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ACCUMULATION OF THREE DIFFERENT SIZES OF PARTICULATE MATTER ON PLANT LEAF SURFACES: EFFECT ON LEAF TRAITS

Xiaoping Chen, Zhixiang Zhou*, Mingjun Teng, Pengcheng Wang and Lin Zhou

College of Horticulture and Forestry Sciences, Huazhong Agricultural University, Wuhan 430070, R. P. China

***Corresponding author**: whzhouzx@mail.hzau.edu.cn

Abstract: Plants not only improve air quality by adsorbing particulate matter (PM) on leaf surfaces but can also be affected by their accumulation. In this study, a field investigation was performed in Wuhan, China, into the relationship between seven leaf traits and the accumulation of three different sizes of PM (PM_{11}, $PM_{2.5}$ and $PM_{0.2}$) on leaves. The retention abilities of plant leaves with respect to the three sizes of PM differed significantly at different sites and species. The average PM retention capabilities of plant leaves and specific leaf area (SLA) were significantly greater in a seriously polluted area, whereas the average values of chlorophyll a (Chl *a*), chlorophyll b (Chl *b*), total chlorophyll, carotenoid, pH and relative water content (RWC) were greater at the control site. SLA significantly positively correlated with the size of PM, but Chl *a*, Chl *b*, total chlorophyll, RWC significantly negatively correlated with the size of PM, whereas the pH did not correlate significantly with the PM fractions. Additionally, SLA was found to be affected by large particles (PM_{11}, $p<0.01$); $PM_{2.5}$ had a more obvious effect on plant leaf traits than the other PM ($p<0.05$). Overall, the findings from this study provide useful information regarding the selection of plants to reduce atmospheric pollution.

Key words: Dust pollution; particle size; accumulation; leaf trait; effect

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INTRODUCTION

Particulate matter (PM), a serious air pollutant in both developed and developing countries, is a mixture of heavy metals, polycyclic aromatic hydrocarbons, black carbon and other substances suspended in the atmosphere (Dzierżanowski et al., 2011; Rai, 2013). PM is mainly derived from anthropogenic activities, and varies in terms of morphology, origin, physical characteristics, chemical composition and size (WHO 2006; Kocić et al., 2014). According to the aerodynamic diameter, PM can be classified as large PM (>10 μm), coarse (2.5-10 μm), fine (0.1-2.5 μm) and ultrafine (≤0.1 μm) (Dzierżanowski et al., 2011; Weber et al., 2014). One of the factors related to the damaging effects of PM is particle size. Large particles are primarily deposited in the conducting and gas-exchange areas of the human respiratory system during mouth–breathing; coarse particles are deposited on the upper respiratory tract; fine particles or ultrafine particles can penetrate the alveoli of the lungs (Popek et al., 2013; Weber et al., 2014).

Plants play an important role in mitigating urban pollution. Leaves and other parts of plants may act as persistent absorbers of particulate matters (Liu et al., 2013). Studies have shown that the PM retention capacity of leaves depends on their surface geometry, hairs, cuticles and epidermal features, length of petioles, phyllotaxy, the height and canopy structure of trees, plant age, leaf surface wettability and local meteorological conditions (Sæbø et al., 2012; Liu et al., 2013; Popek et al., 2013; Wang et al., 2013). Urban trees can significantly improve air quality. For example, a study in Guangzhou, China, found that urban vegetation could retain 8012.9 tons of dust per year (Liu et al., 2013). Yang et al. (2005) reported that trees reduced by 772 tons PM_{10} from the air in Beijing over a year. Speak et al. (2012) concluded that green roof vegetation could remove 0.21 metric tons of PM_{10}

a year, which equates to 2.3% (±0.1%) of the PM_{10} emitted in a UK city. However, most previous studies about the particulate retention capability of plants focused mainly on dust or PM_{10} (Liu et al., 2012, 2013), and only a few studies focused on the $PM_{2.5}$ capturing ability of plant leaves.

Although plants can reduce particulate matter in atmosphere, some plant performance studies have shown that plant growth is influenced by atmospheric pollution, and the level of influence on growth depends on plant species, pollutant type and concentration, as well as a number of environmental factors (Wuytack et al., 2011; Chaturvedi et al., 2013). Particles deposited on leaf surfaces can reduce the illumination reaching the photosynthetic apparatus and block stomata. In both cases, photosynthesis and growth would be reduced (Naidoo and Chirkoot, 2004). For example, Dineva (2004) found that petiole length and leaf area under polluted conditions was reduced. Naidoo and Chirkoot (2004) revealed that coal dust reduced the carbon dioxide exchange of leaf surfaces by 17-39%, and significantly decreased the chlorophyll fluorescence. Kapoor et al. (2013) investigated tree species *Dalbergia sissoo* Roxb. and found an obvious reduction in photosynthetic pigments, pH and RWC in the polluted environment. Chaturvedi et al. (2013) studied the effect of dust load (DL) on leaf traits, and found that the values of SLA, RWC and chlorophyll content were significantly reduced in a polluted site. However, previous studies mainly focused on the effect of particulate matter in the atmosphere on leaf traits (Sharma and Tripathi, 2009; Bamniya et al., 2012a, b; Kapoor et al., 2013; Wuytack et al., 2013), and several studies dealt with the effect of particulate matter on leaf surfaces on leaf traits (Prusty et al., 2005; Chaturvedi et al., 2013), but, to our knowledge, no study has been conducted on the effect of different sizes of particles accumulated on leaf surfaces and on leaf traits.

