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Effects of meteorological factors on the retention of particulate matter in lawn grass blades

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Plant leaves can reduce the concentration of atmospheric particulate matter (PM) by absorbing it in the air, and this mitigates the deleterious human health effects of PM. However, the ability of plant leaves to retain dust is limited and varies continually due to various meteorological factors such as rainfall, extreme wind speed, and PM_{10} concentrations. Here, we measured the ability of seven types of turfgrass with leaves similar in macromorphology but varying in micromorphology to retain dust particles of different sizes; we also analyzed the effects of various meteorological factors, such as rainfall, maximum wind speed, and PM_{10} concentration, on the ability of leaves to retain particles of different sizes. There were significant differences in the ability of the seven types of turfgrass to retain particles of different sizes; the dust retention capacity of Zoysia sinensis was the strongest(2.04 $g \cdot m^{-2}$), and that of *Festuca elata* was the weakest(1.39 $g \cdot m^{-2}$). The elution rates of PM>10 after rainfall of 3 mm and 4 mm were significantly higher than those of $PM_{2.5\text{-}10}$ and $PM_{2.5}$; the elution rates of $PM_{>10}$, $PM_{2.5\text{-}10}$, and $PM_{2.5}$ increased as the amount of rainfall increased. When the amount of dust on leaves is low, wind promotes increases in leaf PM retention. When the blade retains a certain amount of dust, the maximum wind speed is greater than 9.1 $m \cdot s^{-1}$, which leads to a decrease in the dust retention of lawn grass blades. The concentrations of PM_{10} and $PM_{2.5}$ were positively correlated with the retention of particles of different particle sizes. Therefore, evaluations of the dust retention ability of plant leaves require consideration of the effects of local rainfall, maximum wind speed, PM_{10} concentration, and other factors.

KEYWORDS

turfgrass, particulate matter, dust retention, rainfall, extreme wind speed

1 Introduction

The acceleration of urbanization has led to a rapid decline in urban air quality, and air pollution caused by atmospheric particulate matter (PM) has become an issue of wide concern (Zhou et al., 2021). TSP (Total Suspended Particulates) stands for particles that can be suspended in the air and have an aerodynamic equivalent diameter of less than 100 microns, that is, particles with a particle size under 100 microns.These particles can enter the body during breathing and pose a health hazard. Suspended in the atmosphere for a long time without settling, reducing the atmospheric visibility; Participate in atmospheric chemical reactions, increase the degree of pollution (Huang et al., 2012). Particles with an aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$) can pose more harm to human health compared with particles of other sizes because fine particles may penetrate the lining of the alveolar ducts, which promotes the entry of toxins into the bloodstream (Kwon et al., 2020; Qin et al., 2021; Rodriguez-Germade et al., 2014) and increases the incidence of malignant tumors (Karottki et al., 2015; Nowak et al., 2018; Qin et al., 2019). Previous studies have shown that urban plants can effectively retain PM in the atmosphere and alleviate urban PM pollution (Go et al., 2021; Popek et al., 2018; Vos et al., 2013). Urban plants can reduce the production of surface PM (Escobedo et al., 2011) and reduce the concentration of atmospheric PM by absorbing airborne PM on the surface of their leaves. Precipitation of PM is promoted by improving micrometeorological conditions (Beckett et al., 1998; Freer-Smith et al., 2005; Hofman et al., 2014).

The ability to retain PM on the leaf surface varies among species (Bui et al., 2021; Marien et al., 2019; Xu et al., 2018; Zhang et al., 2020), and this is associated with interspecific variation in leaf morphology (Leonard et al., 2016). Macromorphological leaf characteristics include traits such as leaf height, leaf size, and leaf whorl arrangement (Leonard et al., 2016; Nowak et al., 2006; Rasanen et al., 2013). Leaf micromorphological characteristics include traits such as villous number (Burkhardt, 2010; Chiam et al., 2019), surface roughness (Hwang et al., 2011; Sgrigna et al., 2020), groove ratio (Chen et al., 2017; Liang et al., 2016), and wax layer content (Perini et al., 2017; Saebo et al., 2012). Interactions among these leaf structural characteristics significantly affect the retention of PM in plant leaves (Guerrero-Leiva et al., 2016; Leonard et al., 2016; Li et al., 2020; Sun et al., 2018). Previous studies have analyzed the dust retention capacity of substances by sampling leaves after long periods of no precipitation or at the end of the growing season (Bui et al., 2021; Guerrero-Leiva et al., 2016; Xu et al., 2018); however, the amount of dust retained by urban plants in urban environments varies with meteorological factors, such as rainfall, wind, and dust concentrations (Rodriguez-Germade et al., 2014). Previous studies have shown that particles retained on the leaf surface of trees can be removed by the cleaning effect of rainfall (Przybysz et al., 2014; Rodriguez-Germade et al., 2014; Wang et al., 2015), and these particles fall on the soil or ground with rain, where the organic components of PM can be decomposed by natural processes; the inorganic components of PM are fixed in the soil (Dzierzanowski et al., 2011). Coarse PM (particle size greater than 10 μm) in foliar particles is easily displaced from the leaf surface by rain, and approximately 30–41% of PM on the leaves of Pinus sylvestris can be removed by 20 mm of rainfall (Przybysz et al., 2014).

Steubing examined the erosion of pollutants on the surface of ryegrass and found that the amount of pollutants displaced significantly increased after 15 min of rainfall (Steubing, 1982). Rodriguez-Germade et al. demonstrated that rainfall washed away part of the PM accumulated on the leaves of Platamus hispamica (Rodriguez-Germade et al., 2014). Wang et al. found that rainfall events can cause a large loss of PM on Ligustrum lucidum leaves. Cumulative precipitation of 10.4 mm and 31.9 mm washed away 28% and 48% of PM in L. lucidum leaves, respectively (Wang et al., 2015). Xu et al. found that 51–70% of the particles on the blade surface were washed away within the experimental intensity range (Xu et al., 2017).

Wind speed is also an important factor affecting the amount of dust retained on urban plants, and plants are affected by wind when its velocity exceeds a certain threshold. Ould-Dada & Baghini, 2001 found that the amount of PM adsorbed on the leaf surface was not affected by wind when it was less than 5 $m{\cdot}s^{-1}$. Tiwary et al. (2006) found that wind affected the amount of dust retained on hawthorn, Buxus, and purple only when it exceeded 0.8, 1.2, and 1.7 $m{\cdot}s^{-1}$, respectively (Tiwary et al., 2006). The effects of meteorological conditions on particle retention vary (Weerakkody et al., 2018b), and these meteorological conditions continuously limit the PM removal capacity of plants (Chen et al., 2021).

Here, the particle retention abilities of seven common turfgrass species with similar macromorphological characteristics but different micromorphological characteristics was studied. We believe that different weather conditions and different surface micromorphology of the blade have great influence on its dust retention ability. Therefore, We used an *in-situ* sampling method to characterize changes in the dust retention of seven types of common lawn grasses and the influence of weather conditions and leaf surface micromorphology on leaf PM retention was discussed. Overall, our findings provide new insights into the mechanism of leaf PM retention and will aid future quantitative evaluations of the dust retention abilities of leaves.

