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The ability of three climbing plant species to capture particulate matter and their physiological responses at different environmental sampling sites

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The adsorption of particulate matter (PM) by the leaves of urban plants can effectively reduce the particulate matter concentration in the atmosphere. The use of climbing plants to abate particulate matter is an important means of urban greening in China, which is rich in climbing plant species. In this study, three evergreen climbing plants were selected to assess their ability to adsorb particulate matter and determine their physiological responses to particulate pollution. PM deposition was determined gravimetrically. There were four key results. 1) The adsorption capacity of the three evergreen climbers followed the order of *Hedera nepalensis var* > *Ficus pumila Linn* > *Euonymus fortunei*, and was significantly higher in an overpass environment than in a campus environment for all three species. 2) The seasonal characteristics of particulate adsorption by the three types of climbers in both the overpass and campus environments followed the order of winter > autumn > spring > summer. 3) The net photosynthetic rate of the three climbing plants was significantly affected by particulate matter in a size dependent manner, with fine particulate matter on the plant leaf surface and coarse particulate matter in the leaf waxy layer being important factors affecting plant photosynthesis. 4) Particulate pollution led to changes in the activities of plant protective enzymes in plants, with increases in the superoxide dismutase (SOD) and peroxidase (POD) activity, and the malondialdehyde (MDA) and soluble protein contents. There were different trends in the soluble sugar content among the different plant species. In conclusion, *F. pumila* had a strong resistance to particulate pollutants, while *H. nepalensis* was considered suitable for planting in polluted areas where it could improve ambient air quality by adsorbing large amounts of particulate matter.

KEYWORDS

climbing plant, particulate matter, physiological, leaf waxy, biochemistry

1 Introduction

With the ongoing urbanization and industrial development in China, particulate matter (PM) has become the main atmospheric pollutant in most cities and is used as an important indicator in the evaluation of urban air quality (Zou et al., 2015; Segalin et al., 2016; Li et al., 2019; Nisha et al., 2021). The sources of PM are complex and difficult to manage, with motor vehicle emissions, fossil fuel combustion, and industrial dust being the main sources. Particulate matter is a mixture of harmful substances and other suspended matter in the atmosphere, and is of particular concern due to its extreme toxicity to humans, resulting in more serious health effects than any other air pollutant (WHO, 2019). Various epidemiological studies have shown an association between PM and adverse health effects, including exacerbation of chronic respiratory and cardiovascular disease, impaired lung function, and premature death (Shaughnessy et al., 2015). The severity of the human health effects due to PM exposure varies according to the particle size, with PM2.5 being the most toxic size fraction (Gu et al., 2012; Du et al., 2016; Xiong et al., 2021).

In addition to reducing pollutant emissions, planting vegetation is an effective means of mitigating PM pollution and improving the atmospheric environment of urban areas. Green plants have the potential to clean polluted air by capturing PM on the leaf surface (Chen et al., 2017; Panda et al., 2018; Choi et al., 2021; Zhang et al., 2021), and if PM contains lipophilic organic pollutants, additional sequestration can occur when the particles penetrate the leaf wax (Dzierzanowski et al., 2011). The ability of plants to retain PM is not only related to the planted area, but also has a strong correlation with the plant leaf surface morphology. It has been reported that plant leaves with fuzzy, furrowed surfaces have a stronger dust retention capacity than leaves with smooth, thin, waxy layers (De Nicola et al., 2008; Sæbø et al., 2012; Jaconis et al., 2017). The overall plant retention of PM is a combination of retention on the leaf surface and in the waxy layer, and it has also been shown that the thickness of the waxy layer is a key factor affecting the plant retention of PM (Sun et al., 2018; Choi et al., 2021). Atmospheric pollutants, including PM, can cause changes in plant physiological parameters such as pigment deterioration, changes in antioxidant enzyme activity, production of antioxidant metabolites, and membrane damage (Chaudhary and Rathore., 2018; Singh et al., 2018). It has been reported that PM may block plant stomata leading to a decrease in the net photosynthetic rate and may also cause additional radiation absorption by leaves leading to an increase in leaf surface temperature (Popek et al., 2018; Li M et al., 2021), which can alter the enzyme activity in plants. In addition, PM may also lead to an imbalance in osmotic pressure and an increase in free radicals in plants (Singh et al., 2020). It has been found that the soluble protein content decreases when French sycamore and oleander are exposed to industrial and urban pollution, while peroxidase activity increases (Doğanlar and Atmaca, 2011). Singh observed a significant increase in oxidative stress in mustard under exposure to ozone (O_3), leading to a significant decrease in the photosynthetic pigment and soluble protein content in leaves, while strengthening antioxidant defense systems to resist its effects (Singh et al., 2011; Singh et al., 2020). In summary, PM can enter plants through stomata and affect them by inducing the formation of reactive oxygen species and redox-sensitive signaling pathways that exert toxicity through the synergistic effects of oxidative stress and inflammation (Michael et al., 2013). Therefore, plant response to PM pollution is also one of the most important indicators considered in the selection of tree species used for urban greening.

