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Automobile exhaust particles retention capacity assessment of two common garden plants in different seasons in the Yangtze River Delta using open-top chambers\*



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Particulate matter (PM) pollution is a serious environmental problem in most of the cities in the Yangtze River Delta region. Plants can effectively filter ambient air by adsorbing PM. However, only a few studies have paid attention to the dynamic changes and seasonal differences in particle retention capacities of plants under long-term pollution. In this study, we investigated the dynamic changes in particle retention capabilities of the evergreen, broad-leaved, greening plantsdEuonymus japonicus var. aurea-marginatus and Pittosporum tobiradin spring and summer. We employed an open-top chamber to simulate the severity of the tail gas pollution. The results showed that, both the plants reached a satu-rated state in 18e21 days, under continuous exposure to pollution (daily concentration of PM2.5: 214.64 ± 321.33 mg$cm 3). This was 6e8 days longer than that in the field experiments. In spring, the maximum retention of total particulate matter per unit leaf area of E. japonicus var. aurea-marginatus and P. tobira was 188.47 ± 3.72 mg cm 2 (18 days) and 67.63 ± 2.86 mg cm 2 (21 days), respectively. In summer, E. japonicus var. aurea-marginatus and P. tobira reached the maximum retention of the particle on the 21st day, with a net increase of 94.10 ± 3.77 mg cm 2 and 27.81 ± 3.57 mg cm 2, respectively. Irrespective of season, the particle retention capacity of E. japonicus var. aurea-marginatus was higher than that of P. tobira, and it showed a better effect on reducing the concentration of fine particles in the atmosphere. The particle retention of the two plants was higher in spring than that in summer. E. japonicus var. aurea-marginatus displayed a significant difference in particle retention between the seasons, while P. tobira did not show much difference. These results will provide a foundation for future studies on the dynamic changes and mechanism of particle retention in plants and management practices by employing plants for particle retention in severely polluted areas.

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1. Introduction

The Yangtze River Delta region is one of the major economic centers in China. With rapid urbanization, the fine particles emitted by automobile exhausts have become the main source of pollution of particulate matter (PM), especially PM2.5 ([Puett et al., 2009](#page8)). These fine particles harm the human body by inducing various respiratory diseases, such as bronchitis, lung function disorder, and respiratory inflammations. They also increase the incidence of



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heart disease and cancer ([Pope, 2000](#page8)). In general, the large parti-cles settle on the plant surface by the action of gravity, while the fine particles settle via Brownian diffusion or impaction. When particles approach the plant surface in the form of dry deposition, they are captured and adsorbed on the leaf surface. ([Gomez-Baggethun and Barton., 2013](#page8)). Previous studies have revealed that plants’ shape, type, and hairiness of leaves directly affect the PM-retaining capacities ([Powe and Willis., 2004](#page8)). According to the 2016 China eco-city construction and development report, the green coverage of the Yangtze River Delta is 40% and the evergreen broad-leaved plants account for about 60% of the urban plants ([Zheng et al., 2015](#page8)). All of these facts suggest that green tree species have a great particle retention potential in this region ([Chen et al.,](#page8) [2017](#page8)).

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Several studies have evaluated the efficiency and capacity of different plants in particulate air pollution mitigation and retention ([Lu et al., 2019](#page8); [Noh et al., 2019](#page8)). These experiments were con-ducted on the open system and usually took several samplings after a period of heavy rain (rainfall 17 mm or more) and strong wind (max. gusty wind speed ¼ 15 m$s-1), and then calculated the amount of particle on the leaves by the elution weighing method and scanning electron microscope ([Qiu et al., 2009](#page8); [Bharti et al.,](#page8) [2018](#page8)). Obvious correlations exist between particulate deposition and species-specific characteristics like trees size, leaf area index, leaf microstructure and the PM concentration ([Baldauf, 2017](#page8); [Gomez-Moreno et al., 2019](#page8)). Meteorological parameters, such as precipitation, wind speed, air humidity, also have a great influence on plants PM retention ([Yi et al., 2014](#page8); [Tang et al., 2015](#page8); [Dean and](#page8) [Green, 2018](#page8)). Nevertheless, these factors varied greatly with time and space. It would be difficult to analyze the causes of differences in the particle retention capacity of plants. Another common way to study plant particle retention is wind tunnel testing. This method simulates the deposition of particulate matter in plants to test their maximum particle retention for half an hour to a few hours ([Katul](#page8) [et al., 2011](#page8); [Lin et al., 2012](#page8); [Rasanen et al., 2013](#page8)). Neither method gave the plants enough time to settle the dust and paid attention to the dynamic change of dust retention of plants.

In China, due to the environment and climate, the air pollution is more serious in northern cities, such as Jing-jin-ji region ([Zheng](#page8) [et al., 2015](#page8); [Liu et al., 2019](#page8)), Xi’an ([Wang et al., 2010](#page8)). Thus, most of the previous studies have been focused on these cities and re-gions. The studies focusing on the particle retention potential of plants in the Yangtze river delta are insufficient. In addition, spring and summer are the growing period of plants, which are also the period when plants have the strongest particle retention capability. Therefore, it is important to study the particle retention dynamics of plants at high pollution levels under controlled experimental conditions in the Yangtze River Delta region.