2 Materials and methods

2.1 Plant materials

We studied the dust retention of the leaves of seven turfgrass species in Qingdao, China: *Liriope spicata*, *Lolium perenne*, *Festuca elata*, *Poa pratensis*, *Zoysia sinica*, *Cynodon dactylon*, and *Agrostis stolonifera* plants were obtained from the campus of Qingdao Agricultural University and transplanted into pots before the experiment. The rest of the experimental plants were planted in pots (length 40 cm, width 20 cm, height 15 cm) in mid-July 2022, with 8 pots for each plant. Experiments were performed after a lawn was formed. Before testing, the leaves were fully washed, cleaned, and left to dry for a day; they were then placed on the roadside for study of their dust retention ability. The morphological characteristics of the seven types of turf grasses are shown in Table 1.

TABLE 1 The morphological characteristics of the seven turfgrass species.

Plant	Family name	Morphological features
Liriope spicata	Liliaceae Juss	Leaf blade apex acute or obtuse, with 5 veins, midvein conspicuous, margin serrate.
Lolium perenne	Poaceae Barnhart	Leaf blade linear, soft, sometimes auriculae.
Festuca elata	Poaceae Barnhart	Leaf blade linear-lanceolate, apex long acuminate, often flattened, glabrous below, glabrous upper mask.
Poa pratensis	Poaceae Barnhart	Leaf blade linear, flattened or inrolled, apex acuminate, smooth or margin slightly coarse.
Zoysia sinica Hance	Poaceae Barnhart	Leaf blade light green or gray-green, abaxially pale, glabrous, slightly hard in texture, flat or curled in margin.
Cynodon dactylon	Poaceae Barnhart	Leaf blade linear, usually glabrous on both surfaces.
Agrostis stolonifera	Poaceae Barnhart	Leaf blade narrowly lanceolate, both surfaces rough, apex acute.

2.2 Sample collection

From September 2 to November 13, 2022, plant materials were sampled every three days at Chengyang Campus of Qingdao Agricultural University (36° 19' 5" N, 120° 23 '52 "E). In the event of rainfall, plant materials were sampled one day before and one day after rainfall, and six replicate samples were taken for each species. During sample collection, the grass in a well-grown area of 10×10 cm was cut 1 cm away from the roots, placed in a labeled plastic bag to minimize shaking, and transported to the laboratory for testing.All plants used in this study had sufficient number of leaves for taking leaf samples during the experiment, and leaves newly produced during the experiment were not sampled.

The dust retention per unit leaf area was measured using the filtration mass method. The leaf sample was placed into a beaker and immersed in distilled water for 2 h; the attachment point on the leaf was cleaned with a brush, and the leaf was removed with tweezers. The leaf surface was rinsed again with a small amount of distilled water. The leaching solution was filtered using a microporous filter membrane with a diameter of 10 μm that had been dried and weighed, and the filter solution was filtered using a microporous filter membrane with a diameter of 2.5 μm that had been dried and weighed. Finally, the filtrate was poured into a beaker that had been previously weighed, and the beaker was placed in a 60°C oven and dried to a constant weight (i.e., the difference in two measurements was less than 0.0002 g). Next, the filter membrane of trapped particles was also placed in the oven at 65°C and dried to a constant weight, and the different particle sizes were classified as follows: particle mass > 10 μm (referred to as $PM_{>10}$), 10–2.5 μm (referred to as $PM_{2.5-10}$), and ≤ 2.5 μm (referred to as $PM_{2.5}$). The sum of the three was referred to as TSP. The dried leaves were placed on a scanner (CanoScan 5600F) for scanning, and the obtained digital images were imported into ImageJ to calculate the leaf area S (m^2); the dust absorption of the unit leaf area of the plant leaves was calculated using the following formula:

$$Q = (Q2 - Q1) \times S - 1$$

where Q is the dust retention amount per unit leaf area ($g \cdot m^{-2}$), Q2 is the mass of the filter membrane after filtration (g), Q1 is the mass of the filter membrane before filtration (g), and S is the leaf area of the sampled leaf (m^2).

Variation in dust retention per unit leaf area was calculated using the following formula:

$$\text{Dynamic variation } M = M2 - M1$$

where M2 represents the maximum dust retention per unit leaf area ($g \cdot m^{-2}$) and M1 represents the minimum dust retention per unit leaf area ($g \cdot m^{-2}$) during the sampling period.

The precipitation elution rate of particles with different particle sizes on the leaf surface was calculated using the following formula:

$$W = (P2 - P1) \times P2 - 1$$

where P2 represents the amount of dust retention per unit leaf area before rainfall ($g \cdot m^{-2}$), and P1 represents the amount of dust retention per unit leaf area after rainfall ($g \cdot m^{-2}$).

After excluding the effect of rainfall on foliar PM following previous studies (Beckett et al., 2010; Freer-Smith et al., 2004), data with maximum wind speed greater than 9 m·s-1 during the sampling period were used to study the effect of maximum wind speed on particle retention.

Variation in particle retention associated with the effect of maximum wind speed was calculated using the following formula:

$$M3 = M5 - M4$$

where M4 represents the dust retention per unit leaf area before the maximum wind speed ($g \cdot m^{-2}$), and M5 represents the dust retention per unit leaf area after the maximum wind speed ($g \cdot m^{-2}$).

2.3 Determination of leaf surface structure

Leaves were cut and placed in a clean plastic bag; care was taken to ensure that leaf villous were not damaged. A 3 mm × 3 mm tissue block was placed in the middle of the blade with a new blade; it was then placed into a small glass bottle and fixed in FAA(Formalin-Aceto-Alcohol) fixing solution for more than 4 h. After drying the sample using a vacuum, the samples were dehydrated using a graded ethanol series (60%, 70%, 80%, 90%, and 100% ethanol solution) for 10 min at each ethanol concentration and finally replaced with tert-butanol. The samples were then placed into a freeze-dryer for vacuum drying. After completely drying, the samples were removed and placed on the platform. A scanning

electron microscope JSM-7500F (JEOL Ltd., Tokyo, Japan) was used to observe the surface structure of plant leaves at different magnifications (Figure 1). The surface microstructure parameters of 7 species of turfgrass were calculated (Table 2), and the correlation between particle retention per unit leaf area and that of turfgrass was analyzed (Figure 2).

2.4 Collection of meteorological data

Precipitation, relative humidity, and maximum wind speed data during the study period were obtained from the China Meteorological Data Network (http://data.cma.cn/). Data on PM_{10} and $PM_{2.5}$ concentrations during the study period were obtained from the China Air Quality Online Monitoring and Analysis platform (https://www.aqistudy.cn/) (Figure 3). After excluding the effect of rainfall and maximum wind speed on the dust retention of turfgrass, correlations of the average daily PM_{10} concentration, average daily $PM_{2.5}$ concentration, and average daily relative humidity at each sampling interval with the retention of particles of different sizes by the seven turfgrass species were analyzed.

2.5 Data analysis

Differences in the amount of particles (TSP, PM_{10}, $PM_{2.5-10}$, and $PM_{2.5}$) retained on the leaf surface of seven types of turfgrass during the sampling period were analyzed by one-way ANOVA, and multiple comparisons were made using least significant difference (LSD) tests and Duncan multiple-range tests. All statistical analyses were performed using SPSS25.0 (SPSS, IBM, USA) software, and the threshold for statistical significance in all analyses was $P < 0.05$ (Chen et al., 2024).