China has a rich variety of climbing plants, most of which have high ornamental value. Climbing plants do not occupy space at the street level, but use existing building walls, or vertical greening methods on highways and slopes. Vertical greening using climbing plants in urban areas not only expands urban garden space and increases the artistic beauty of urban architecture, but also increases urban green coverage. Climbing plants can also serve as an ideal natural filter to mitigate air pollution (Naomi et al., 2020). However, there have been few studies of the adsorption effects of climbing plants on atmospheric PM. This study analyzed and compared the adsorption of PM by three evergreen climbing plants at different levels of PM pollution and assessed their physiological responses to PM pollution. The results can be used in the selection of climbing species with high PM adsorption and resistance, and will provide a reference for the construction of urban forests.

2 Materials and methods

2.1 Study area and sampling collection

To ensure that the test results were representative of the greening characteristics of the main climbing plants in Nanjing, we selected Himalayan ivy [*Hedera nepalensis* var. sinensis (Tobl.) Rehd], climbing fig (*Ficus pumila* Linn), and Fu Fang vine [*Euonymus fortunei* (Turcz) Hand Mazz] as the test subjects for preliminary research. The climbing plants were growing on bridge pillars in an overpass and on a wall in a university campus. Sampling sites were located at Nanjing Forestry University campus and Yingtian overpass in Nanjing, China. Yingtian overpass is an important section of the Nanjing Inner Ring Expressway. Traffic is heavy, and air pollution caused by vehicle exhaust is a serious problem around the sampling site. Samples were collected in May, August, and November 2021 and January 2022. To evaluate the dust retention ability of different species of climbing plants for different sizes of particulate matter, we selected 28 consecutive days without rainfall for sampling. This