In this study, E. japonicus var. aurea-marginatus and P. tobira, the typical, native, evergreen, and broad-leaved plants in the Yangtze River Delta region were selected as the experimental objects. We exposed them to vehicle exhaust, using the open-top chamber (OTC), to simulate heavy particulate pollution. Our objectives were

1. to explore the capability of particle retention of the two ever-green broad-leaved plants under continuous exhaust pollution over the study period, 2) to investigate the seasonal difference in particle retention capability, 3) to assess the difference of particle retention capacity and select suitable landscaping anti-pollution tree species in heavily polluted areas.

2. Materials and methods

2.1. Overview of the research site

The Yangtze River Delta is one of the main economic centers in China, with many modern metropolises. Hangzhou is a central city in the Yangtze River Delta, with the geographical coordinates of

1. 210e120 300E and 29 110e30 330N. The experimental site is located in the Pingshan experimental base of Zhejiang A&F Uni-

versity, Lin’an, Hangzhou City, Zhejiang Province (119 430E, 30 150N). It has a typical subtropical ocean monsoon climate, with

Table 1

Introduction of experimental plants.

158 days of precipitation, mainly in spring and summer, and an annual average temperature of 16 C.

2.2. Test material

Evergreen broad-leaved trees play an important role in urban greening in the Yangtze River Delta. Among them, E. japonicus var. aurea-marginatus and P. tobira are the common road greening plants. They are good for landscaping and have the advantages of rapid growth, strong ecological adaptability, and easy management. In this study, we planted 3-year old seedlings with similar heights (0.8 m in average) and base diameters (3 cm in average) in plastic containers, with a diameter of 30 cm and a height of 28 cm, in March 2017. Garden soil, peat soil, and vermiculite were mixed in a 7:7:6 ratio, and the maximum field water holding capacity was about 50%. The details of experimental plants are shown in [Table 1](#page8).

2.3. Open-top chamber

A modified open-top chamber (OTC) was used to expose the test plants to exhaust gases ([Lin et al., 2020](#page8)) ([Fig. 1](#page8)). The chamber is composed of plastic steel and toughened glass. The main body is 3.5 m tall, the cross-section is a regular octagon with a side length of 1.5 m, and the top is a 45 -tapered cone with a height of 1 m, connected to the gas. A piece of toughened glass is placed 0.5 m above the top of the tapered end to prevent the precipitation from entering the air chamber.

2.4. Experimental design

Before the experiment, a portable water spray pot was used to

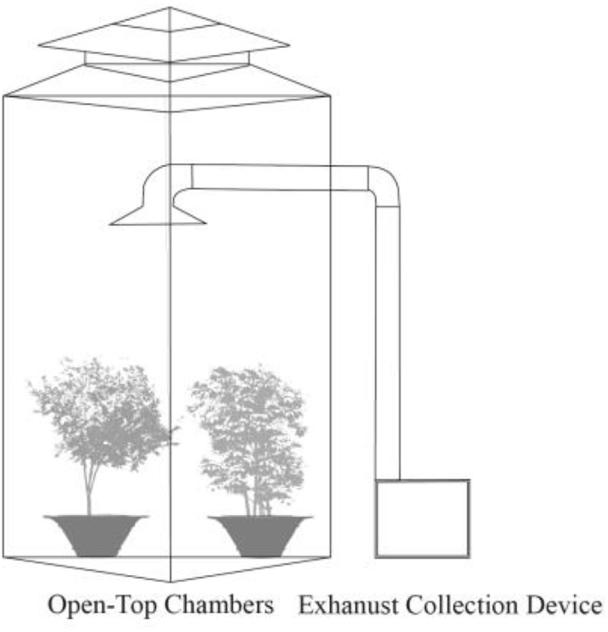


Fig. 1. Experimental equipment schematic.

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| --- | --- | --- | --- | --- | --- | --- | --- |
| Plant name | Section | Genus | Life form | Type | Height | Basal diameter | Visible leaf characteristics |
|  |  |  |  |  |  |  |  |
| Euonymus japonicus var. aurea-marginatus | Euonymus | Euonymus | Shrub | evergreen | 80 cm | 3 cm | Leathery, glabrous, rough |
| Pittosporum tobira | Pittosporaceae | pittosporum | Shrub | evergreen | 80 cm | 3 cm | Leathery, glabrous, smooth |
|  |  |  |  |  |  |  |  |

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wash away the particles on the leaves to avoid the influence of particles on the experimental results. In order to achieve the best cleaning effect, the plants were cleaned 2e3 times. During the cleaning process, we paid attention to the back of the leaves and avoided any damage to the leaf tissue. After cleaning, E. japonicus var. aurea-marginatus and P. tobira were placed in the air chamber and subjected to the continuous particle exposure treatment.