3 Results

3.1 Comparison of the maximum retention capacity of particles of different sizes of lawn grass blades

As shown in Figure 4, the results showed that the retention of particles of each size was significantly higher on the leaf surface of *Z. sinica* than on that of other plants ($P < 0.05$). The maximum TSP retention of the tested plants ranged from 1.34 to 2.04 $g \cdot m^{-2}$, and *A.*

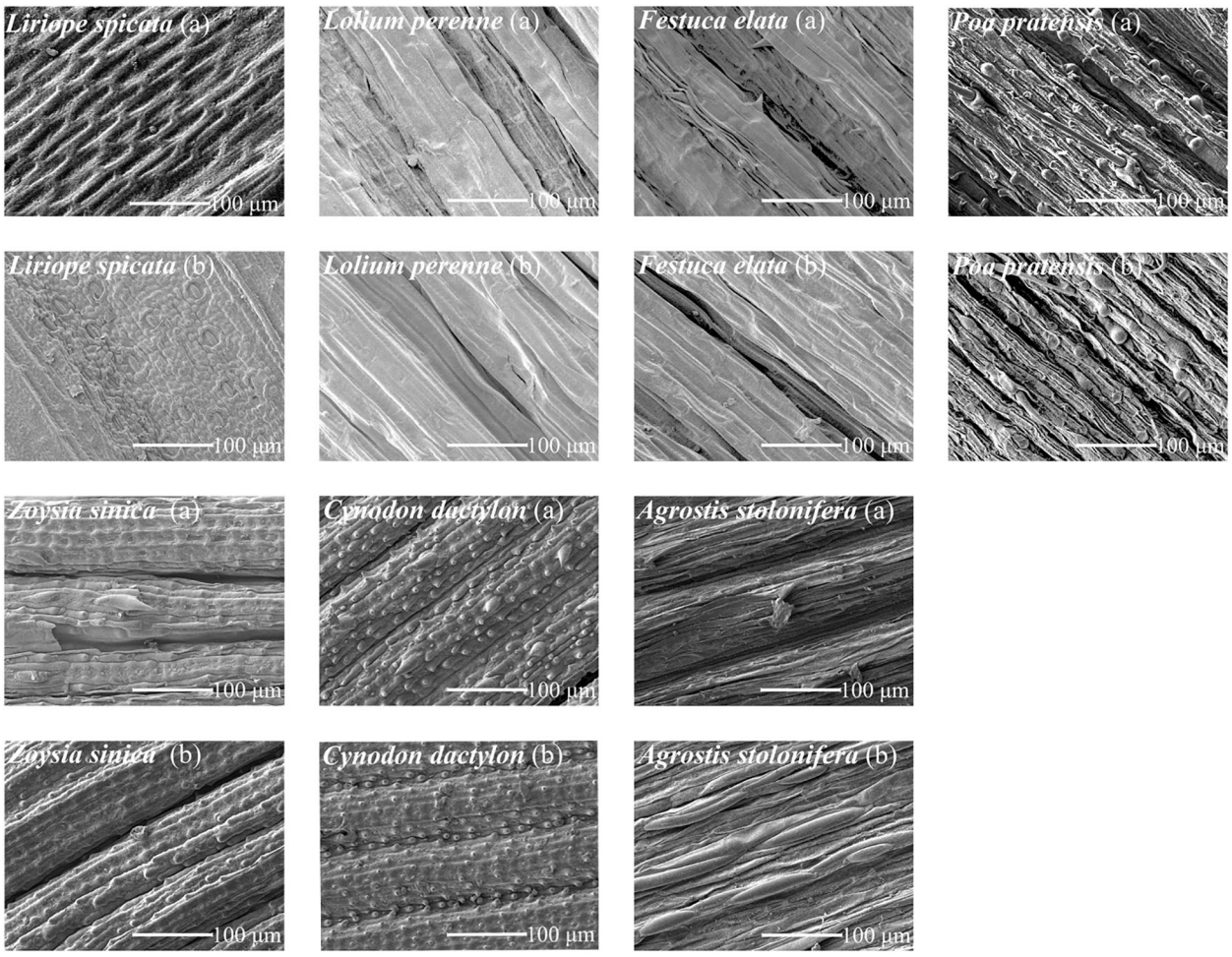

FIGURE 1
Scans of the surface of different turfgrasses. upper **(A)** and lower **(B)** leaf surface.

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TABLE 2 Microstructural parameters of the blade surface.

Species	GP (%)	GW (μm)	SS (μm^2)	SD ($N \cdot mm^{-2}$)	TD ($N \cdot mm^{-2}$)
L. spicata	57±4a	28.89±6.11cd	225.83±23.42c	229.79±12.95a	–
L. perenne	34±3g	71.83±3.43a	364.77±70.14b	88.16±27.56c	–
F. elata	47±2bc	76.03±22.94a	490.05±31.97a	131.93±24.91b	45.26±6.50abc
P. pratensis	40±3de	47.75±11.62b	264.37±10.84c	154.88±16.11b	49.18±4.10ab
Z. sinica	50±9b	48.99±3.79b	135.15±11.14d	249.27±29.96a	35.57±6.17d
C. dactylon	38±2ef	23.72±0.83d	138.34±17.98d	141.56±6.30b	55.50±15.56a
A. stolonifera	44±3cd	40.44±7.12bc	161.37±38.63d	63.74±10.15d	42.27±7.85bc

Leaf surface microstructure parameters are expressed as mean ±SE, n=6. "GP" stands for "Groove proportion," "GW" stands for "Groove width," "SS" stands for "Stomatal size," "SD" stands for "Stomatal density," "TD" stands for "Trichome density," and "-" stands for "No data".

stolonifera and *C. dactylon* had the lowest maximum TSP retention. The maximum retention of $PM_{>10}$ ranged from 0.70 to 1.06 g·m-2, and *A. stolonifera* had the lowest retention of $PM_{>10}$. The maximum retention of $PM_{2.5\text{-}10}$ ranged from 0.28 to 0.53 $g \cdot m^{-2}$, and *C. dactylon* and *F. elata* had the lowest retention of $PM_{2.5\text{-}10}$. The maximum retention of $PM_{2.5}$ ranged from 0.25 to 0.48 $g \cdot m^{-2}$, and *L. perenne* and *A. stolonifera* had the lowest retention of $PM_{2.5}$.

3.2 Changes in the retention of particles of different sizes in turfgrass blades.

The retention of particles of different sizes on the leaf surface of the tested plants decreased significantly after rainfall ($p<0.05$) and then gradually increased. During the sampling period, the lowest value of PM appeared after 158 mm of rainfall, and the average retention of TSP was only 0.29 g·m-2. The values of TSP in the tested plants ranged from 0.17 to 2.04 g·m-2; the most variation in TSP retention was observed in *Z. sinica* (1.78 $g \cdot m^{-2}$), and the least variation in TSP retention was observed in *F. elata* (0.97 $g \cdot m^{-2}$) (Figure 5-1). The values of $PM_{>10}$ for the tested plants ranged from 0.08 to 1.06 g·m-2; the most variation in $PM_{>10}$ retention was observed in *Z. sinica* (0.94 $g \cdot m^{-2}$), and the least variation in $PM_{>10}$ retention was observed for *A. stolonifera* (0.54 $g \cdot m^{-2}$) (Figure 5-2). Values of $PM_{2.5\text{-}10}$ of the tested plants ranged from 0.05 to 0.53 g·m-2; the most variation in $PM_{2.5\text{-}10}$ retention was observed in *L. perenne* (0.42$g \cdot m^{-2}$), which was 2.47 times higher than the variation in $PM_{2.5\text{-}10}$ retention observed in *F. elata*, the species with the least variation in $PM_{2.5\text{-}10}$ retention (Figure 5-3). The values of $PM_{2.5}$ in the tested plants ranged from 0.03 to 0.48 g·m-2; the most variation in $PM_{2.5}$ retention was observed in *Z. sinica* (0.43 $g \cdot m^{-2}$), which was 2.15 times higher than that observed in *L. perenne*, which was the species with the least variation in $PM_{2.5}$ retention (Figure 5-4).