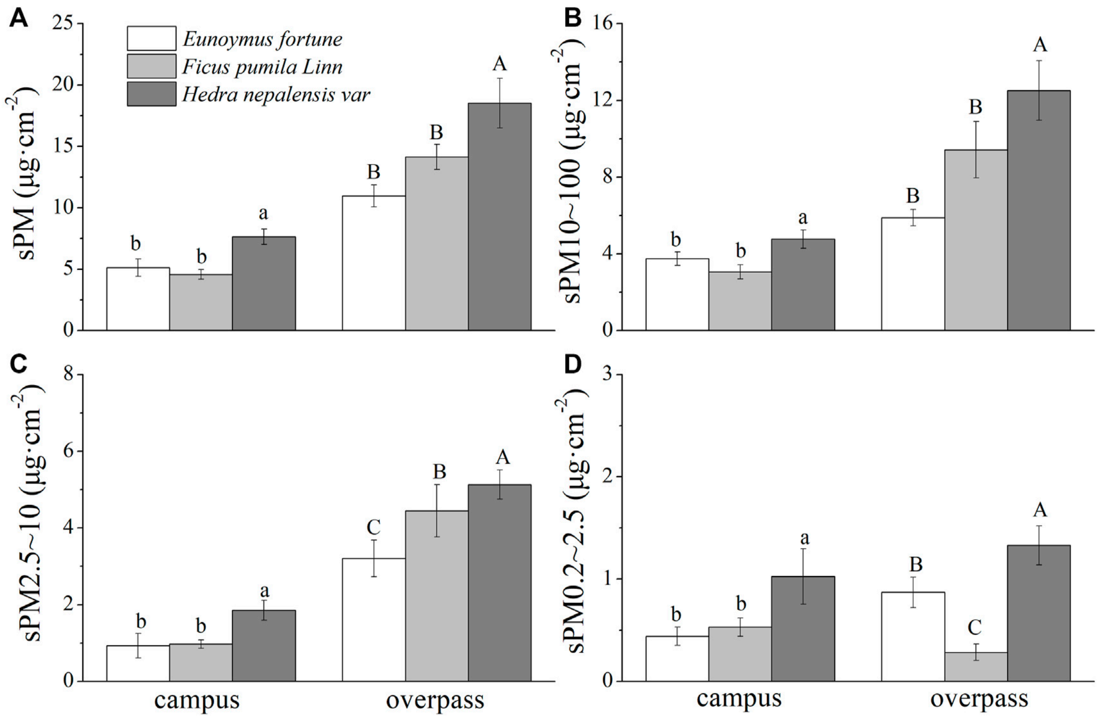


FIGURE 1
The mass of retained particulate matter on the leaf surface in spring (mean ± SE). **(A)** The total mass of particulate matter. **(B)** The mass of PM10–100. **(C)** The mass of PM2.5–10. **(D)** The mass of PM0.2–2.5.*Bars with different letters indicate signigicant differenc ($p < 0.05$) between the sites at a specific season. The same below.

ensured that the dust retention of each type of climbing plant reached a saturation value for particulate matter (Liu et al., 2012).

In this study, mature individuals of three common climbing tree species were studied. To ensure that a representative sample was investigated, a range of tree forms, landscape applications, growth conditions, and leaf characteristics were included. Plants that were in good condition with luxuriant foliage, no pests, and aged between 25 and 30 years were selected. For each species of tree, three climbing trees were selected, and leaves collected randomly in four directions (east, south, west, and north) of column, and in four directions (up, down, left, and right) at 1.0–2.5 m above ground, depending on the plant structure with a pruner. Five sample trees were collected for each climbing tree species, as well as 10 pieces in each direction per plant (200 pieces in total for five plants) for *H. nepalensis*. *E. fortune and F. pumila,* from which 15 leaf samples in each direction were collected, for a total of 60 pieces (300 pieces in total for five plants) as their leaves were small. Samples for the determination of particulate retention were placed in self-sealing bags and brought back to the laboratory. The surface of each leaf was wiped clean and immediately soaked with liquid nitrogen. All samples were placed back into the self-sealing bags and stored in an ultra-low-temperature refrigerator prior to the enzyme assay.

2.2 Extraction and determination of PM on the leaf surface and from the waxy layer

Dust retention was determined using Przbysz's method (Przbysz et al., 2014). Filter papers with pore sizes of 10, 2.5, and 0.2 μm were placed inside half-open weighing bottles in an oven at 60°C for 60 min (Dzierżanowski et al., 2011; Chiam et al., 2019; Kończak et al., 2021; Li X. L et al., 2021). The bottles were then covered for 60 min, removed, and placed in a drying dish until a constant weight was obtained. The dried filters were placed on an analytical balance (readability = 0.0001 g) (ME204E, Mettler Toledo, Columbus, OH, United States) and weighed to obtain both the initial weight of each filter paper (g) and the total initial weight of the weighing bottle and filter paper (g).

Particulate matter on the surface of the leaves that could be washed off by water was referred to as "particulate matter on the surface (sPM)." Leaves were placed into beakers with deionized water and stirred for 1 min with a glass rod. The beakers were placed in an ultrasonic cleaner (JP-020, Skymen, Guangdong, China) and shaken for 1 min to remove the PM adsorbed on the leaf surface. The resulting solution was passed through a standard splitting sieve (160 mesh, pore size of about 100 μm), followed by filtering in turn through filter

