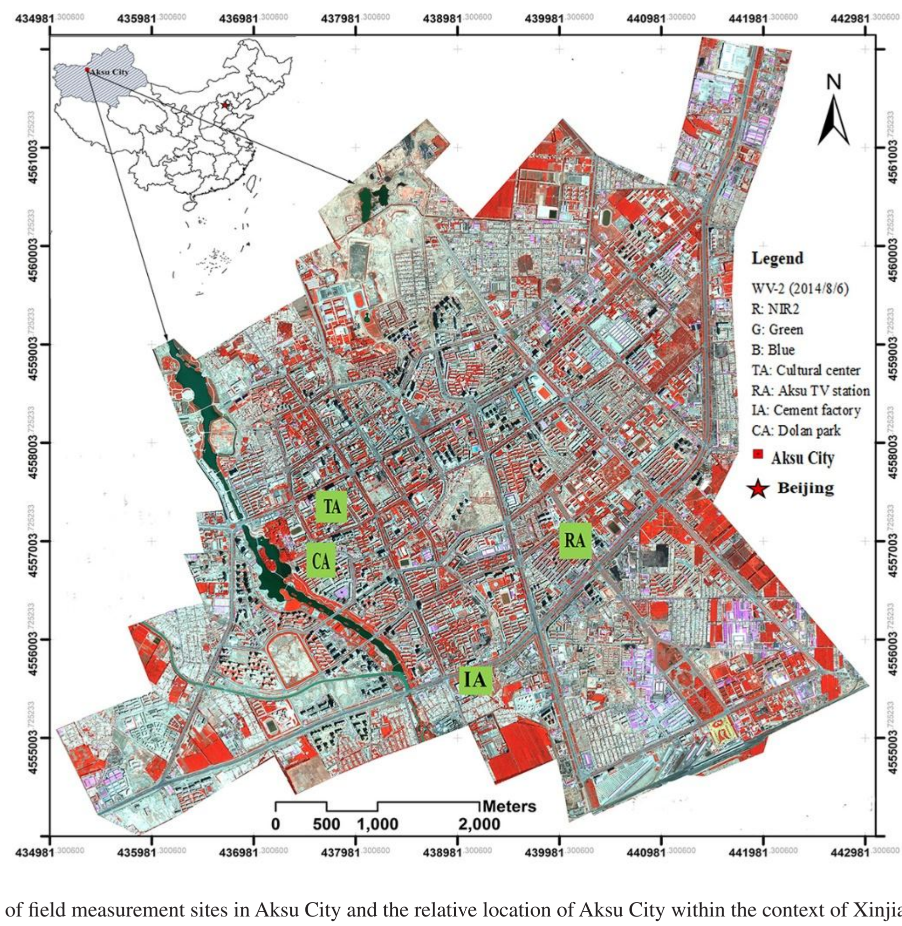

Fig.1: The sketch map of field measurement sites in Aksu City and the relative location of Aksu City within the context of Xinjiang Uygur Autonomous Region, China. (1) Transportation area (TA): Cultural Centre; (2) Residential area (RA): Aksu TV Station Courtyard; (3) Industrial area (IA): Cement factory; (4) Clean area (CA): Dolan Park.

MATERIALS AND METHODS

Study Area and Sampling Site

Aksu City (39°30'-41°27' N, 79°39'-82°01' E, 1050-1150 m ASL) is located in the southwestern part of Xinjiang Uygur Autonomous Region, China, on the northwestern edge of the Taklimakan Desert. The average annual temperature is 10.8°Çand the average annual precipitation is 74.5 mm with potential annual evaporation of over 2000 mm (Churkina et al. 2015, Chai et al. 2002). A northwest wind prevails throughout the year, especially in spring and summer. There are approximately 20 days per year with a wind speed greater than 17 $m.s^{-1}$, and the maximum wind speed is 24 $m.s^{-1}$. *P. acerifolia*, *U. densa,* and *S. babylonica* were selected as targets of this study, which are commonly used in urban greening projects in Aksu.

Four sampling sites were selected within the Aksu urban area as shown in Fig. 1. Each site was plotted in relation to the various functional areas, greening types, and their distribution within the city.