The overall dust retention of particles of different sizes of the seven types of lawn grass blades gradually increased over time; particles were displaced and replaced when rainfall and maximum wind speed were high. Rainfall had a significant effect on the removal of particles of different particle sizes in lawn grass blades, and the maximum wind speed had a weak effect on $PM_{>10}$ and a stronger effect on $PM_{2.5\text{-}10}$ and $PM_{2.5}$.

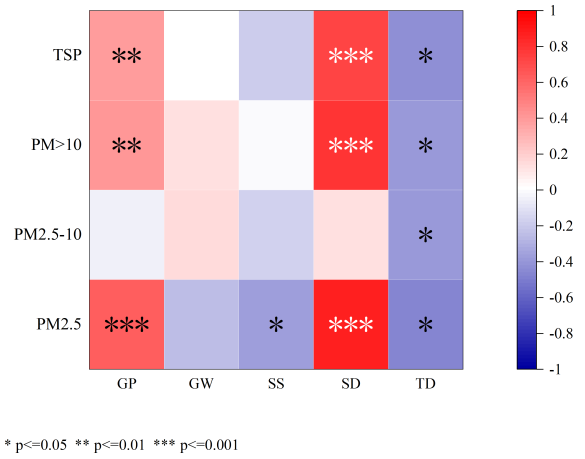

FIGURE 2
Correlations of the groove proportion, groove width, stomatal size, stomatal density, and trichoid density with the retention of TSP, PM>10, PM10, and PM2.5 per unit leaf area. "*" indicates ($P < 0.05$), "**" indicates $P < 0.01$.

3.3 Effect of leaf micromorphology on the retention of particles of different sizes

As shown in Figures 1, 2, and Table 2, the groove proportion was significantly positively correlated with the retention of TSP and $PM_{>10}$ ($P<0.05$) and highly significantly positively correlated with the retention of $PM_{2.5}$ ($P<0.01$). There was no significant correlation between the groove width and particle retention on the leaf surface ($P>0.01$). Stomatal density was significantly positively correlated with TSP, $PM_{>10}$, and $PM_{2.5}$ retention ($P<0.01$). Stomatal size was negatively correlated only with $PM_{2.5}$ retention ($P<0.05$). There was a significant negative correlation between leaf villous number and particle retention ($P<0.05$).

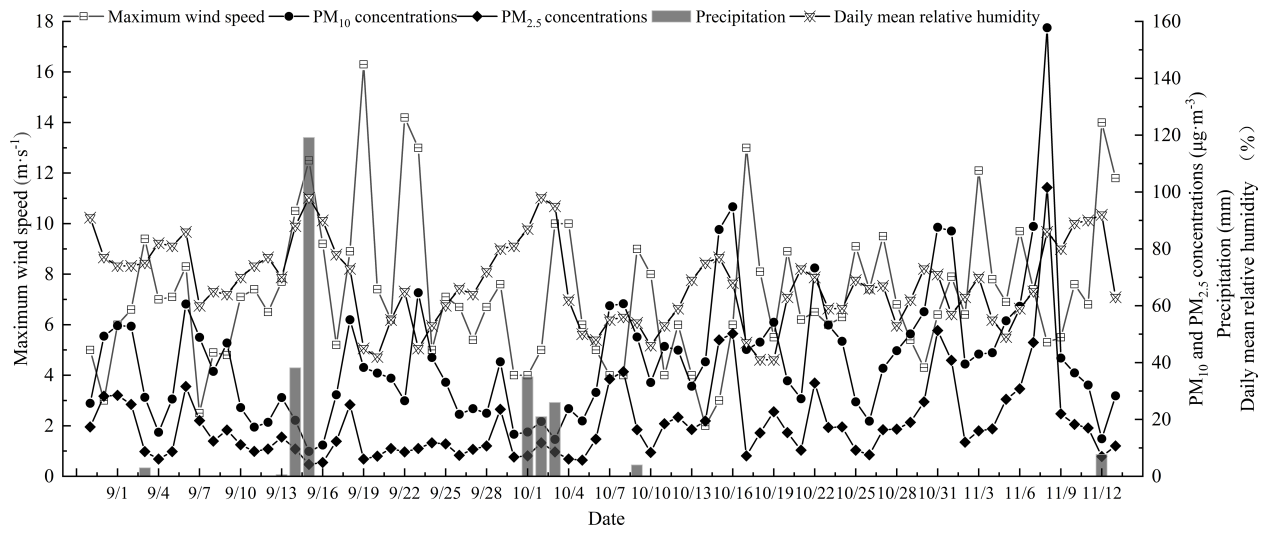

FIGURE 3
Diurnal variation in precipitation, maximum wind speed, PM10, and mean relative humidity.

3.4 Effect of rainfall on the retention of particles of different sizes in lawn grass blades

Rainfall occurred on five days during the sampling period (Figure 3). After rainfall, the elution amount of $PM_{>10}$ on the leaf surface of the tested plants was significantly higher than that of $PM_{2.5\text{-}10}$ and $PM_{2.5}$ ($P<0.05$), and no significant difference in the elution amount of $PM_{2.5\text{-}10}$ and $PM_{2.5}$ was observed (Figure 6). The elution of particles of different sizes on the leaf surface of the tested plants was highest after 7.7 mm of rainfall, followed by 82 and 158 mm of rainfall; particle elution was lowest after 3 and 4 mm of rainfall. However, there were some exceptions; for example, the elution of $PM_{2.5\text{-}10}$ particles on the leaf surface of *F. elata* and *C. dactylon* was the highest after 82 and 152 mm of rainfall, followed by 4 and 7.7 mm of rainfall; the elution of $PM_{2.5\text{-}10}$ particles on the leaf surface of these species was the lowest after 3 mm of rainfall.