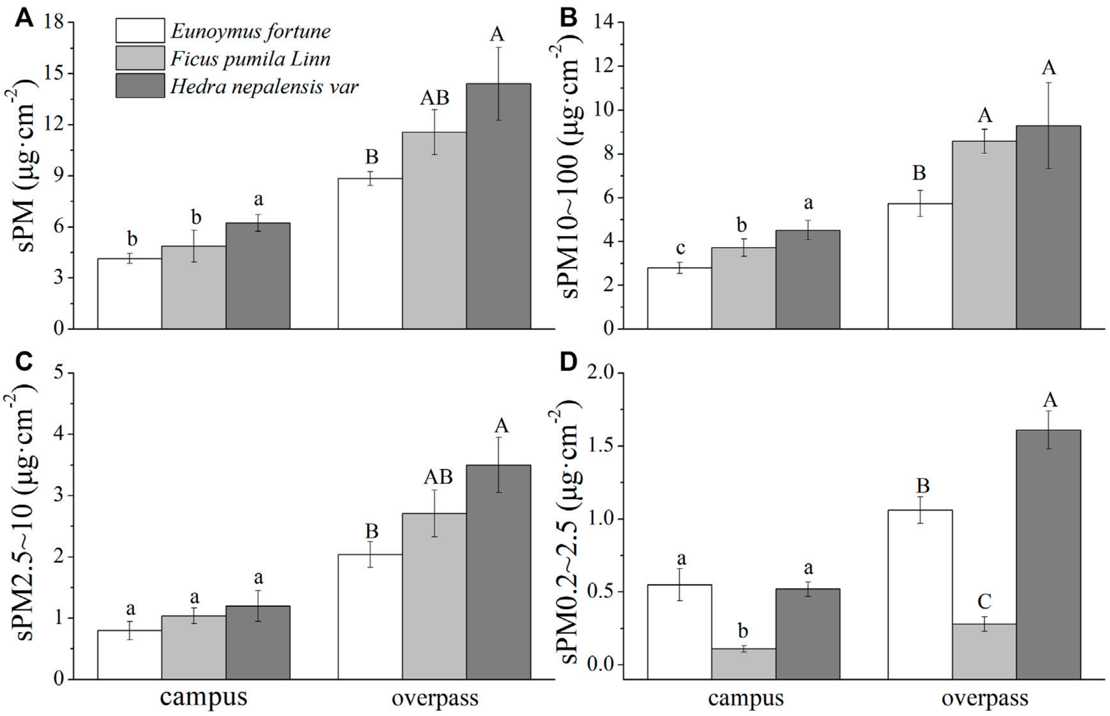


FIGURE 2
The mass of retained particulate matter on the leaf surface in summer (mean ± SE). **(A)** The total mass of particulate matter. **(B)** The mass of PM10–100. **(C)** The mass of PM2.5–10. **(D)** The mass of PM0.2–2.5.

papers with pore sizes of 10 and 2.5 μm to obtain three particle size ranges: large particles of 10–100 μm, coarse particles of 2.5–10 μm, and fine particles of 0.2–2.5 μm. The filter paper was placed into an oven to dry, removed, and left to stand in a drying dish. After reaching a constant weight, the weight of each filter paper after filtration (g) and the total weight of the weighing bottle and filter paper after filtration (g) were determined using an analytical balance. The amount of "surface PM" attached to each sample at each particle size was calculated using the weight difference method.

The mass of PM contained in wax layer (wPM) was detected the rinse and weight method (Dzierżanowski et al., 2011; Chiam et al., 2019). Clean leaf samples were rinsed with deionized water and then rinsed again for 40 s in 150 cm^3 of chloroform to dissolve the epicuticular waxes and wash the micro-particles fixed in the wax to obtain the wPM fraction. The liquid obtained from the rinsing was filtered continuously through a filter according to the procedure used to filter aqueous fractions containing surface PM, with the difference that the chloroform remaining after filtration was poured into an empty pre-weighted clean flask. After the chloroform evaporation (more than 10 or even 48 h), the flasks were weighed on a laboratory microbalance. Then, the difference between the masses of the empty flask and flask containing wax was determined. Filtration was performed following the same procedure used for sPM washing. After drying, the filters were also weighed and the PM was determined based on the difference in weight.

2.3 Leaf area determination

After drying, the leaves were scanned using an electronic scanner (V370, Epson, Nagaon, Japan) and then imported into ImageJ 1.48 software to determine the leaf area, with the leaf area of each sample obtained as S (cm^2).

2.4 Measurement of the photosynthetic parameters of plant leaves

Four leaves from each climbing plant were selected from the upper, middle, and lower well-developed mature parts of the climbing plant. The analytical instrument used for the measurements was a Li-6400 portable photosynthesis meter (Li-COR, Lincoln, NE, United States). Gas exchange parameters, including the maximum net photosynthetic rate (*Pn*), stomatal conductance (*Gs*), intercellular carbon dioxide (CO_2) concentration (*Ci*), and transpiration rate (*Tr*), were measured in May, August, and November