In order to assess the effect of different size particles accumulation on leaf surfaces on leaf traits, this study measured the accumulation of three sizes of PM (PM_{11}, $PM_{2.5}$ and $PM_{0.2}$) on leaf surfaces and seven parameters of leaf traits among 24 plant species that are commonly cultivated as urban vegetation in central China. The hypotheses of this study were that the capture ability of three differently sized particles differs significantly in site, species and fraction, and leaf traits such as SLA, pigment contents (Chl *a*, Chl *b*, total chlorophyll and carotenoid), pH and RWC were significant affected by the size of PM on leaf surfaces.

MATERIALS AND METHODS

Study sites and species selection

This study was conducted in Wuhan, the capital city of Hubei Province, China, which is located at 113°41´-115°05´E, 29°58´-31°22´N. The two sites chosen for the study were Wuhan Iron and Steel Company (WISC – the polluted site) and Huazhong Agricultural University campus (HZAU – the control site). WISC is an ancient iron and steel industrial site situated in the eastern part of Wuhan and is mainly engaged in iron and steel processing and production, with coal particulates and SO_2 as the main air pollutants. HZAU is located about 38 km from WISC in the south of Wuhan, with the campus spreading across an area of over 1223 acres. The particulate concentrations of WISC and HZAU measured in the field were 3.143 mg m^{-3} and 0.152 mg m^{-3}, respectively. To acquire more plant species, 24 plant species, which included trees, shrubs, climbers and herbs, were selected in both places based on the field investigation, and their detailed information is presented in Table 1.

Sample collection

The plants analyzed were in good condition, with little or no disease or pests. Any leaves contaminated with diseases and pests were not used for analysis. For each species, leaves were collected from five individuals (replicates) with a similar size. For each tree, mature and healthy leaves were collected from east-, south-, west- and north-facing aspects in open habitats at a height of 0.1 to 2.5 m above ground level according to the plant height (Liu et al., 2012). To obtain sufficient material for measuring the $PM_{0.2}$ and

Table 1. Characteristics of selected plants at the two study sites

Plant species	Family	Habit	Leaf shape
Koelreuteria bipinnata Lamx.	Sapindaceae	Tree	Ovate
Elaeocarpus sylvestris (Lour.) Poir.	Elaeocarpaceae	Small tree	Obovate
Platanus acerifolia Willd.	Platanaceae	Tree	Ovate
Magnolia grandiflora L.	Magnoliaceae	Tree	Elliptic
Ligustrum lucidum Ait.	Oleaceae	Small tree	Ovate
Prunus cerasifera Ehrh. cv. Atropurpurea	Rosaceae	Small tree	Ovate
Morus alba L.	Moraceae	Tree	Ovate
Osmanthus fragrans (Thunb.) Lour.	Oleaceae	Small tree	Elliptic
Parthenocissus tricuspidata (S. Et Z.) Planch.	Vitaceae	Climber	Ovate
Viburnum odoratissimum Ker-Gawl. var. *awabuki* (K.Koch) Zabel ex Rumpl.	Caprifoliaceae	Shrub	Obovate
Pyracantha fortuneana (Maxim.) Li	Rosaceae	Shrub	Obovate
Mahonia fortune (Lindl.) Fedde	Berberidaceae	Shrub	Lanceolate
Loropetalum chinense (R. Br.) Oliver var. *rubrum* Yieh	Hamamelidaceae	Shrub	Ovate
Trachycarpus fortunei (Hook.) H. Wendl.	Palmae	Small tree	Subrotund
Pittosporum tobira (Thunb.) Ait.	Pittosporaceae	Shrub	Obovate
Reineckia carnea (Andr.) Kunth	Liliaceae	Herb	Lanceolate
Ginkgo biloba Linn.	Ginkgoaceae	Tree	Sector
Eriobotrya japonica (Thunb.) Lindl.	Rosaceae	Small tree	Lanceolate
Jasminum mesnyi Hance	Oleaceae	Shrub	Elliptic-lanceolate
Rhododendron simsii Planch.	Ericaceae	Shrub	Ovate-oval
Nerium indicum Mill.	Apocynaceae	Small tree	Lanceolate
Photinia serrulata Lindl.	Rosaceae	Small tree	Oval
Sophora japonica Linn. var. *pendula* Loud.	Fabaceae	Shrub	Ovate
Iris tectorum Maxim.	Iridaceae	Herb	Sword