Sample Collection

This study combined field investigation with laboratory testing to analyze the different dust retention capabilities of leaves collected from tree species, which are commonly used for urban greening in Aksu City. Generally, precipitation of more than 15 mm or a wind speed stronger than 17 $m.s^{-1}$ can wash the dust off the leaves, thereby the dust retention beginning a new dust release-retention cycle for the tree leaves (Qiu et al. 2009, Liu et al. 2013). However, because precipitation is scarce in southern Xinjiang, particularly in Aksu City, we used the artificial cleaning method (washing the dust off the surface of leaves on the tree with distilled water) before sampling to clear the dust retention amount of leaf surfaces and begin a new dust release-retention cycle. Therefore, on 4th May 2014, we cleaned healthy and mature leaves (350-560 blades) on each selected tree species through the artificial cleaning method and marked them as sample leaves to analyze the changing tendency of dust amount per unit leaf area with time. The three species of trees in the IA, TA, RA, and CA functional areas were sampled seven times at 4-day intervals up to 28 days during the period May 8th to June 2th 2014, and sampling began on the 8th of May, 4 days after artificial cleaning. Each time sampling was conducted on the same day. Each sample was collected three times and averaged, resulting in a total of 252 leaf samples collected between May and June 2014. The samples then were placed in polyethylene bags, labeled, and stored in the laboratory with constant relative humidity and temperature until analysis. During transport to the laboratory, the samples were stored in an icebox. Dust samples were collected using iron containers every four days from four different functional areas in non-vegetated areas near the selected tree. All the fieldwork was conducted on sunny mornings with light wind and metrological parameters were recorded by a portable meteor graph (M307592/NK4000, Beijing Dongxiyi Technology Co., China).

Quantitative Analysis of Dust Particles

After field collection, samples were stored in plastic bags (for leaves) and iron containers (for dust) at room temperature in a laboratory. According to the method of Chai et al. (2002), all leaf samples were first washed in distilled water, then had brush cleaning to remove dust. The Micro-quartz fiber filters were used to determine the quantity of dust on the leaf surface, and the membrane pore size was 0.45. Filter membranes were weighed before (M_1) and after (M_2) filtration by electronic scales with an accuracy of 1 μg (PTX-FA-210, Shanghai Shirun Industrial Co., China). The total leaf area of washed samples was measured by Image J software (version 1.40, National Institutes of Health, USA) after scanning (DCP-7080D, Brother Co., China) (Wang et al. 2013). A laser leaf area meter (CI-203, CID, USA) was used to examine the washed sample leaf total area (S). The average weight of dust retention per unit leaf area was described as dust weight (removed from leaves) per total leaf area, and it was calculated according to the following formula:

$$D= (M_2-M_1)/S \quad \ldots(1)$$

The particulate matters were washed from the leaves and the dust samples collected from the non-vegetated sites were analyzed by a laser particle size analyzer (Microtrac S3500, Machk Co., USA) to determine the size and the quantity of PM on the different species of leaf surfaces and the natural landing dust from different urban areas.

Statistical Analysis

The data were statistically analyzed with SPSS (version 15.0, IBM Software Co., USA), using analysis of variance (ANOVA) suitable for a completely randomized design, and a *P*-value of < 0.05 was taken as statistically significant. Multiple comparisons were performed using one-way ANOVA, followed by posthoc testing using Tukey's multiple comparisons test. Results are mentioned as means ± SEM (Standard Error of Mean).

RESULTS AND DISCUSSION

The Dust Retention Patterns of Tree Species in Different Urban Areas

During the measurement after artificial cleaning, the amount of dust retained by greening species in the four types of

Table 1: The accumulation of dust retention amounts on three common tree species leaves from the 4th day to the 28th day after artificial cleaning in four types of urban areas in Aksu city. (Mean ± standard deviation)