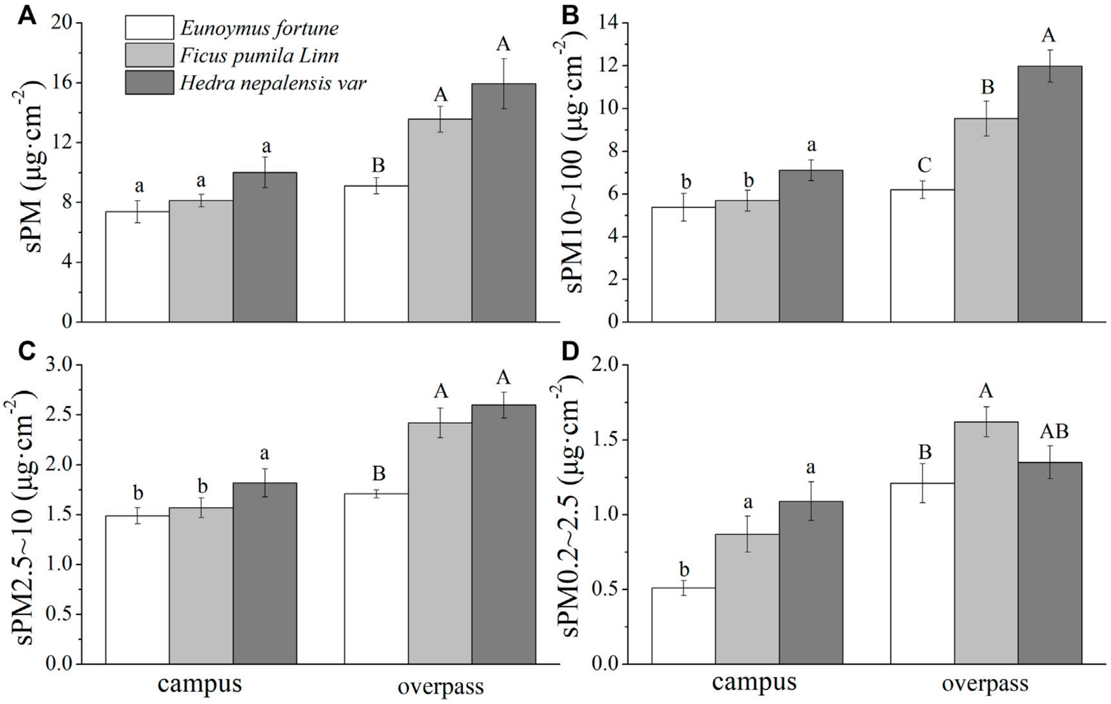


FIGURE 3
The mass of retained particulate matter on the leaf surface in autumn (mean ± SE). **(A)** The total mass of particulate matter. **(B)** The mass of PM10–100. **(C)** The mass of PM2.5–10. **(D)** The mass of PM0.2–2.5.

2021 and January 2022 for the tagged leaves. Mature leaves with healthy growth and a similar growth status were selected for measurements from 09:00 to 11:00 after eight consecutive days without precipitation.

2.5 Determination of the biochemical indexes of plant leaves

About 0.5 g of intact and similarly colored leaf samples were randomly selected from each package of leaves, cut into small pieces, and placed in 5 ml centrifuge tubes with 2 ml of phosphate buffer. The samples were ground with an automatic sample rapid grinder (JXFSTPRP-24, Jingxin Technology, Shandong, China) and then the centrifuge tube was rinsed with extraction medium. The final volume was fixed to 5 ml with the extraction medium, and then the supernatant was extracted with a ST8R centrifuge (Thermo Fisher Scientific, Waltham, MA, United States) at 4,500 rpm for 15 min. The supernatant was then extracted with a 10 ml pipette for the determination of superoxide dismutase (SOD) and peroxidase (POD) activity. Enzyme extract (2.5 ml) was added to 2.5 ml of distilled water for the determination of malondialdehyde (MDA) and soluble protein content.

2.6 Measurement of the photosynthetic parameters of plant leaves

About 0.5 g of intact and similarly colored leaf samples were randomly selected from each package of leaves, cut into small pieces, and placed in 5 ml centrifuge tubes with 2 ml of phosphate buffer. The samples were ground with an automatic sample rapid grinder (JXFSTPRP-24, Jingxin Technology, Shandong, China) and then the centrifuge tube was rinsed with extraction medium. The final volume was fixed to 5 ml with the extraction medium, and then the supernatant was extracted with a ST8R centrifuge (Thermo Fisher Scientific, Waltham, MA, United States) at 4,500 rpm for 15 min. The supernatant was then extracted with a 10 ml pipette for the determination of superoxide dismutase (SOD) and peroxidase (POD) activity. Enzyme extract (2.5 ml) was added to 2.5 ml of distilled water for the determination of malondialdehyde (MDA) and soluble protein content.