to avoid filter blockage by particles during filtration, the leaf area per species ranged between 300 and 400 cm^2, and a larger leaf area was required in the control site (Dzierżanowski et al., 2011). All the samples were collected in September 2013, at the end of the growing season. Sampling was conducted two weeks after a period of heavy rain as described by Wang and Li (2006). All the samples of the two sites were collected on the same day, and were placed in polyethylene bags, labeled and stored in the laboratory with a constant relative humidity and temperature until analysis. During transport to the laboratory, the samples were stored in an icebox.

Quantitative analysis of PM

The PM on leaf surface was measured by the gravimetric method according to Dzierżanowski et al. (2011). Filter membranes were pre-weighed and post-weighed by an electronic balance with an accuracy of 0.0001 g (YR-30001, Shanghai Yue-ping Scientific Instrument Co., China). Grade 1 filter paper (retention of 11 μm) was used for the first filtration, Type 42 (retention 2.5 μm) for the second filtration and PTFE membrane (retention of 0.2 μm) for the final filtration (Dzierżanowski et al., 2011). Three fractions of PM were collected from the filters: (i) greater than 11 μm (PM_{11}), (ii) 2.5-11 μm ($PM_{2.5}$) and (iii) 0.2-2.5 μm ($PM_{0.2}$). The leaf area of washed samples was measured by Image J software (Version 1.40, National Institutes of Health, USA) after scanning (HP LaserJet Pro M1213nf, HP, Japan) (Wang et al., 2013). Since PM was from both upper and lower surfaces of the leaves, the amount accumulated for each species was expressed per unit area of leaf surface and calculated using the following equation:

$$W = (W_2 - W_1)/2A \quad (1)$$

where W is the accumulated PM (μg cm^{-2}) on the leaf, W_1 is original weight of filter paper (μg), W_2 is the final weight of filter paper with PM (μg), and A is the scanning area of the sample leaves (cm^2).

Leaf trait determination

SLA represents the area per dry mass of leaf, which was measured according to the theory of Chaturvedi et al. (2013), but in the present research, to attenuate the influence of particles on leaf surface, the leaf was washed before oven-drying. RWC was expressed as a percentage of (leaf fresh mass-leaf dry mass)/(leaf saturated fresh mass-leaf dry mass), which was determined as described by Sen and Bhandari (1978). The concentration of chlorophylls (expressed as Chl *a* and Chl *b*) and carotenoids of fresh leaf samples collected at both WISC and HZAU were analyzed using colorimetric methods at wavelengths of 665 nm, 649 nm, and 470 nm with an ultraviolet spectrophotometer (752, Shanghai, China) after extraction in 95% v/v ethanol (Alsaadawi et al., 1986). Leaf extract pH was assayed by the method of Prasad and Rao (1982). One gram of leaf sample was homogenized in 10 ml of deionized water. The homogenate was centrifuged and the supernatant was collected and measured by a digital pH meter (FE20, Shanghai).

Statistical analysis

SPSS 17.0 was applied to carry out analysis of variance (ANOVA) and two-tailed Pearson correlation. Differences in the accumulated PM on different plant species and leaf traits in the two sites were tested with two-way ANOVA and the relationships between the accumulation of different sizes of PM and leaf traits were assessed by two-tailed Pearson correlation.

RESULTS

PM accumulation of plant species

ANOVA results revealed a significant influence of site and species on the accumulation of all the PM fractions (PM_{11}, $PM_{2.5}$, $PM_{0.2}$) (Table 2), and the two-way interactions were also significant (p<0.01). The PM accumulated on the leaves of 24 plant species in WISC and HZAU are presented in Figs. 1A and B, respectively. They indicate that PM_{11} represented the majority of particles accumulated on the leaf surfaces, and $PM_{0.2}$ just accounted for a tiny part of the total in both WISC and HZAU.

Table 2. ANOVA statistics of particulate matter retention amount and leaf traits of 24 plant species at the two experimental sites

	Site ($F_{1, 144}$)	Species ($F_{23, 144}$)	Site×species ($F_{23, 144}$)
PM_{11}	97960**	1659**	1211**
$PM_{2.5}$	9408**	266.9**	186.4**
$PM_{0.2}$	798.2**	22.5**	17.5**
SLA	821058**	52545**	14683**
Chl *a*	809.4**	46.0**	12.8**
Chl *b*	639.8**	45.7**	13.0**
total chlorophyll	1138**	52.7**	14.8**
carotenoid	219.4**	38.2**	8.3**
pH	4400**	6640**	358.7**
RWC	3118**	324.7**	169.8**