According to the spring and summer seasons, the experiment was divided into two parts: March 6e28 and June 8e30, 2017. The exhaust gas exposure test was carried out in OTC. The exhaust gas of a motorcycle (Suzuki 125, 125 mL actual display, No. 92 gasoline) running at idle speed was directly discharged into the exhaust gas collection device outside the gas room. It was then injected into the gas room through a pipeline and a blower system. The exhaust gas was mainly composed of solid carbon-containing substances, ash, soluble volatile organic compounds (SOF), and sulfates, which were highly condensed ([Gomez-Moreno et al., 2019](#page8)). Exhaust gas injec-tion time mimicked the morning and evening rush hour, 7:00e10:00 a.m., 18:00e20:00 p.m. At the same time, the intelli-gent environment data acquisition system (CS-WSN-2) was used to detect the PM concentration, temperature and humidity in OTC ([Fig. S1,S2,S3,S4,S5](#page8)). According to the daily average data of PM2.5 from Hangzhou meteorological station in recent five years([Fig. S6](#page8)) and the Chinese Technical Regulations on Ambient Air Quality Index (AQI)(on trial) (HJ633e2012) and, the air quality in the air chamber was set to be heavily polluted. In Spring (Summer), the average hourly PM2.5 concentration during the exhaust gas injection was 561.05 (587.37) mg$cm-3, while the daily concentration in OTC was 154.59 (134.22) mg$cm-3([Fig. S1](#page8)).

2.5. Experimental method

2.5.1. Leaf collection

Leaf samples were collected every three days to measure the particle retention of plants. Each sampling targeted 150e200 cm2 area of leaves, equivalent to 15e20 pieces of leaves. This was to ensure sufficient fine particles for the experiment, to avoid too much coarse particles blocking the filter paper, and not to affect the normal growth of plants. Four repetitions each experiment were made for E. japonicus var. aurea-marginatus and P. tobira. The par-ticles on the leaf surface could be lost by artificial vibrations or touching of the leaves when collecting them. In order to avoid that, we reduced the movement range as much as possible, paid atten-tion to the distance between the collected leaves, and packed the leaves in clean plastic, self-sealing bags. The bags were then appropriately labeled and stored in the refrigerator, until the analysis.

2.5.2. Determination of particles on the surface of plant leaves

The elution weighing method, coupled with a particle size analysis, was used to determine the number of particles on the leaf surface ([Lu et al., 2019](#page8)). The leaf samples were placed in a 500 mL beaker and soaked it in a 250 mL of deionized water for 2 h. They were subjected to ultrasonic cleaning for 2e3 min, to fully separate the particles from the surface of the leaves. The leaves were then taken out and cleaned with deionized water. The two wash solu-tions were first filtered using a standard sieve (160 mesh, pore diameter ~100 mm). Then, they were filtered through filter papers with pore diameters of 10 mm (Whatman type 91, UK), 2.5 mm (Whatman type 42, UK), and 0.22 mm (Whatman PTFE membrane, UK), using a 47 mm diameter suction filtration device. The filter papers were dried in the oven at 60 C for 1 h. After drying, they were placed in a drying dish for 24 h to keep the humidity of the filter paper and the weighing bottle consistent. The bottles con-taining the filter papers were weighed with an analytical balance.

The weights of the particles on the surface of the leaves were calculated through the weight difference(Wi), which were recorded as PM10e100, PM2.5e10, and PM0.22e2.5, corresponding to large par-ticles, coarse particles, and fine particles, respectively. For surface area determination, the washed leaves were dried and placed on an Epson perfection v370 photo scanner (Epson (China) Co., Ltd., China). The digital images obtained were imported into Image J 1.46r (National Institute of Health, USA) for calculation of leaf area

1. in cm2. The retention weight of particles per unit leaf area was calculated for each sample and the three particle sizes. The amount, hereinafter referred to as “particle retention per unit leaf area”, is the ratio of Wi to S (mg$cm 2). Simple cleaning did not completely remove the particles from the leaves ([Uppalapati et al., 2012](#page8)). The experiment also used the net particle retention to reduce the initial particle retention to affect the experimental results.

2.5.3. Statistical analysis

Assumption of normality was first evaluated for all datasets using the Shapiro-Wilk test and distribution was assumed normal based on resulting P values above 0.05 in all cases. Some data that failed the normality test were converted using natural logarithms. Two-way ANOVA was performed to evaluate the combined influ-ence of the two factors (species and season) on different-sized PM retained on the leaf surface. The differences in means were considered significant if P < 0.05 according to the LSD test. The statistical analysis of the data was completed using SPSS 25.0 (IBM, USA) and all plots were drawn in Origin 2018 (Origin Lab, USA).

The relative change rate of particle retention between seasons, hereinafter referred to as CR\_s, was used to measure the difference between the seasonal differences of the two plants. It was calcu-lated using the formula:

CR\_s ¼ ½ðPMspring PMsummerÞ=PMspring 100%

3. Results and analysis

3.1. Dynamics in particle retention capability

The particle holding capabilities of the two plants increased gradually ([Table 2](#page8)). The total particle retention of P. tobira reached a maximum value of 67.63 ± 2.86 mg$cm 2 in spring and 56.70 ± 3.57 mg$cm 2 in summer, on the 21st day. The average increase in the capacity was 5.85 mg$cm 2 and 3.97 mg$cm 2 every three days, in spring and summer, respectively. The net particle retention of E. japonicus var. aurea-marginatus reached a maximum value of 94.10 mg$cm 2 on the 21st day in summer. However, it was significantly reduced on the 21st day in spring, and only 70% of the maximum value on the 18th day (LSD-t ¼ 7.32, P≪0.001). On the 21st day, though the particle retention of E. japonicus var. aurea-marginatus and P. tobira was higher than that on the 18th day, the difference was not significant ([Table .2](#page8)). However, it was significant compared to that on the 15th day. Hence, it could be concluded that the two plants reached a saturation state in 18e21 days.