Site	No. Samples	Time	Dust retention amount ($g.m^{-2}$)		
			P. acerifolia	U. densa	S. babylonica
TA	15	4th day	1.358±0.07a	0.410±0.05b	0.972±0.02c
		8th day	1.025±0.24a	1.883±0.07b	0.875±0.07c
		12th day	3.875±0.47a	1.891±0.35c	0.631±0.17c
		16th day	5.139±0.42a	2.711±0.12c	1.354±0.10d
		20th day	7.986±0.44a	3.542±0.30c	3.580±0.71c
		24th day	10.895±0.50a	5.321±0.29b	4.243±0.22c
		28th day	10.548±0.62a	6.521±0.19c	4.093±0.25d
RA	15	4th day	1.708±0.22a	0.155±0.06b	0.943±0.03d
		8th day	1.168±0.07a	1.599±0.14b	0.519±0.09c
		12th day	2.386±0.23a	1.718±0.11c	0.905±0.06c
		16th day	4.905±0.43a	1.813±0.15c	0.841±0.06d
		20th day	6.012±0.46a	3.457±0.06c	1.896±0.18d
		24th day	8.581±0.07a	4.580±0.15c	2.040±0.04e
		28th day	9.411±0.06a	5.243±0.12c	3.074±0.42e
IA	12	4th day	2.078±0.08a	1.454±0.09c	0.454±0.05d
		8th day	2.632±0.13a	1.812±0.05b	0.349±0.08d
		12th day	4.464±0.12a	3.192±0.05c	2.869±0.10e
		16th day	5.212±0.07a	5.357±0.06c	3.332±0.07e
		20th day	8.226±0.12a	6.471±0.05c	4.181±0.08e
		24th day	10.981±0.10a	8.130±0.08c	6.383±0.10d
		28th day	11.293±1.01a	8.308±0.54c	6.387±0.25d
CA	15	4th day	0.954±0.02a	0.655±0.03b	0.131±0.01c
		8th day	2.245±0.07a	0.989±0.23c	0.517±0.05d
		12th day	2.809±0.11a	1.018±0.01c	0.710±0.04d
		16th day	3.244±0.14a	1.527±0.07d	1.423±0.07d
		20th day	4.268±0.21a	2.894±0.14d	1.876±0.09e
		24th day	4.510±0.15a	3.980±0.23b	1.421±0.14d
		28th day	5.876±0.25a	3.562±0.18c	2.510±0.11d
Dust retention amount$_{max}$	48	-	13.212±0.90	9.960±0.77	6.876±0.24

A, b, c, d, and e show the difference among different trees within the same species at the same time and site. TA: Transportation area; RA: Residential area; IA: Industrial area; CA: Clean area

urban areas increased from day 4 to day 28 and reached its maximum in 28 days, as shown in Table 1. On the fourth day after artificial cleaning, the dust amount per unit leaf area was the lowest; on the 28th day, the value reached its highest amount, which was close to saturation. ANOVA showed that the dust amount on the 24th and 28th days had no significant difference ($p>0.05$). However, different species within the same functional area required different durations to make dust retention levels reach close to saturation.

Additionally, plant leaves from the same species in different functional areas used different time durations to get to a similar dust retention point because of environmental factors (including the different air particulate matter pollution degrees). The dust amount per unit leaf area on day 28 in order of greatest dust retention to least in the Industrial Area is *P. acerifolia* (11.3 $g.m^{-2}$)> *U. densa* (8.3 $g.m^{-2}$)> *S. babylonica* (6.3 $g.m^{-2}$). The same pattern was observed in the other three sampling sites, and dust amounts of all species reached close to saturation in all functional areas. The maximum dust retention amount of greening species showed the same order in four types of urban areas which are *P. acerifolia* (13.212 g.m^{-2})> *U. densa* (9.960 g.m^{-2})> *S. babylonica* (6.876 g.m^{-2}). Among different species in the same functional area, the dust retention capacity varies, which might depend on the tree species' physiological characteristics and environmental conditions. The total amount of dust retained on the tree leaves varied between the four urban functional areas: dust retention in rank order is IA (103.165 g.m^{-2})> TA (78.852 g.m^{-2})> RA (62.954 g.m^{-2})> CA (47.119 g.m^{-2}).