Levels of significance: *P<0.05, **P<0.01. PM_{11} – particulate matter with aerodynamic diameter above 11 μm, $PM_{2.5}$ == particulate matter with aerodynamic diameter between 2.5 μm and 11 μm, $PM_{0.2}$ – particulate matter with aerodynamic diameter between 0.2 μm and 2.5 μm, *SLA* – specific leaf area, *Chl a* – chlorophyll a concentration, *Chl b* – chlorophyll b concentration, *total chlorophyll* – total chlorophyll concentration, *carotenoid* – carotenoid concentration, *pH* – potential of hydrogen, *RWC* – leaf relative water content

In WISC, *Eriobotrya japonica*, *Jasminum mesny*, *Rhododendron simsii* and *Nerium indicum* showed high PM_{11} accumulation, ranging from 112-167 μg cm^{-2} (Fig. 1A). *Ginkgo biloba* and *Sophora japonica* had very low PM_{11} retention (28-34 μg cm^{-2}). The remaining species showed moderate PM_{11} accumulation, accounting for about 75% of the total selected species. $PM_{2.5}$ accumulation on plant leaves ranged from 1.61-19.46 μg cm^{-2} in WISC, *Koelreuteria bipinnata*, *Parthenocissus tricuspidata*, *Loropetalum chinense*, *E. japonica* and *N. indicum* showed high $PM_{2.5}$ accumulation ability (16.06-19.46 μg cm^{-2}); whereas *G. biloba* and *S. japonica* showed the lowest $PM_{2.5}$ accumulation ability (1.60-3.19 μg cm^{-2}). The species with the largest retention (3.28-4.04 μg cm^{-2}) of $PM_{0.2}$ included *Osmanthus fragrans*, *P. tricuspidata, L. chinense*, *J. mesny* and *R. simsii*. However, *Prunus cerasifera, Pittosporum tobira, Reineckia carnea,*