The total retention of large particles (PM10e100) by E. japonicus var. aurea-marginatus was 106.70e111.46 mg$cm 2, accounting for 57e75% of the total particles ([Fig. 2](#page8)). The total retention of large particles by P. tobira was 35.70e47.21 mg$cm 2, accounting for 63e70% of the total particles. The retention of fine particles (PM0.22e2.5) by the two plants was similar, accounting for 7e11% of the total retention. Also, the change in the retention of the particles of each size was similar to the basic retention of the total particles. The retention of coarse particles in E. japonicus var. aurea-margin-atus decreased significantly in summer and the maximum

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Table 2

The changes in particle retention capability of two common garden plants with the seasons (mean ± SE).

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | E. japonicus var. aurea-marginatus(mg$cm 2) | | |  |  |  | P. tobira (mg$cm | | 2) |  |  |
|  | Spring |  | Summer | | | | Spring | | Summer | | |
|  |  | |  |  | | |  |  |  |  | |
| 0 day | 47.53 ± 6.70e | | 54.39 | ± 1.20f | | | 26.68 | ± 1.54f | 28.89 | ± 0.59e | |
| 3rd day | 74.89 ± 4.19d | | 60.12 | ± 2.01ef | | | 33.82 | ± 0.66e | 36.56 | ± 2.23de | |
| 6th day | 107.76 | ± 11.03c | 73.75 | ± 4.68de | | | 39.69 | ± 3.43d | 43.31 | ± 2.88cd | |
| 9th day | 125.65 | ± 3.61b | 82.82 | ± 4.80d | | | 48.90 | ± 1.82c | 43.68 | ± 3.31cd | |
| 12th day | 129.41 | ± 2.08b | 106.39 | | ± 4.29c | | 52.94 | ± 0.87b | 52.73 | ± 3.21bc | |
| 15th day | 173.60 | ± 6.42a | 127.14 | | ± 5.26b | | 57.50 | ± 1.91b | 56.29 | ± 2.78 ab | |
| 18th day | 188.47 | ± 3.72a | 140.61 | | ± 10.28 ab | | 63.52 | ± 1.89a | 56.39 | ± 6.54 ab | |
| 21st day | e |  | 148.49 | | ± 3.77a | | 67.63 | ± 2.8a | 56.70 | ± 3.57a | |
|  |  |  |  |  |  |  |  |  |  |  |  |

retention decreased by 60% compared to that in spring.

3.2. Seasonal differences

From the perspective of the net particle retention amount ([Fig. 3](#page8)), the total particle retention amount per unit leaf area of both plants was higher in spring than that in summer, and a significant difference was found in E. Japonicus var. aurea-marginatus between spring and summer (P≪0.001). In spring, the total particle reten-tion per unit leaf area of E. japonicus var. aurea-marginatus increased from 47.53 ± 6.70 mg$cm 2 (0th day) to a maximum of 188.47 ± 3.72 mg$cm 2(18th day), was 1.63e4.77 times than that in summer. The total particle retention per unit leaf area of P. tobira reached a maximum of 67.63 ± 2.86 mg$cm 2 (21st day), and there was no significant difference in the seasonal retention of total particles.

The retention capacities of two plants for the three particle sizes revealed different rules in different seasons ([Fig. 4](#page8)). In terms of particle composition of various sizes, the difference in retention of three particle sizes per unit leaf area of P. tobira was not significant in spring and summer (P > 0.24), except for the large particles on the 21st day (P ¼ 0.01). The retention of coarse particles and fine particles per unit leaf area of E. japonicus var. aurea-marginatus was higher in spring than that in summer, and the seasonal difference of coarse particles was significant (P 0.005).

3.3. Species differences

During the experiment, there were obvious differences in par-ticle retention and seasons between the two plants. In the first 18 days ([Fig. 1](#page8)), the retention rate of E. japonicus var. aurea-marginatus in spring was about 3.8 times higher than that of P. tobira, and 2.6 times in summer. In three kinds of particles, the proportion of coarse particles of E. japonicus var. aurea-marginatus was higher than P. tobira. In spring and summer, the particle retention of the three particle sizes was higher in E. japonicus var. aurea-marginatus (18 days) than in P. tobira (21 days). The difference in coarse par-ticles of P. tobira between spring and summer was not obvious(P > 0.241), while that of E. japonicus var. aurea-marginatus was significant (P 0.005).

According to the above analysis, the particle retention by both plants was higher in spring than that in summer. Compared to spring, the amount of particle retention by P. tobira in summer began to decrease after six days of the experiment. Its CR\_s was 33.42% on the 9th day of the experiment. It then stabilized at 9.21e32.09%, which may be related to the gradual saturation of the leaves by particle. The CR\_s of E. japonicus var. aurea-marginatus (18 days) was different from that of P. tobira. From the 3rd to 12th day of the experiment, the particle retention dropped rapidly, CR\_s decreased from 79.07% to 36.50%, and then became stable. In summer, there was a significant decrease in the particle holding

capacity of the coarse particles in E. japonicus var. aurea-marginatus ([Fig. 4](#page8)). In the 21 days of the experiment, the CR\_s of coarse par-ticles reduced from 87.73% to 45.62%.