The elution amount of particles of diferent sizes on the *C. dactylon* leaf surface was highest after 3 and 4 mm of rainfall (Figure 6). After 7 mm of rainfall, the elution amounts of TSP, $PM_{>10}$, and $PM_{2.5}$ on the leaf surface of *L. spicata* and *Z. sinica* were highest, and the elution amount of $PM_{2.5\text{-}10}$ was highest for

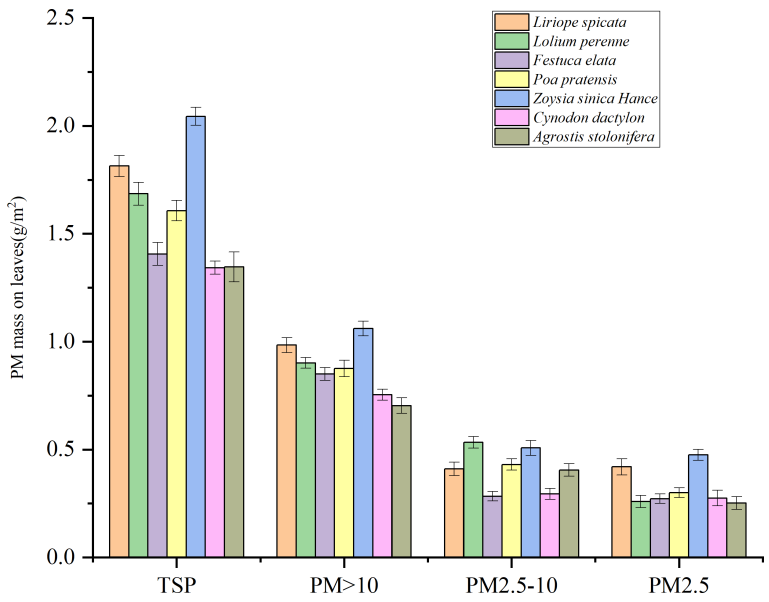

FIGURE 4
Maximum retention of PM of different particle sizes per unit leaf area of the experimental plants. Different lowercase letters indicate significant differences in the retention of PM of a particular size in different turf grasses ($P < 0.05$).

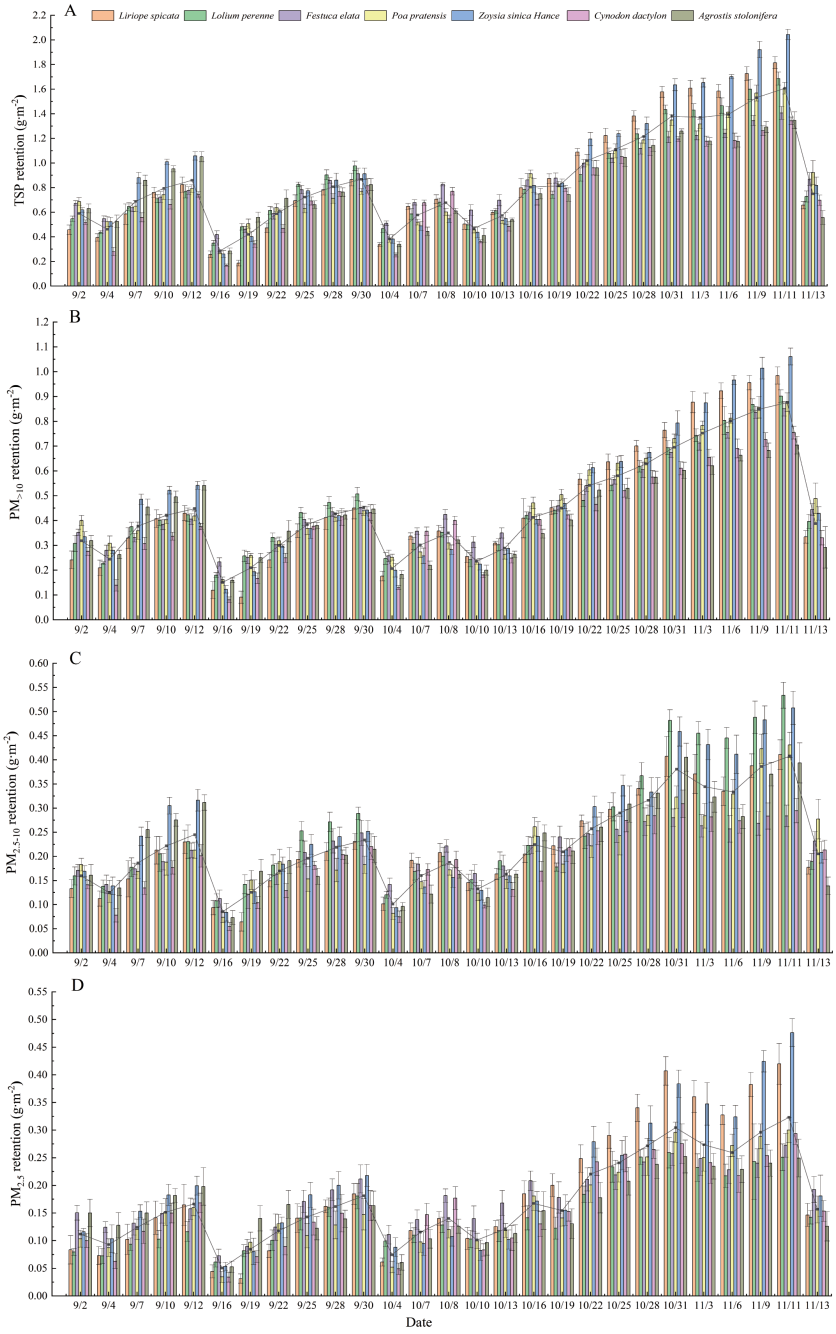

FIGURE 5
TSP, PM>10, PM2.5-10, and PM2.5 retention per unit leaf area of L. spicata, L. perenne, F. elata, P. pratensis, Z. sinica, C. dactylon, and A. stolonifera at each sampling event.

L. perenne. After 82 mm of rainfall, the elution amounts of TSP and $PM_{>10}$ on the leaf surface of the tested plants were highest; the elution amount of $PM_{>10}$ was highest in *C. dactylon*, the elution amount of $PM_{2.5\text{-}10}$ was highest *L. perenne*, and the elution amount of $PM_{2.5}$ was highest in *L. spicata* and *Z. sinica*. After 158 mm of rainfall, the highest amounts of PM were observed in *Z. sinica* and *A. stolonifera*. The total elution amount of each particle size on the leaf surface of the tested plants was highest in *Z. sinica*, followed by *L. spicata*, *C. dactylon*, *A. stolonifera*, *L. perenne*, *P. pratensis*, and *F. elata*.

3.5 Effect of maximum wind speed on the retention of particles of different sizes in lawn grass blades

The effect of maximum wind speed on the TSP retention per unit leaf area of tested plants is shown in Figure 7-1. The TSP retention of the tested plants significantly increased when the maximum wind speed was 9.1, 9.5 and 14.2 $m{\cdot}s^{-1}$. When the maximum wind speed was 12.1, 13, and 16.3 m·s-1, the retention of TSP on the leaf surface of *A. stolonifera*, *P. pratensis*, and *L.*