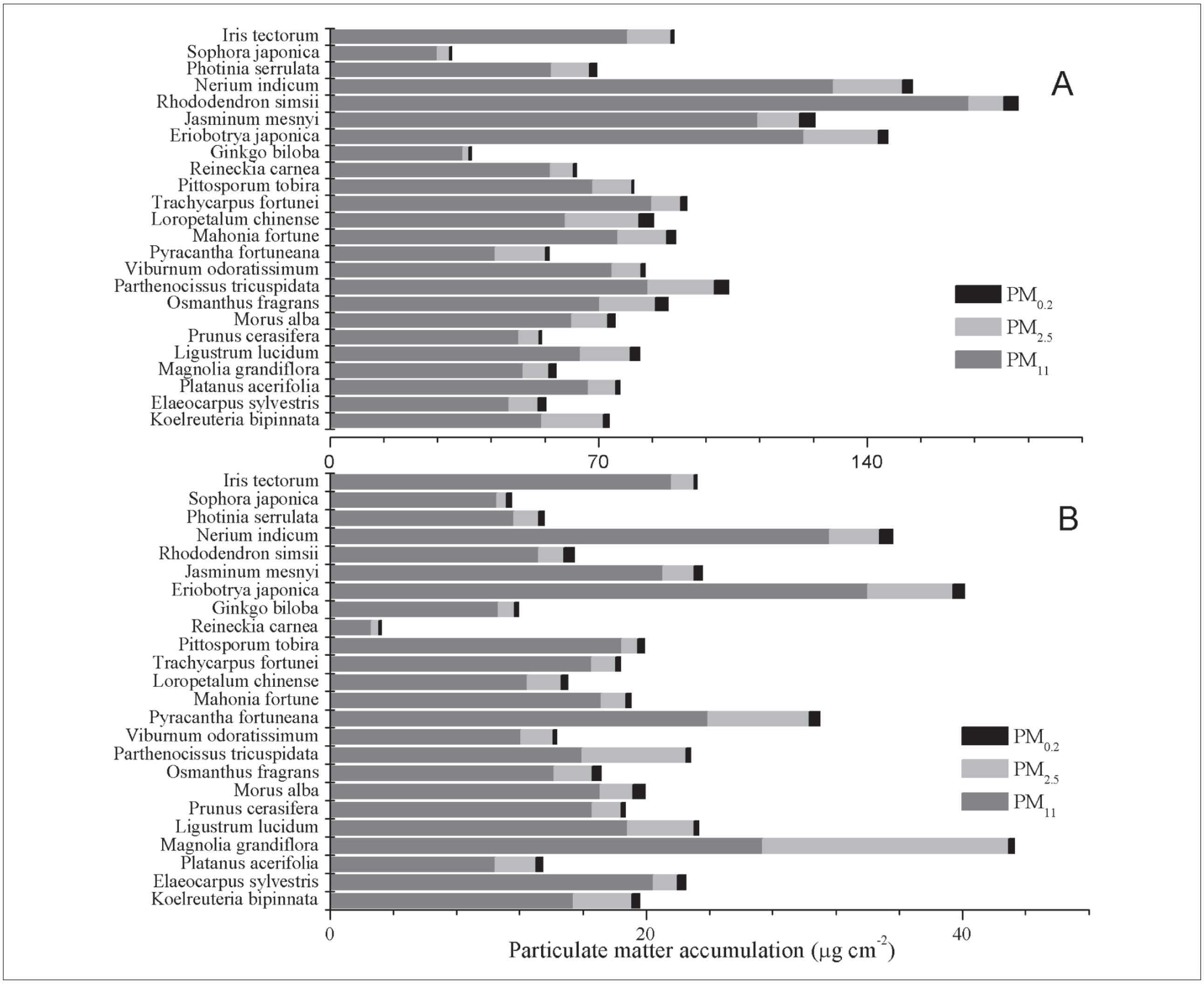

Fig. 1 Accumulation of different-size particulate matters on the leaves of 24 plant species in A) WISC and B) HZAU.

G. biloba, S. japonica and *Iris tectorum* had the lowest $PM_{0.2}$ retention, ranging from 0.49-0.81 μg cm^{-2}, while the others showed intermediate $PM_{0.2}$ retention.

In HZAU, *Magnolia grandiflora, Pyracantha fortuneana, E. japonica, N. indicum* and *I. tectorum* had the highest PM_{11} accumulation (20-32 μg cm^{-2}), and *R. carnea* was the only species containing PM_{11} (2.64 μg cm^{-2}) (Fig. 1B). The $PM_{2.5}$ that accumulated on the plant leaves ranged from 0.47-15.53 μg cm^{-2} in HZAU; 87.5% of plants accumulated PM that was below 6.0 μg cm^{-2}. The accumulated $PM_{2.5}$ of all plant species in HZAU were lower than 1μg cm^{-2}.

Leaf traits

ANOVA results indicated a significant effect of site and species on the leaf traits (SLA, Chl *a*, Chl *b*, total chlorophyll, carotenoid, pH and RWC) of 24 plant species, and the two-way interactions were also significant ($p<0.01$) (Table 2). The average values of leaf traits were greater at HZAU, except for SLA (Table 3). SLA showed a maximum increase of 1.97-fold for *R. carnea* and a minimum increase of 0.08-fold for *L. chinense* in WISC compared to HZAU. On the whole, Chl *a* exhibited higher quality than either Chl *b* or carotenoid for all plants at both places, Specifi-

Table 3. Average leaf trait parameter values of 24 plant species at the two different sites

Species	SLA (cm^2 g^{-1})		Chl a (mg g^{-1})		Chl b (mg g^{-1})		total chlorophyll (mg g^{-1})		carotenoid (mg g^{-1})		pH		RWC (%)	
	WISC	HZAU	WISC	HZAU	WISC	HZAU	WIS	HZAU	WISC	HZAU	WISC	HZAU	WISC	HZAU
K. bipinnata	146.8	69.39	1.17	1.54	0.56	0.95	1.73	2.49	0.48	0.57	5.69	5.74	74.11	82.61
E. sylvestris	158.73	87.27	0.97	1.38	0.50	0.95	1.47	2.33	0.50	0.54	3.70	3.83	74.73	92.47
P. acerifolia	161.86	105.11	1.11	1.20	1.27	1.31	2.38	2.52	0.60	0.56	5.36	5.71	71.64	76.92
M. grandiflora	88.97	66.18	1.00	1.21	0.49	0.67	1.49	1.58	0.47	0.51	5.46	5.59	74.56	76.60
L. lucidum	113.37	98.84	1.06	1.45	0.54	1.10	1.59	2.54	0.40	0.55	5.80	5.90	68.20	79.69
P. cerasifera	267.78	103.38	0.82	1.17	0.60	0.87	1.42	2.04	0.45	0.51	5.54	5.20	67.74	76.62
M. alba	173.18	125.00	1.01	1.34	1.03	1.61	2.04	2.95	0.50	0.55	6.95	7.96	71.60	81.58
O. fragrans	128.84	68.03	0.98	1.22	0.67	1.15	1.65	2.37	0.53	0.56	6.01	6.97	74.75	80.38
P. tricuspidata	238.49	179.12	0.74	0.76	0.33	0.37	1.07	1.13	0.32	0.40	5.43	5.76	72.73	78.33
V. odoratissimum	143.64	71.60	1.11	1.29	0.65	0.90	1.76	2.19	0.44	0.56	5.26	5.67	78.49	86.72
P. fortuneana	207.07	152.81	0.97	1.38	1.11	1.26	2.07	2.64	0.39	0.43	5.04	5.14	77.50	83.91
M. fortune	122.93	68.44	1.26	1.34	0.79	1.09	2.04	2.43	0.50	0.56	5.05	5.20	80.56	84.21
L. chinense	157.95	146.33	1.11	1.13	0.67	0.70	1.78	1.82	0.52	0.54	3.92	3.97	64.94	70.49
T. fortunei	101.25	84.78	0.87	1.11	0.53	1.62	1.41	2.74	0.31	0.56	5.67	5.71	86.58	81.82
P. tobira	117.11	63.82	1.01	1.30	0.49	0.77	1.50	2.07	0.32	0.37	5.90	5.93	68.27	65.83
R. carnea	175.14	58.98	1.08	1.27	0.78	1.15	1.86	2.41	0.48	0.56	5.89	5.94	73.86	86.03
G. biloba	173.93	110.11	0.90	1.41	0.54	0.81	1.44	2.22	0.32	0.36	4.66	5.55	71.36	84.10
E. japonica	123.08	86.44	1.11	1.32	0.59	0.95	1.70	2.28	0.42	0.49	5.69	5.79	82.42	85.78
J. mesnyi	214.76	132.99	1.31	1.35	0.73	1.08	2.05	2.43	0.52	0.58	5.55	5.61	81.25	63.46
R. simsii	142.32	115.39	1.22	1.26	0.86	1.01	2.08	2.26	0.50	0.50	5.60	5.65	66.15	71.43
N. indicum	209.65	108.56	1.13	1.41	0.81	1.13	1.94	2.54	0.54	0.55	5.73	5.79	78.31	85.45
P. serrulata	91.14	72.34	1.26	1.38	0.78	1.15	2.04	2.53	0.55	0.57	5.18	5.21	72.34	84.06
S. japonica	285.90	124.49	1.19	1.32	0.99	1.16	2.17	2.48	0.49	0.55	5.61	6.30	75.58	87.93
I. tectorum	180.15	129.14	0.90	1.17	0.54	1.33	1.44	2.51	0.38	0.56	5.82	6.09	63.22	81.82