4. Discussion

4.1. Leaf morphology and particle retention

In this study, we limited the particle retention analysis of E. japonicus var. aurea-marginatus in spring to the first 18 days. This may be due to an insufficient number of old leaves and an increased number of new leaves during sampling. Previous studies have re-ported that as new leaves are incompletely developed and have poor resistance to pollution, their ability to retain particles is weaker than mature leaves ([Wang et al., 2010](#page8); [Masiol et al., 2015](#page8)). We observed that the particle retention by E. japonicus var. aurea-marginatus, in spring and summer, was higher than that of P. tobira, which may be related to its leaf and physiological character-istics([Ling et al., 2013](#page8); [Shao et al., 2019](#page8)). Generally, the ability of plants to capture particles is directly proportional to the coarseness of the leaf surface and the leaf area index ([Wang et al., 2010](#page8)). A large leaf area index makes it easier for air vortex to be formed between the plant leaves. The existence of the local gas cycle would increase the probability of contact between particles and the plant leaves, and the amount of fine particles (PM2.5) retained in the plant leaves would also increase ([Qifu and Murray, 2010](#page8)). E. japonicus var. aurea-marginatus has denser leaves and a larger leaf area index. Hence, it is strongly affected by turbulence, which was beneficial to PM2.5 settlement. In addition, the results of scanning electron microscopy of leaf microstructure showed that the leaf surface P. tobira was smoother and the stomata were smaller, while E. japonicus var. aurea-marginatus had smaller verrucous protuberance ([Liu et al.,](#page8) [2012](#page8)), which were more conducive to the retention of particles ([Franklin et al., 2007](#page8)).

E. japonicus var. aurea-marginatus and P. tobira are native ever-green broad-leaved plants in the Yangtze River Delta, which are widely used in the Yangtze River Delta because of their good landscaping function. Previous studies have found that E. japonicus var. aurea-marginatus had good resistance to automobile exhaust and resisted the physiological damage caused by exhaust ([Cao et al.,](#page8) [2016](#page8); [Jiang et al., 2012](#page8)). The dust retention ability and resistance of E. japonicus var. aurea-marginatus will be a good choice for heavily polluted areas.

4.2. Seasonal and species differences

We noticed an upward trend in the total particle retention by the two plants in both spring and summer seasons. This retention was lower in summer than in spring, which is consistent with the conclusions of previous studies ([Masiol et al., 2015](#page8)). In spring, the temperature is low, humidity is high, and the surface of leaves is

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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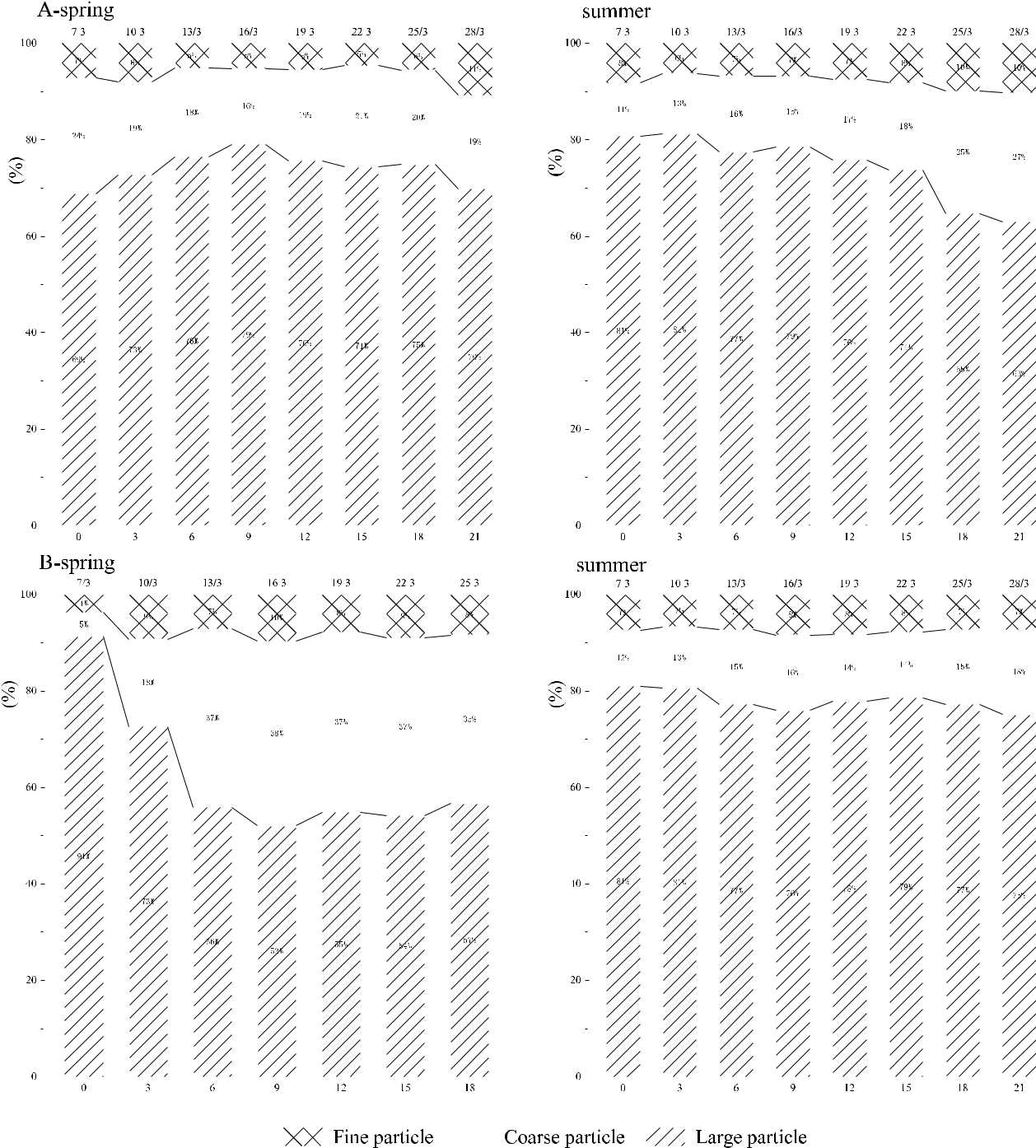