Dust Particle Size Distribution in Different Functional Areas

The dust deposited on tree leaves affects their photosynthesis in various ways, depending on the dust amount and particle sizes (Paredes & Quiles 2015). Analysis was carried out for dust amount per leaf area and particle distribution under natural conditions within the four different functional areas (Fig. 2).

The average values of particle diameters in these four areas were significantly different, the largest in IA with a diameter of 168.56 μm and the smallest in CA with a diameter of 43.25 μm. The difference in dust particle diameter

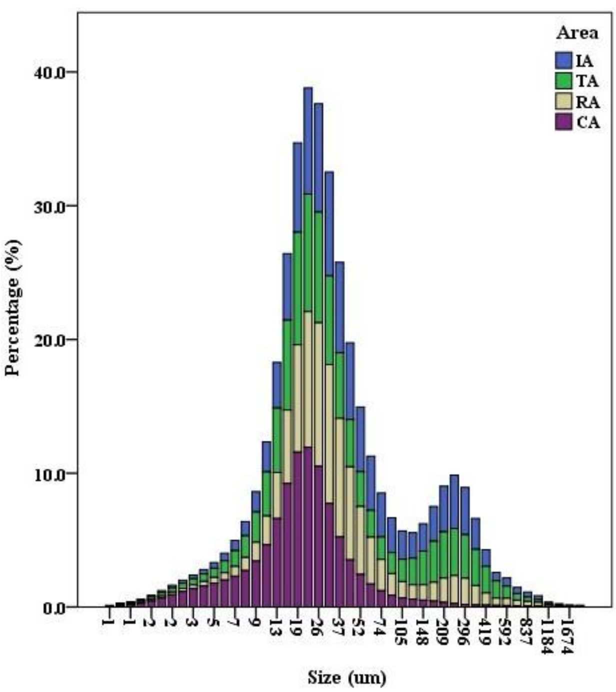

Fig. 2: The box map of particle matter size distribution in different functional areas of Aksu city.

indicates that the retained dust comes from various sources and that airborne particles are distinctive. Dust particle size distribution can be reflected in a bar graph (Fig. 2), which has one or two peaks.

The volume distribution curve of CA only has one peak, approximately between 40-52 μm. Others had two peaks at 24.4 μm and 296 μm, respectively. The dust retention capabilities of the various species within different functional areas in Aksu can be shown by using a bar graph (Fig. 3). *S. babylonica* retained the most $PM_{2.5}$ and PM_{10} particles in natural conditions, 0.15% and 1.39% respectively; while U. densa absorbed the least $PM_{2.5}$ and PM_{10} particles, 0.08% and 0.37%.

With regard to absorption of various particle sizes, the size distribution of particles D50 is the value of the particle diameter at 50% in the cumulative distribution, often known as the median diameter or the medium value of the particle size distribution. In the cumulative distribution, D10 represents the value of the particle diameter at 10%. D90 refers to a total diameter of 90% (Fig. 4). D10 indicated that the three species are similar in their capability to retain small particles, the smallest diameter value was *S. babylonica* with 15.6 μm, and the largest one *U. densa* 31.1 μm, which was shown in Fig. 4. However, the selected urban tree species showed significant differences in retention capabilities for D50 and D90 particle sizes. For medium size particles, the average size for *P. acerifolia* was the smallest at 40.5 μm and *U. densa* was the largest at 114.5 μm, almost three times as large as *P. acerifolia*. D90 large particle sizes reflected the same pattern, with *U. densa* absorbing the largest average particle size of 352 μm.

Differences in Dust Deposition Between Vegetation and Non-vegetated Areas

Fig. 5 shows that particle size distributions of leaf dust and natural landing on dust collectors have similar trends. Both have two peaks at similar dust diameter points. Dust particle retention capacity on leaves and collectors are mostly similar. With the exception of the clean area, particle size and retention graphs show two peaks in retention amounts based on varied particle sizes in all functional areas. The dust on the leaves includes more fine particles than the dust on the collectors. This means fine particles can be retained on the leaves more readily. Generally speaking, the average particle size of natural landing dust is bigger than the particle size on leaves. Bigger particle sizes indicate a larger specific surface area and this implies having stronger toxicity. Therefore, natural landing dust seemingly has stronger toxicity.