Values are means (SD). *WISC* – Wuhan Iron and Steel Company, HZAU – Huazhong Agriculture University campus, *SLA* – specific leaf area, *Chl a* – chlorophyll a concentration, *Chl b* – chlorophyll b concentration, *total chlorophyll* – total chlorophyll concentration, *carotenoid* – carotenoid concentration, *pH* – potential of hydrogen, *RWC* – leaf relative water content

Table 4. Pearson correlation analysis of the accumulation of different-sized fractions of particulate matter on leaf and leaf traits of 24 plant species at the two study sites/

	SLA	Chl *a*	Chl *b*	total chlorophyll	carotenoid	pH	RWC
PM_{11}	0.402**	-0.357*	-0.442**	-0.445**	-0.273	-0.037	-0.353*
$PM_{2.5}$	0.354*	-0.425**	-0.534**	-0.566**	-0.300*	-0.117	-0.369**
$PM_{0.2}$	0.346*	-0.301*	-0.432**	-0.411**	-0.155	-0.154	-0.337*

ANOVA, values are means (SD). Levels of significance: *P<0.05, **P<0.01 (n=48)
PM_{11} – particulate matter with aerodynamic diameter above 11 µm, $PM_{2.5}$ – particulate matter with aerodynamic diameter between 2.5 µm and 11 µm, $PM_{0.2}$ – particulate matter with aerodynamic diameter between 0.2 µm and 2.5 µm, *SLA* – specific leaf area, *Chl a* – chlorophyll a concentration, *Chl b* – chlorophyll b concentration, *total chlorophyll* – total chlorophyll concentration, *carotenoid* – carotenoid concentration, *pH* – potential of hydrogen, *RWC* – leaf relative water content

cally, when compared with HZAU, in WISC Chl *a* showed the greatest reduction (35.86%) for *G. biloba*, and the least (1.6%) for *L. chinense*; Chl *b* showed a maximum reduction (67.1%) for *Trachycarpus fortunei*, and a minimum reduction (3.5%) for *Platanus acerifolia*; *carotenoid* showed a maximum reduction (44.7%) for *T. fortunei*, and an increase (6.4%) for *P. acerifolia*. Additionally, when compared with HZAU, pH in WISC showed a maximum reduction (13.9%) for *O. fragrans*, but an increase (6.7%) for *P. cerasifera*; RWC showed a maximum reduction (22.7%) for *I. tectorum*, but a slight increase (5.8%, 3.7% and 3.4%) for *T. fortunei*, *P. tobira* and *J. mesny*, respectively.

Relationship between PM and leaf traits

The Pearson correlation analysis revealed that PM (PM_{11}, $PM_{2.5}$, $PM_{0.2}$) significantly correlated ($p<0.05$) with SLA, Chl *a*, Chl *b*, total chlorophyll and RWC, and pH exhibited a non-significant correlation every examined PM fraction (Table 4). Specifically, PM_{11} was significantly related to SLA, Chl *b*, and total chlorophyll ($p<0.01$), and $PM_{2.5}$ correlated very significantly with Chl *a*, Chl *b*, total chlorophyll and RWC ($p<0.01$). $PM_{2.5}$ was the only parameter with significant correlation with carotenoid ($p<0.05$).