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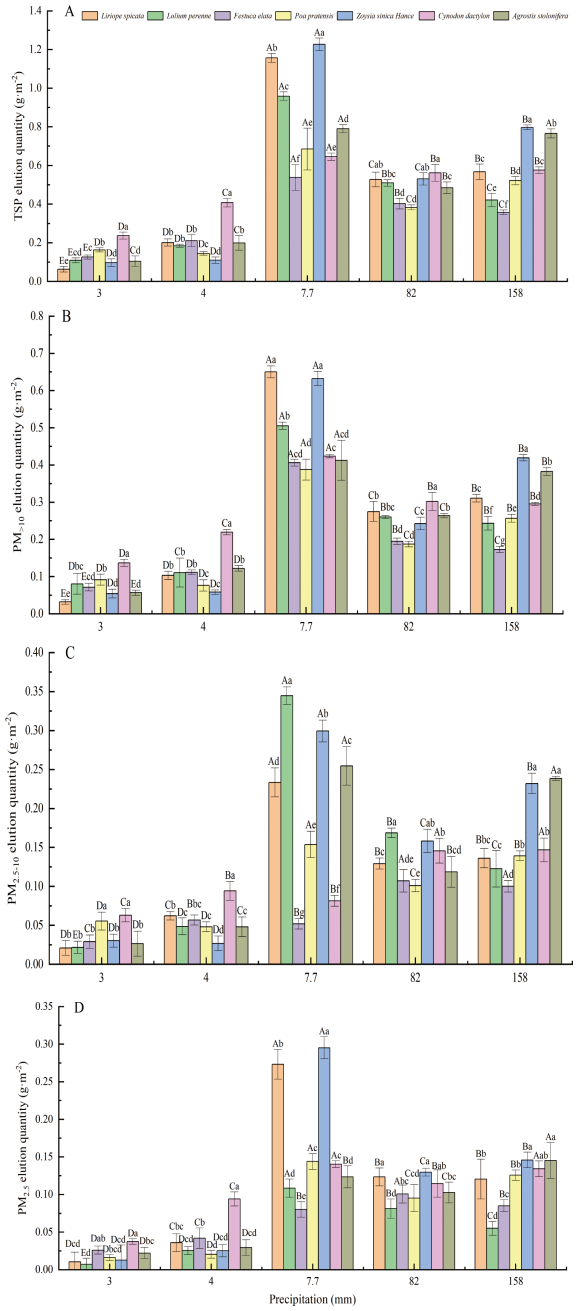

FIGURE 6
The amount of particles of different sizes eluted on the surface of seven types of turfgrass blades after rainfall. Different capital letters indicate significant differences in the retention of PM by the same plant after different amounts of rainfall; different lowercase letters indicate significant differences in the retention of PM by different plants after the same amount of rainfall.

spicata significantly decreased, respectively. Maximum wind speed did not significantly weaken the retention of $PM_{>10}$ per unit leaf area of turfgrass (Figure 7-2). The retention of $PM_{>10}$ in *L. spicata* leaves decreased by 0.03 g·m-2 after exposure to a maximum wind speed of 16.3 m·s-1, but this reduction was not significant (P >0.05). The effect of maximum wind speed on the retention of PM2.5-10 on the leaf surface of tested plants is shown in Figure 7-3. After exposure to maximum wind speeds of 9.1, 9.5, and 14.2 m·s-1, the retention of $PM_{2.5-10}$ on the leaf surface of the tested plants increased significantly. Significant increases and decreases in the retention of $PM_{2.5-10}$ on the leaf surface of the tested plants were observed following exposure to maximum wind speeds of 9.7, 13, and 16.3 m·s-1. After exposure to a maximum wind speed of 12.1 m·s-1, the retention of $PM_{2.5-10}$ on the leaf surface of the tested plants was significantly reduced. The effect of maximum wind speed on the retention of $PM_{2.5}$ per unit leaf area of lawn grasses is shown in Figure 7-4. The retention of $PM_{2.5}$ significantly increased following exposure to the maximum wind speeds of 9.1, 9.5, 14.2, and 16.3 m·s-1. The retention of $PM_{2.5}$ significantly decreased following exposure to maximum wind speeds of 9.7, 12.1, and 13 $m{\cdot}s^{-1}$.

Following exposure to maximum wind speeds, the reduction in particle retention on the middle surface of the tested plants was highest in *L. spicata*, followed by *A. stolonifera*, *Z. sinica*, *L. perenne*, *P. pratensis*, *C. dactylon*, and *F. elata*. When the grass blades contain a certain amount of dust, a maximum wind speed greater than 9.7 m·s-1 reduced the retention of TSP, $PM_{2.5-10}$, and $PM_{2.5}$ on the surface of the blades; maximum wind speed significantly promoted the retention of $PM_{>10}$. In addition, when the dust retention of grass blades is low, a maximum wind speed of 16.3 $m{\cdot}s^{-1}$ did not reduce the dust retention of grass blades.

3.6 Effects of PM_{10} concentration, $PM_{2.5}$ concentration, and relative humidity on the retention of particles of different sizes of lawn grass blades

The average daily PM_{10} concentration and average daily $PM_{2.5}$ concentration were significantly positively correlated with the retention of particles of different sizes on the leaf surface of turfgrass ($P<0.05$) (Figure 8). There was no significant correlation between the average daily relative humidity and the retention of particles of different sizes on the leaf surface of turfgrass ($P>0.05$).

4 Discussion

4.1 Dust retention of the leaves of different plants and dynamic changes

The dust retention ability of the leaves of plants varies extensively among species and is affected by the roughness of leaves (Beckett et al., 1998), the shape and amount of lint (Rasanen et al., 2013), the groove proportion and groove width (Sabin et al., 2006), the content of wax (Saebo et al., 2012), and wettability and other factors (Leonard et al., 2016; Nowak et al., 2006; Rasanen et al., 2013; Speak et al., 2012). Sabin et al. (2006) found that the roughness of the leaf surface, the number of villi, and the content of mucous oil were positively correlated with the amount of dust retention on the leaf surface. Rasanen et al. (2013) also found that more particles could be retained in the foliage of plants with more villous, higher wettability, and low stomatal density. Kwak et al. (2020) concluded that stomatal size

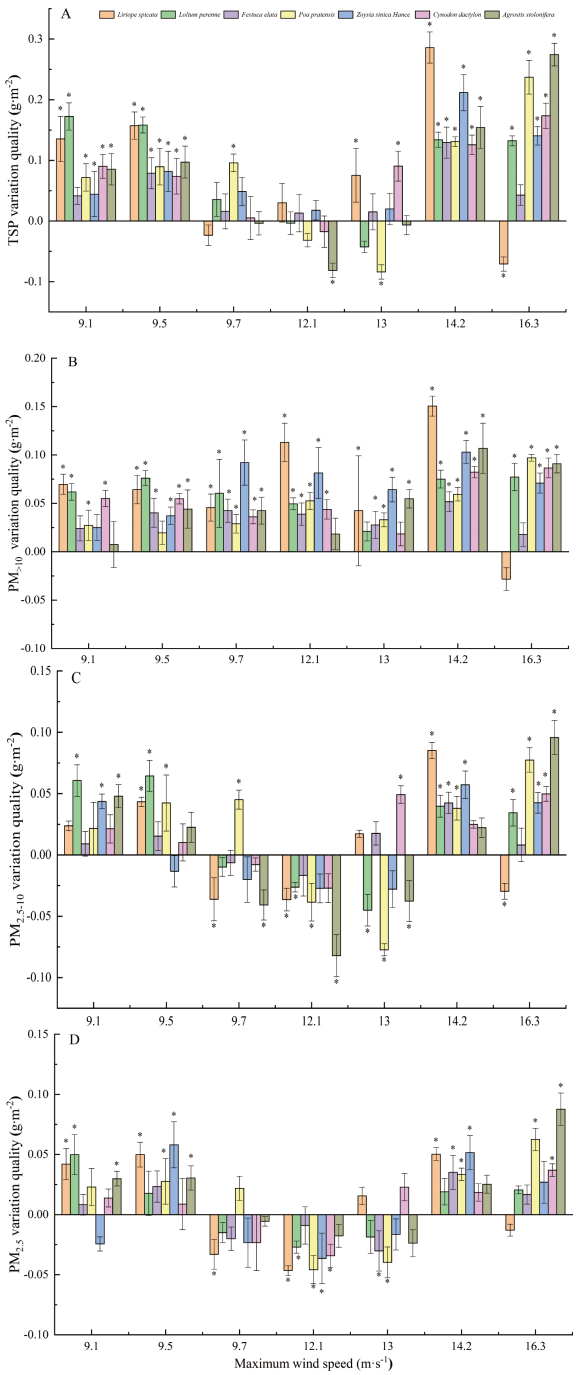

FIGURE 7
Variation in particles of different sizes on the surface of seven types of turfgrass blades after exposure to the maximum wind speed. (* indicates significant differences in the retention of particles on the leaves between two samples according to LSD tests).