Difference in Dust Retention Amount of Greening Species by Sites and Species

Among different species in the same functional area, the dust retention capacity varies and increases with time, but will reach the saturation point after a different time which depends on the environmental conditions (for example, wet or dry and the interval between rainfall events) and tree physiological characteristic (Chai et al. 2002). Dust-retention capacities of the different urban-type areas have a significant difference ($p<0.05$). It is apparent that the industrial area (IA) is the most dust-polluted area and the clean area (CA) is the least dust-polluted area. The total amount of dust retained on the tree leaves varied between the four urban functional areas: dust retention in rank order is IA (103.165 $g.m^{-2}$)> TA (78.852 $g.m^{-2}$)> RA (62.954 $g.m^{-2}$)> CA (47.119 $g.m^{-2}$). The highest amount of dust in IA means that a greater amount of atmospheric pollutants was emitted in the industrial area where more in-situ dust was locally generated. The smallest amount of dust in CA means that the dust generated from the urban settings did not significantly affect the clean area and also lends support that the dust was not from large-scale atmospheric processes (Baidourela et al. 2015).

However, different species within the same functional area required different durations to make dust retention levels reach close to saturation (Qiu et al. 2009). The maximum dust

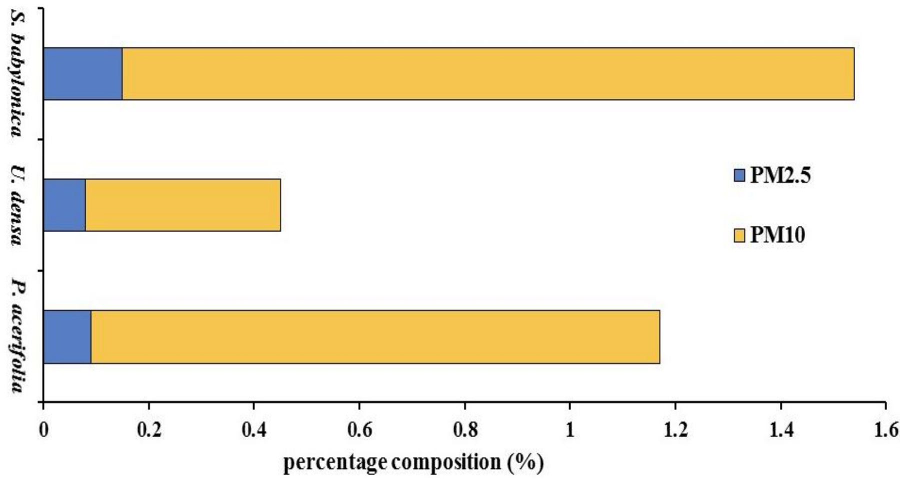

Fig. 3: PM_{10} and $PM_{2.5}$ content of dust deposited into three selected species leave in the study area.

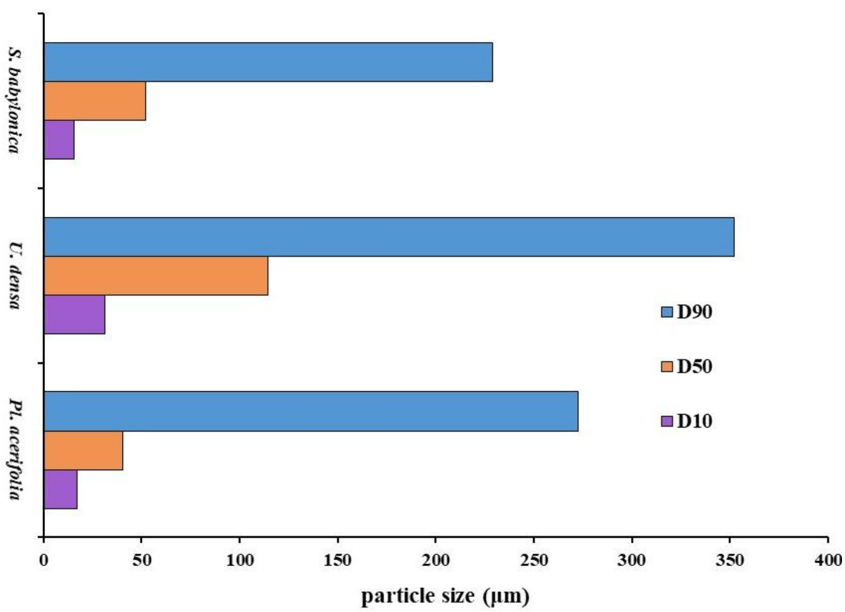

Fig. 4: Dust particle size (D10, D50, D90) distribution on three tree species leaves in the study area.