DISCUSSION

Our findings suggested that the accumulation of three PM fractions differed significantly ($p<0.05$) at the examined sites and with the species. PM retained on leaf surfaces produced considerably harmful effects on all leaf traits except leaf pH, and leaf traits were more significantly affected by $PM_{2.5}$ than by PM_{11} and $PM_{0.2}$.

Difference of PM accumulation by site, species and fraction

The results showed the differences in PM (PM_{11}, $PM_{2.5}$, $PM_{0.2}$) accumulation at the 2 sites and among 24 species (Table 2, Fig. 1A and B), verifying our first hypothesis. PM accumulation data showed greater PM accumulation on the leaf surfaces in WISC, probably due to the higher air pollution due to coal combustion and huge traffic volume (where the particulate concentration was 3.143 mg m^{-3}). Conversely, HZAU campus is on the edge of the Third Ring Road of Wuhan city with high forest coverage and a relatively low traffic volume (particulate concentration 0.152 mg m^{-3}). The total PM retention of selected species ranged from 31.75 to 179.41μg cm^{-2} at WISC and 3.29 to 43.29μg cm^{-2} at HZAU. Tallis et al. (2011) suggested that the deposition of pollutants depends on deposition velocity and pollution concentration. Chaturvedi et al. (2013) found that a greater dust load on the tree species was present at the most polluted site. Sæbø et al. (2012) proposed that PM accumulation on leaves is a species-specific property for plant species and pollution levels.

The PM retention differences of various plant species in the same place were also significant ($p<0.01$). In WISC, *R. simsii* showed the highest total PM retention of 179.4 μg cm^{-2} as compared to 31.8 μg cm^{-2} observed on *S. japonica,* while in HZAU, *M. grandiflora* had the largest total PM of 43.3μg cm^{-2} on the leaf surfaces as compared with PM of 3.3 μg cm^{-2} observed on *R. carnea*. Paoletti et al. (2011) found that *Aesculus hippocastanum* (182 g $tree^{-1}$) and *Pinus pinea* (164 g $tree^{-1}$) accumulated the largest amount of PM_{10}, whereas *Carpinus betulus* (2.6 g $tree^{-1}$) had the lowest amount of PM_{10} on leaves. A study in Norway calculated the amount of PM per unit and found that *Pinus sylvestris* held the largest amount of PM and *Acer platanoides* retained the least PM on leaf surfaces (Sæbø et al., 2012). Furthermore, Dzierżanowski et al. (2011) observed the largest amount of PM on low shrubs (*Spiraea*) as compared to trees. Sæbø et al. (2012) explained that *Stephanandra incise* had high amounts of PM as it grew near the ground and was more easily exposed to soil splash. The dust-trapping capacity was found to differ considerably among different plant species (Kapoor et al., 2009, 2012; Bamniya et al., 2012a, b). In the present study, *R. simsii* had the largest amount of total PM (179.4 μg cm^{-2}), while *G. biloba* retained a considerably lower total PM (36.9 μg cm^{-2}) on leaf surfaces in WISC. This investigation has also identified the interaction effect of site and species on the PM accumulation of leaves.

Our results also showed an obvious difference among the three PM fractions retained on leaf surfaces. PM_{11} accounted for about 84.6% of the total particulate matter, and $PM_{2.5}$ and $PM_{0.2}$ accounted for only about 13.0% and 2.4%, respectively (Fig. 1A and B), which agreed with the reports by Dzierżanowski et al. (2011), Sæbø et al. (2012) and Terzaghi et al. (2013). Beckett et al. (2000) observed more coarse particles than fine particles deposited on the leaves. Terzaghi et al. (2013) found the mass of large particles contributed to about 87-89% of the total particles.

Effect of the size of PM on leaf traits

In the present study, SLA was considerably higher in WISC than in HZAU and was within the range reported by Poorter et al. (2009). The results were consistent with previous studies that reported higher SLA in more polluted places (Kardel et al., 2010; Chaturvedi et al., 2013).

SLA was significantly affected by PM_{11} ($p<0.01$) (Table 4), supporting our second hypothesis. Sæbø et al. (2012) also reported that SLA correlated significantly with PM_{10}. The main reason for this result was that SLA increased with increasing degree of shading, and large amounts of large particles on leaf surfaces would produce big shadow regions (Wuytack et al., 2011; Kołodziejek, 2014). Moreover, thinner and broader leaves could absorb more light (White and Montes-R, 2005). Wuytack et al. (2011) proposed that the effect of air pollution on SLA is species-dependent and related to the protective or adaptive mechanism of plants; in the present investigation it also occurred that the influence of PM on SLA of different plant species was different. Overall, differences in SLA are perhaps the result of synthesis between environmental factors and plant attributes.