Fig. 2. Different size of exhaust particulate dust amount per unit area of spring leaves of two species of evergreen broad-leaved afforestation tree species (A: P. tobira; B: E. japonicus var. aurea-marginatus.).

wet, all of which are favorable for the adsorption of particles ([Masiol et al., 2015](#page8); [Lu et al., 2019](#page8)). In summer, the temperature is higher. In order to avoid loss of water in plants, the stomatal

conductance of the leaves decreases (Ras€anen€ et al., 2013). Tran-spiration and respiration are inhibited, and the interaction intensity with the outside air is reduced ([Lu et al., 2019](#page8)). The number of particles retained by plants through stomata decreases, resulting in lower particle retention in summer than in spring.

Both P. tobira (3.52 ± 0.62 mm) and E. japonicus var. aurea-mar-ginatus (3.81 ± 1.26 mm) had a thick waxy layer. But the thickness

levels of the main vein and palisade tissue of P. tobira were 1.32 and 1.54 times higher than E. japonicus var. aurea-marginatus ([Fan et al.,](#page8) [2019](#page8)). Observation of leaf microstructure by paraffin section from previous experiments indicated that, the stomata of P. tobira were smaller and denser, which could enhance the heat dissipation of blades ([Fan et al., 2019](#page8)). These factors played an important role in adapting to high temperature in summer (R€asanen€ et al., 2013; [Fan](#page8) [et al., 2019](#page8)). Therefore, P. tobira was less affected in summer, and there was no significant difference in its particle retention capacity between spring and summer(P > 0.24). On the contrary, E. japonicus

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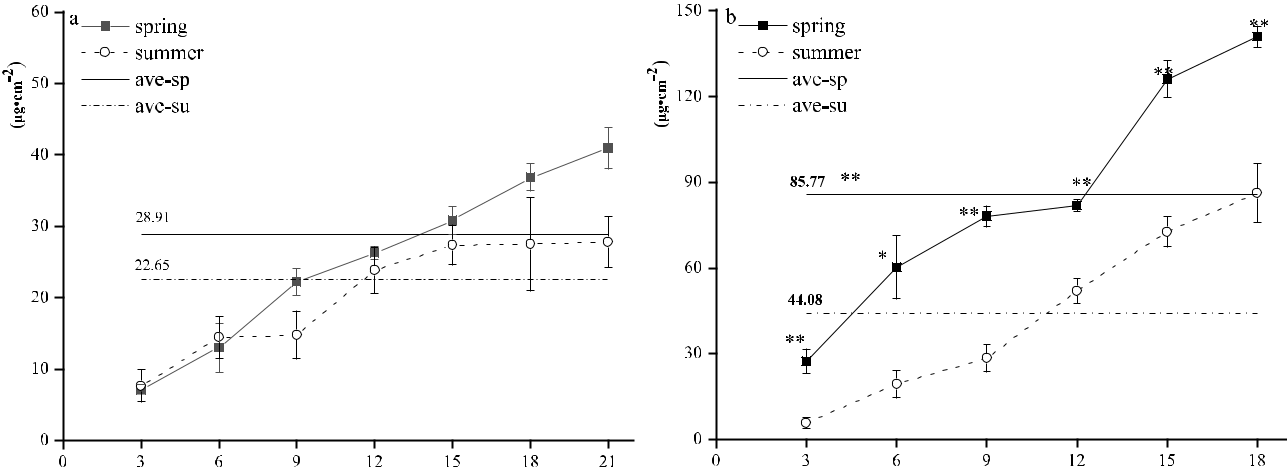


Fig. 3. Analysis of the change in the relative particle retention of total particles by two garden plants (A: P. tobira; B: E. japonicus var. aurea-marginatus, "\*P < 0.05 " "\*\*P < 0.01 “represents the significance level of particle accumulation between the seasons at that time.).

var. aurea-marginatus was greatly affected by the high temperature in summer, and its particle retention capacity was changed in spring and summer(P < 0.01) ([Fig. 3](#page8)). Besides, the seasonal differ-ences in the retention of coarse particles in E. japonicus var. aurea-marginatus were particularly prominent. In the first 18 days, the retention of coarse particles was 1.63e4.77 times higher in spring than that in summer, at any time of treatment, which was statis-tically significant. This may be related to the sedimentation mode of the particles. The size of coarse particles was 2e10 mm and its settlement mode was via collision ([Petroff et al., 2008](#page8)). The parti-cles are more likely to collide when their size is larger, the tem-perature in summer is higher, and the air-flow velocity is faster. When the particles collide with the plant surface, some of them return to the air due to secondary suspension, which was not easy to be captured. Hence, the difference in particle retention between spring and summer was significant.