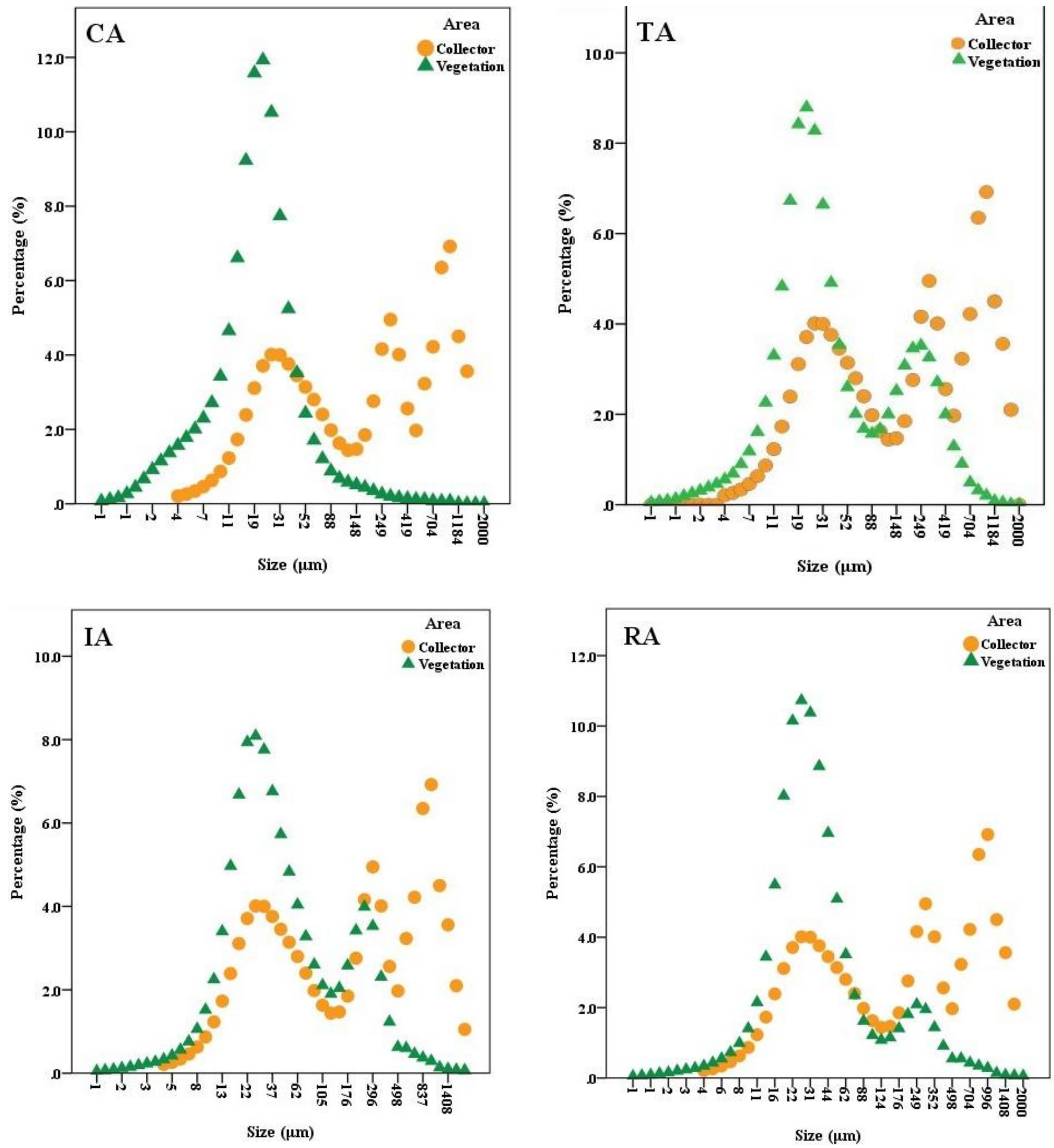

Fig. 5: Particle size distribution of natural landing dust and dust on selected tree species leaves in four functional areas of the study area. (TA: Transportation area; RA: Residential area; IA: Industrial area; CA: Clean area)

retention amount of greening species showed the same order in four types of urban areas which are *P. acerifolia* (13.212 $g.m^{-2}$)> *U. densa* (9.960 $g.m^{-2}$)> *S. babylonica* (6.876 $g.m^{-2}$). *P. acerifolia* has a stable dust retention capacity and the best performance in removing dust in different functional areas of the city. It was confirmed that the dust retention capacity of the three sampled greening species in four types of urban areas decreased in the same following order: *P. acerifolia*> *U. densa*> *S. babylonica*, which roughly follows their decreasing single leaf size (Guan 2013). Other studies conducted in Chinese urban areas also show that dust retention capacity varies between tree species (Liu et al. 2008).

Difference in Dust Particle Size Distribution on Leaves and Collectors in Different Functional Urban Areas

Particulate matter accumulation data showed that the greater particulate matter accumulation on the leaf surfaces was probably due to the higher air pollution due to coal combustion and the huge traffic volume in urban areas (the maximum percentage content of particulate matter rank is following the order: IA (38.9%) > TA (32.1%) > RA (21.6%) > CA (11.8%)) (Shi et al. 2017). The average values of dust diameters in these four areas were significantly different, the largest in IA with a diameter of 168.56 µm and the smallest in

CA with a diameter of 43.25 μm. D10 indicated that the three species are similar in their ability to absorb small particles, the smallest diameter value was *S. babylonica* with 15.6 μm, and the largest one was *U. densa* with 31.1 μm.

However, the three species showed significant differences in retention capabilities for D50 and D90 particle sizes. *S. babylonica* retained the most $PM_{2.5}$ and PM_{10}, 0.15% and 1.39% respectively; while *U. densa* absorbed the smallest $PM_{2.5}$ and PM_{10}, 0.08% and 0.37%; *P. acerifolia*, foliar dust particulate density is the highest, and have stable dust retaining ability; However, the *S. babylonica* foliar dust particulate density is the lowest under the same conditions (height/location, pollution exposition, weather). The dust retention capacity for PM was found to differ considerably among different greening species (Sæbø et al. 2012). It was approved that *P. acerifolia* has the best performance in removing dust in different functional areas of the city and the *S. babylonica* was more suitable for CA because of having the capacity to remove fine particle matters. This investigation has also identified the interaction effect of site and species on PM accumulation of leaves. The study demonstrates that the variation of the particle size distribution on three tree species' leaf surfaces under different dust retention durations was species-specific and may be dominated by the leaf microstructure and the different functional areas with different pollution intensities (Chen et al. 2015).

The dust on the leaves includes more fine particles than the dust on the collectors. It means that fine particles can be located on the leaves more readily than bigger size particles. Bigger particle sizes indicate a larger specific surface area and this implies having stronger toxicity. Generally speaking, the average particle size of natural landing dust is bigger than dust on leaves. Therefore, natural landing dust seemingly has stronger toxicity.

CONCLUSION

Urban greening species improved air quality through the removal of dust-related particulate matters. In our study, the variation of the dust retention capacity and the particle size distribution on the leaf surfaces of three tree species in different functional urban areas under different dust retention durations were species-specific. Fine particles can be located on the leaves more readily than bigger size particles. It was observed that *P. acerifolia* has the best performance in removing dust in different functional areas of the city and *S. babylonica* was more suitable for clean areas based on the capacity to remove fine particle matters. This research would provide urban greening planners with recommendations on the selection and configuration of urban greening tree species for reducing the environmental pollution in arid regions.

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