Leaf trait data indicated that Chl *a*, Chl *b*, total chlorophyll and carotenoid were reduced in WISC. Chl *b* and total chlorophyll were very significantly affected by the amount of all PM fractions ($p<0.01$), and Chl *a* was significantly affected by $PM_{2.5}$ ($p<0.01$), supporting our third hypothesis. The results were in agreement with those of Prusty et al. (2005) and Sharma and Tripathi (2009). The reduction in pigment concentration might be due to two reasons: one was that particles accumulated on leaf surfaces reduced the light available for photosynthesis and resulted in the inhibition of chlorophyll biosynthesis (Prusty et al., 2005), and the other one was that metals and polycyclic hydrocarbons were dissolved in cell sap and blocked the stomatal pores from exchange of air, thus putting stress on plant metabolism and resulting in chlorophyll degradation (Kapoor et al., 2013).

Bamniya et al. (2012a) reported that the reduction percentage of Chl *a* was slightly greater than that of Chl *b*, indicating that Chl *a* is more sensitive than Chl *b*. However, these trends were varied due to climatic and environmental reasons (Bamniya et al., 2012a). In the present study, the reduction ratio of Chl *b* was higher than that of Chl *a*, mainly because of the difference in the composition of pollutants and the time of sample collection. Similar results were obtained from samples collected in September and October (Kapoor et al. 2012; 2013; Bamniya et al., 2012b; Younis et al., 2013). At a polluted place, Chl *b* is more easily decomposed than Chl *a* (Yan and Yang, 2007).

Carotenoids protect chlorophyll against photooxidative destruction and thus their reduction would have serious effects on chlorophyll concentration. The amount of $PM_{2.5}$ correlated significantly with Chl *a*, Chl *b* and total chlorophyll ($p<0.01$) and was the only PM fraction that correlated with carotenoid ($p<0.05$). This suggests that the effect of $PM_{2.5}$ on plants was more significant than that of the other PM fractions. The main reason may be due to the presence of metals in $PM_{2.5,}$ which has the largest area and can adsorb more metals. Rai et al. (2010) suggested that fine particles would play a more important role in hindering plant growth compared to ultrafine and coarse particles, but in the present study, *P. acerifolia* showed an increase of 6.4% in WISC, indicating that this plant has a better tolerance of pollution and should be given preference in plant selection for seriously polluted places.

pH is a biochemical parameter that serves as a sensitivity indicator of air pollution (Joshi et al., 2011), and plants with a pH of around 7 are more pollution-tolerant. The leaf extract pH of plant species collected from WISC was lower than that of HZAU, which agreed with Rai and Panda (2013). However, pH showed no significant correlation with the amount of any of the PM fractions, and thus refuted our fourth hypothesis. It indicated that a decrease in pH could be due to the effect of atmospheric SO_2 and NO_X but not of particles on leaf surfaces.

The RWC of plant species collected from WISC was lower than that of HZAU, and was observably correlated with the amount of all PM fractions ($p<0.05$), supporting our fifth hypothesis. Chaturvedi et al. (2013) reported that RWC was considerably reduced in polluted sites, and significantly negatively correlated with dust (Rai and Panda, 2013). Higher RWC in plants will help maintain their physiological balance when exposed to air pollution and favors drought resistance; thus, plants with higher RWC may have higher tolerance to air pollution. In WISC, the RWC of *T. fortunei*, *P. tobira* and *J. mesny*, when compared with the control (HZAU), showed an increase of 5.8%, 3.7% and 3.4%, respectively, indicating that these plants have a better tolerance to pollution, and should be planted in seriously polluted areas.

This investigation explored the accumulation of three sizes of PM on plant leaves and examined the effect of their amount on leaf traits. However, this investigation was carried out only in September, and the influence of leaf surface structure on PM accumulation was not discussed. Studies could focus on seasonal variations of the responses of plants to the amount of different-sized PM, differences in the responses of plants to particles from different sources, and on the differences between various plant species (tree, shrub, climber and herb).

CONCLUSIONS

This work investigated the accumulation of three different sizes of PM on leaf surfaces by the gravimetric method, and determined the leaf traits of 24 plant species. The PM retention abilities of plant leaves varied significantly by site, species and particle fraction. The average PM retention capabilities of plant leaves and SLA were significantly greater in the very polluted area, while the average values of Chl *a*, Chl *b*, total chlorophyll, carotenoid, pH and RWC were greater at the control site. The size of PM correlated significantly with SLA, Chl *a*, Chl *b*, total chlorophyll, carotenoid and RWC, but not with pH. $PM_{2.5}$ had a more obvious effect on plant leaves than the other PM fractions. The results of PM accumulation on plant leaves and the effect of PM on leaf traits in this study provides further evidence that specific plants can help improve air quality.

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