4.3. The saturation time of particle retention

The removal of particulate matter removed appears not limitless over time but periodic ([Gao et al., 2007](#page8); [Guo et al., 2012](#page8); [Tang et al.,](#page8) [2015](#page8)). The amount of particulate matter retained on the plant leaves gradually increased with time until reaching a plateau after a period of time which may be indicative of saturation of the storage capacity ([Liu et al., 2012](#page8)). When particles stay on the leaves, they will also rebound into the air. The particle retention saturated state is the balance between particle retention and rebound. The satu-ration time of evergreen shrubs revealed by previous experiments was about 10e15 days ([Ram et al., 2015](#page8); [Liu et al., 2019](#page8)). In this study, the particle retention saturation time of the two plants was 18e21 days, which was 6e8 days longer than previous experi-ments. The field experiment of particle retention is greatly affected by environmental factors, especially wind and rain ([Achakzai et al.,](#page8) [2017](#page8); [Dean and Green, 2018](#page8); [Mori et al., 2018](#page8)). The wind and rain are uncontrollable factors in field experiments. They can spread particles and reduce the concentration of particles in the air ([Achakzai et al., 2017](#page8); [Shafique et al., 2018](#page8)). When sampling in the field, wind makes plants unable to fully retain particles, so the saturation time of particle retention obtained in field experiments will be short than that in OTC. In our study, prolonged exposure to the exhaust gas in the OTC reduced the impact of external factors, especially rain and wind, on particle retention of plants. OTC

implied that shrub with particle retention of 10e15 days could not reach the true saturation state under field conditions. Furthermore, the concentration of PM2.5 in OTC reached the level of heavy pollution, but there was little persistent heavy pollution in the actual environment. Hence, we hypothesize that the saturation time of E. japonicus var. aurea-marginatus and P. tobira in the field may be longer.

Under real conditions, when the particle retention capacity of plants reaches saturation, precipitation washes away the particles from the surface of plant leaves ([Armenise et al., 2018](#page8); [Shafique](#page8) [et al., 2018](#page8)). This is the key to restoring the particle retention ca-pacity of plants. According to the precipitation data of Hangzhou City in 2017 (<http://www.hangzhou.gov.cn/col/col805867/>), Hang-zhou received 7e19 days of rainfall in a month, with an average of one precipitation every four days ([Table S2](#page8)). There were also stretches of high pollution, non-precipitation days, lasting for more than 18 consecutive days. This indicates that before reaching saturation, E. japonicus var. aurea-marginatus and P. tobira would continue to carry out a new round of particle retention under the effect of the water drop, which could create a good particle reten-tion effect.

4.4. Limitations and recommendations for future studies

Plants are extremely complex systems, posing known and un-known hurdles in experimental design. In spring, trees undergo shedding of leaves. Hence, with the extension of exposure to exhaust gases, the leaves of our experimental plants were aging, withered, or dead ([Masiol et al., 2015](#page8); [Lin et al., 2020](#page8)). It is probable that the resistance of E. japonicus var. aurea-marginatus to shedding during the leaf changing period is relatively poor, resulting in an insufficient number of mature leaves in the study. In summer, the plants grow vigorously, and their physiological functions are stable, making them more resistant to the shedding of leaves. Under the continuous stress of vehicular exhaust gases, no serious leaf abscission was observed. In addition, OTC was transformed on the basis of the transparent greenhouse. Under the influence of pre-venting wind and rain, as the top was open, the air was circulating, which reduced the difference between the air environment of the air chamber and the external environment. But OTC was not completely open, the temperature inside might be 1e3 higher than the outside in spring, and 3e5 higher in summer ([Fig.S5](#page8)). It