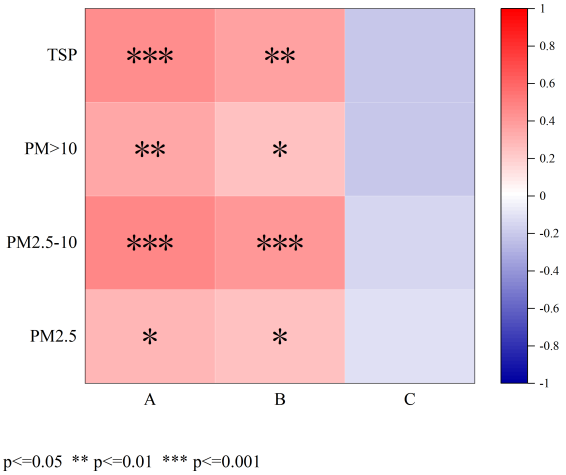

FIGURE 8
Relationship of PM10 concentration, PM2.5 concentration, and relative humidity with the retention of particles of different sizes on the blade surface. "A" stands for "PM10 concentration," "B" stands for "PM2.5 concentration," and "C" stands for "Relative humidity.".

may be significantly related to the adsorption capacity of $PM_{2.5}$ on the leaf surface, and stomatal density, capillary density, and roughness have weak effects on PM adsorption (Kwak et al., 2020). Li et al. suggested that a deeper surface texture of plant leaves was conducive to the capture of a greater number of particles. In addition, pore diameter length was significantly negatively correlated with PM retention, and pore density was significantly positively correlated with PM retention (Li et al., 2024).

The microstructure and characteristics of leaf surfaces play a pivotal role in the deposition and retention of PM. Leaf surfaces with dense villous and undulations significantly contribute to $PM_{2.5}$ retention, as these structures provide increased surface area for particle adhesion through physical forces such as van der Waals forces or electrostatic interactions. The retention capacity is also influenced by the leaf's roughness, with larger undulations enhancing the capture of PM_{10}, suggesting that the physical texture of the leaf surface is crucial for PM retention (Prigioniero et al., 2023). Moreover, the specific variations in leaf microstructures can influence the phyllosphere microbial community by providing distinct microhabitats for PM-borne microorganisms. Dense leaf villous facilitate the capture of $PM_{2.5}$ associated fungi, while bacteria are less impacted by PM and struggle to adhere to leaf microstructures (Xu et al., 2024).

The results of this study showed that the proportion of grooves and stomatal density were positively correlated with dust retention on the leaf surface, which was consistent with the results of previous studies. However, we found a negative correlation between the total amount of particles and particle retention, which is inconsistent with the results of previous studies. This can be explained by the fact that the leaves of Radix ophiopogonicum, which showed high dust retention in our study, lack a villous surface and a waxy layer. However, *A. stolonifera* and *C. dactylon* have a villous surface, but the dust retention of these surfaces is low. This indicates that the microstructural characteristics of the leaf surface affect the dust retention of the leaves, and the dust retention of the leaves is affected by various factors.

The dust retention of plants is affected by meteorological factors, such as precipitation, wind, and dust, and dust retention and dust fall occur simultaneously. Dust retention is thus a complex

process. However, this study found that the overall dust retention still increased gradually, and some particles remained in the leaf surface of the seven plants tested after precipitation and maximum wind speed, indicating that precipitation and wind speed can only remove some particles, but their changes are different. Before rainfall, the retention of particles of each particle size increased with the increase of dust retention days. The variation of particle size after rainfall compared with that before rainfall showed a trend of TSP(0.17-2.04g $\cdot m^{-2}$) >$PM_{>10}$(0.08-1.06 $g \cdot m^{-2}$)>$PM_{2.5\text{-}10}$(0.05-0.53g $\cdot m^{-2}$) >$PM_{2.5}$(0.03-0.48g $\cdot m^{-2}$). This is consistent with the results of previous studies (Łukowski et al., 2020; Popek et al., 2013; Xu et al., 2022). In addition, precipitation can effectively impact TSP and $PM_{>10}$, and $PM_{2.5\text{-}10}$ and $PM_{2.5}$ are more sensitive to wind speed. However, in this experiment, the maximum wind speed on September 19 and 22 did not reduce the amount of dust retention on the grass leaf surface of the lawn, possibly because the strong rainfall on September 14 and 15 had washed most of the particles on the leaf surface, and the maximum wind speed could no longer have a great impact on the variation of particles.

4.2 Effect of rainfall on leaf PM retention

The effect of rainfall on the retention of foliar particles varies; greater rainfall is generally thought to promote the elution of foliar particles (Yan et al., 2019; Zhou et al., 2021). In this study, the leaf PM elution amount was higher after 7.7 mm of rainfall than after 82 and 158 mm of rainfall, indicating that the leaf PM elution amount was not only affected by rainfall but also correlated with the accumulation of PM on the surface of plant leaves and the dust retention ability of plant leaves (Dzierzanowski et al., 2011; Popek et al., 2013). Species with rough leaf surfaces can capture more PM (Saebo et al., 2012), which in turn allows more PM to be washed away under the same amount of rainfall (Xu et al., 2017). In addition, 15 mm of precipitation is generally thought to be sufficient to wash all of the PM off the leaf surface, which initiates a new round of PM retention (Liu et al., 2013; Przybysz et al., 2014). In this study, even after a rainfall event of 158 mm, PM remained on the leaf surface of the tested plants, indicating that precipitation could not completely remove PM on the leaf surface (Przybysz et al., 2014; Xu et al., 2019).

We observed significant differences in the elution amounts of particles of different particle sizes on the leaf surface of tested plants under different amounts of rainfall; the cleaning effect of rainfall on particles on the leaf surface of different plants was closely related to the morphology of the leaf surface, including the grooves and villous (Chen et al., 2017). Leaf surfaces with densely ridged grooves can firmly hold a large number of particles (Wang et al., 2015). The leaves of *C. dactylon* leaves have many narrow grooves. During rainfall, raindrops first hit the leaves and splash the dust particles intercepted by the leaves; the raindrops then collect on the leaf surface and form runoff. In addition, the grooves are shallow, and the particles mostly rest on the leaf surface, which makes the particles easier to displace. This may be the reason why the particle elution rate on the leaf surface was higher under low amounts of rainfall; *F. elata* King has fewer and wider grooves with some microvillous. Grass leaves have villous and globular bulges, their grooves are not obvious, and their surfaces are rough. This may be the reason for the high particle elution rate on the leaf surface of *F. elata* and *Poa annua*, which is consistent with the results of Perini et al. indicating that leaf surface villous can reduce the strength of the scouring effect of rainfall events on leaf surface PM (Perini et al., 2017). Zhou et al. (2021) also found that the leaf surface dust retention capacity of P. annua was strong after rain. The amount of PM eluting on the *L. spicata* leaf surface was also high, and its leaf surface is smooth but villousless. Particles on plants with smooth leaf surfaces can be easily removed by rain (Beckett et al., 2010).

Previous studies suggest that precipitation can effectively wash out particles greater than 10 μm in size, and the ability of precipitation to displace $PM_{2.5\text{-}10}$ and $PM_{2.5}$ is poor (Przybysz et al., 2014; Wang et al., 2015; Xu et al., 2019; Zhou et al., 2020); however, these studies were all conducted on trees or shrubs. The effect of rainfall on the removal of PM from the leaf surface of herbs was stronger than on the removal of PM from the leaf surface of trees and shrubs (Zhou et al., 2021). Tomson et al. (2024) studied the removal effect of rainfall on PM on the leaf surface of green wall plants and found that rainfall had a significant scouring effect on small particles (PM_1 and $PM_{10-2.5}$). The scouring rate of large particles ($PM_{10-2.5}$) was relatively low (Tomson et al., 2024). In our study, the elution amount of $PM_{>10}$ was significantly greater than that of $PM_{2.5\text{-}10}$ and $PM_{2.5}$, but the elution amount of $PM_{2.5\text{-}10}$ and $PM_{2.5}$ also increased as the amount of rainfall increased, which was consistent with the results of Zhou et al. (2021). This might be related to two factors. First, the particles retained on the surface of lawn grass blades are mostly resting on the surface; they can thus be easily removed (Prusty et al., 2005; Wang et al., 2007). Second, turfgrass blades are mostly linear or lance-shaped, and there are several grooves in the blades; the raindrops form leaf surface runoff on the blade surface, which can mediate the removal of particles.

Based on the amount of dust retained on each type of lawn grass after rainfall, the content of retained PM of the seven lawn grasses was lowest after 82 mm and 158 mm of rainfall, and more PM remained on the leaf surface after 7.7 mm of rainfall; the difference between rainfall of 7.7 mm and 82 mm was substantial. The amount of rainfall that results in the optimal removal effect on the tested plants requires further study. In addition, the particle elution amount after 7.7 mm of rainfall was significantly higher than that after 82 mm and 158 mm of rainfall, indicating that the particle elution amount is not only related to rainfall but also to the content of retained particles on the leaf surface.

4.3 Effect of wind speed on leaf PM retention

The effect of different wind speeds on plant dust retention varies. Freer-Smith et al. (2004) found that when the wind speed increased from 3 $m \cdot s^{-1}$ to 9 $m \cdot s^{-1}$, the particle deposition rate

increased, and the deposition rate of conifers was greater than that of deciduous trees. Beckett et al. suggested that when the wind speed is less than 8 m·s, the particle adsorption capacity increases as the wind speed increases, but continued increases in the wind speed may lead to a decrease in the particle adsorption capacity (Beckett et al., 2010). The relationship between the dust retention and wind speed of seven turfgrass species in this study was consistent with the findings of the above studies. When a certain amount of dust is present on the surface of turfgrass blades, a maximum wind speed of 9.1 $m{\cdot}s^{-1}$ can lead to a reduction in leaf PM retention; the leaf PM retention was not reduced, even if the maximum wind speed was 16.3 $m{\cdot}s^{-1}$. However, this leads to an increase in the retention of PM on the leaf surface.

Under high winds, the maximum reduction in total PM was 3.1 times higher in *L. spicata* than the lowest reduction in total PM observed in *F. elata*. Generally, the surface of the leaves is rough, the depth of the folds and grooves varies, and the amount of villous and waxy mucus on the surface is large; these all facilitate the interception and adsorption of PM and dust retention (Sgrigna et al., 2016; Weerakkody et al.,2018a). In contrast, leaves with a relatively smooth surface, a regular distribution of pores, and shallow and sparse grooves have a relatively weak dust retention ability (Weerakkody et al., 2018). In this study, the leaf surface of *L. spicata* is smooth, and the particles on the leaf surface can be easily displaced by wind; however, the leaf surface of *F. elata* has wide grooves, and the particles between the grooves contact the leaf surface and enter the villous; once attached to the villous, the particles are difficult to dislodge.

4.4 Effect of the PM_{10} concentration, $PM_{2.5}$ concentration, and relative humidity on leaf PM retention

The concentration of PM in the air is correlated with the amount of dust retained on the leaves (Dang et al., 2022; Liu et al., 2013). Mori et al. (2015) found that the distribution of dust retained in highway shelterbelts was highly correlated with the PM_{10} concentration. Liu et al. found that the dust accumulation of leaves in industrial areas was higher than that in clean areas (Liu et al., 2013). Dang et al. (2022) also found that the retention of PM by plants is positively correlated with air quality, and the retention of TSP, PM_{10}, and $PM_{2.5}$ by plants is greater in industrial areas than in non-industrial areas. In this study, the direct effects of the PM10 concentration and $PM_{2.5}$ concentration on the dust retention of seven turfgrass species were all positive, and changes in PM_{10} and $PM_{2.5}$ concentrations were consistent with changes in $PM_{2.5\text{-}10}$ concentrations, which was consistent with the results of previous studies.

The increase in relative humidity can condense particles in the air; at the same time, particles become larger by absorbing moisture in the air, which is conducive to particle sedimentation (Ruijgrok et al., 1997). During the study period, high relative humidity occurred mostly before and after rainfall, and the dust retention on the grass leaf surface was significantly affected by rainfall. Therefore, a clear correlation between relative humidity and dust retention on the grass leaf surface was not detected.

The relative humidity was high mostly a few days before or after rainfall. At this time, the effect of rainfall on the dust retention of the grass leaf surface was stronger, and a clear correlation between relative humidity and dust retention on the surface of grass leaves was not observed.

5 Conclusions

There were significant differences in the retention of TSP, $PM_{>10}$, $PM_{2.5\text{-}10}$, and $PM_{2.5}$ on the blades of seven turfgrass species, and the dust retention ability of *Z. sinensis* was the strongest among all species tested. The dust retention on the leaf surface decreases after exposure to rainfall and wind, and this promotes the subsequent retention of dust particles. Weather factors had the strongest and weakest effect on the dust retention ability of *Z. sinensis* and *F. elata*, respectively. Rainfall can effectively elute particles of different sizes retained on lawn grass blades, and the amount of particles eluted increases as the amount of rainfall increases. In addition, the elution amount $PM_{>10}$>$PM_{2.5\text{-}10}$>$PM_{2.5}$. When the leaf surface of the plants had a certain amount of dust, a maximum wind speed greater than 9.7 $m{\cdot}s^{-1}$ reduces the amount of dust retained on the leaves, and a maximum wind speed of 16.3 $m{\cdot}s^{-1}$ does not reduce the amount of dust retained on grass leaves when the amount of dust retained on the grass blades is low. PM_{10} and $PM_{2.5}$ concentrations in the environment were positively correlated with the retention of particles of different sizes on the leaf surface.In short, rainfall, maximum wind speed, and PM_{10} concentrations have significant effects on the ability of plant leaves to retain atmospheric particles. In practical applications, *Zoysia sinensis* and *Festuca elata* can be preferentially selected according to climatic conditions in different regions to reduce particulate matter in the air.The effects of these factors should be taken into account in studies of the accumulation of atmospheric particles on plant leaves.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JW: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. WK: Writing – original draft. HL: Data curation, Writing – review & editing. XS: Methodology, Writing – review & editing. YS: Visualization, Writing – review & editing. YL: Investigation, Writing – review & editing.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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