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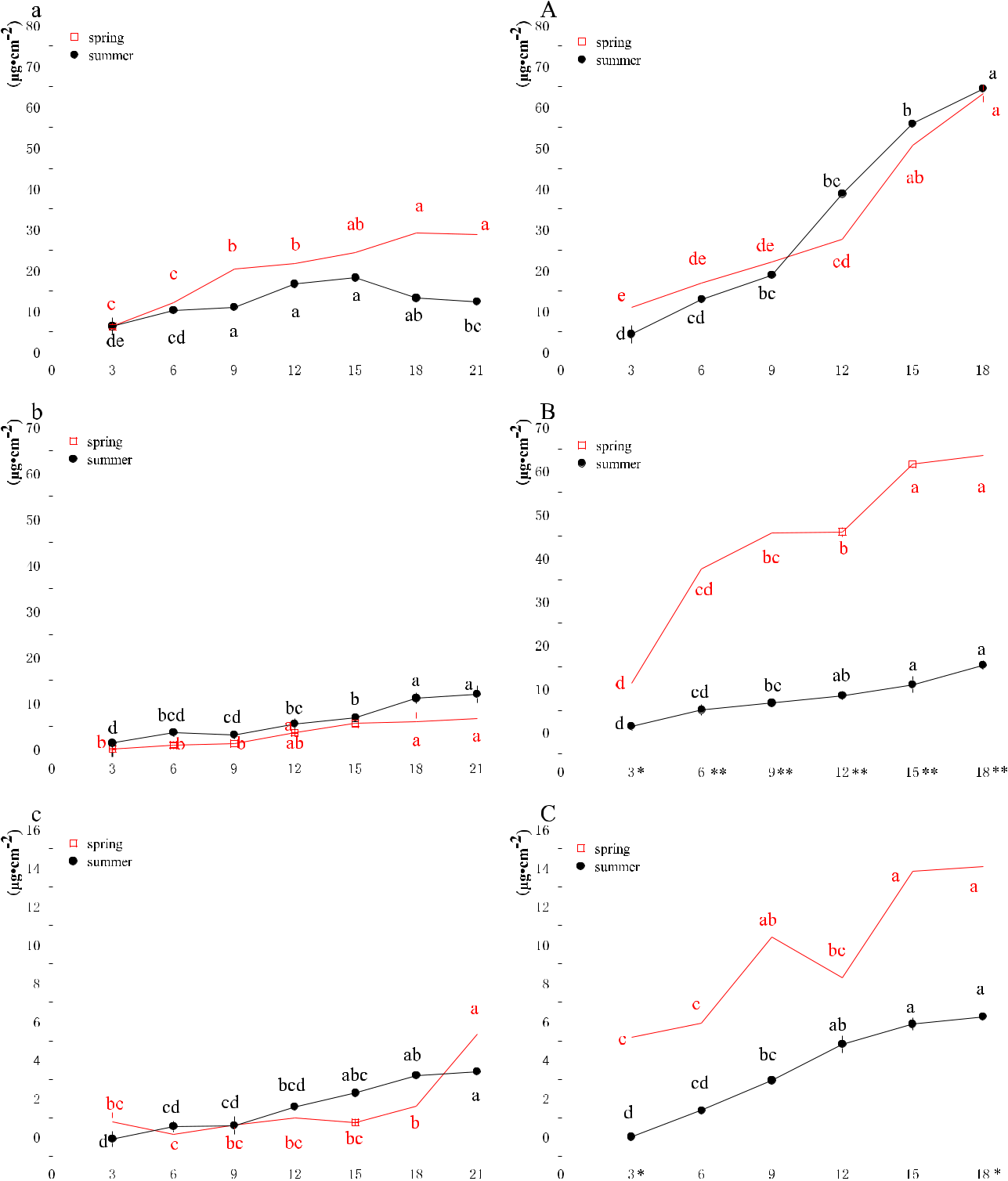


Fig. 4. Seasonal variation analysis of particle retention of three kinds of particles in two garden plants. (A: P. Tobira-large particles, B: P. Tobira-coarse particles, C: P. Tobira-fine

particles, a: E. japonicus var. aurea-marginatus- large particles, B: E. japonicus var. aurea-marginatus- coarse particles, C: E. japonicus var. aurea-marginatus- fine particles, Litter letters represent the differences of the particle accumulation among time at the level of 0.05, "\*P < 0.05 " "\*\*P < 0.01 00 represents the significance level of particle accumulation between the seasons at that time.)

will influence the quantitative analysis of leaf surface morphology. Waxy crystal structure and composition synthesis will change with the temperature, which will affect the adaptation of plants to the

environment ([Li et al., 2011](#page8)). Physiological changes of plants will also be affected by the temperature. High temperatures can inhibit the net photosynthetic rate of plants ([Rasanen et al., 2013](#page8)). The

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change of these factors will further affect the particle retention ability of plants and worth focusing on in later experiments.

5. Conclusion

In this study, we used vehicle exhaust to simulate particulate pollution in an open-top chamber (OTC). The observation and analysis of the particle retention dynamics of E. japonicus var. aurea-marginatus and P. tobira in spring and summer revealed the following: 1) Irrespective of the season, the retention capacity of E. japonicus var. aurea-marginatus was greater than that of P. tobira.

1. The particle holding capacity of both plants reached saturation state in 18e21 days, after continuous tail gas pollution. E. japonicus var. aurea-marginatus had a better effect at reducing the concen-tration of atmospheric fine particles. 3) In the case of both plants, the amount of particle retention per unit leaf area was higher in spring. Also, the seasonal differences in E. japonicus var. aurea-marginatus were significant.

E. japonicus var. aurea-marginatus, as color-leaved tree species, is the major urban ornamental tree species in the Yangtze river delta. In this study, under heavy pollution, E. japonicus var. aurea-mar-ginatus had long particle retention ability and saturation time, and great particle retention potential. This indicates that E. japonicus var. aurea-marginatus can also be used as an ornamental and anti-pollution tree species in heavily polluted areas, such as in parti-clerial and construction areas.

This study focused on the measurement of particulate matter on the surface of plant leaves, without considering the particulate matter absorbed by the waxy layer of plant leaves and plant bodies. Future experiments will systematically address and supplement this area.

Declaration of competing interest

The authors have no competing interests to declare.

CRediT authorship contribution statement

Miao Zhou: Writing - original draft, Visualization, Data curation. Xiang Wang: Visualization. Xintao Lin: Data curation, Investiga-tion. Shan Yang: Investigation. Jing Zhang: Investigation. Jian Chen: Conceptualization, Resources, Project administration, Fund-ing acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envpol.2020.114560>.

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