2.7 Data processing

The experimental data were subjected to both a one-way and two-way analysis of variance (ANOVA) using SPSS22.0 software,

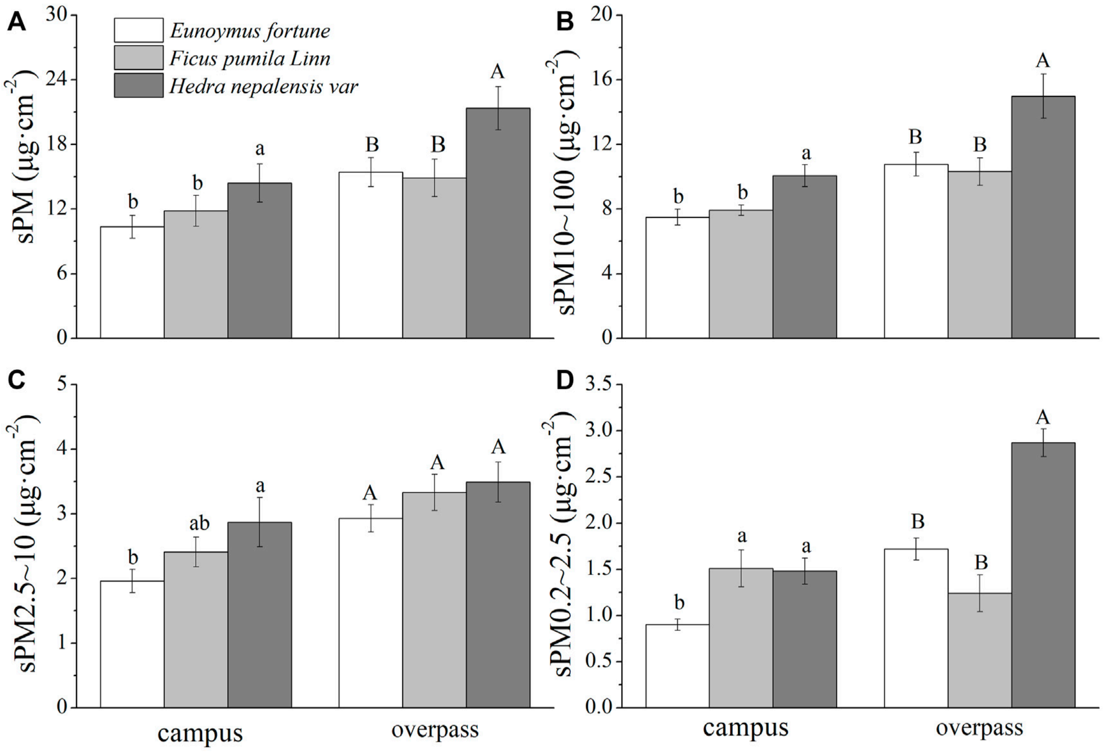


FIGURE 4
The mass of retained particulate matter on the leaf surface in winter (mean ± SE). **(A)** The total mass of particulate matter. **(B)** The mass of PM10–100. **(C)** The mass of PM2.5–10. **(D)** The mass of PM0.2–2.5.

with multiple testing applied to detect whether statistical differences existed between the treatments. Independent sample t-tests were used to rapidly analyze the differences between the physiological and biochemical indices of plants located at the campus and the overpass. Pearson's correlation coefficient was used to analyze the relationship between plant dust retention capacity and photosynthetic gas parameters. Plots were constructed using Origin 2016 software.

3 Results

3.1 The mass of PM retained on leaf surface in different seasons

There were significant differences in the mass of the different sizes of PM among the different species in spring (Figure 1). Both campus and overpass *H. nepalensis* had a significantly higher adsorption capacity for total suspended particulate (TSP) and the different particle size classes of PM than the other two climbers, with overpass *H. nepalensis* adsorbing sPM (18.97 ± 2.03 $\mu g\ cm^{-2}$) (Figure 1A), sPM10–100 (12.51 ± 1.56 $\mu g\ cm^{-2}$) (Figure 1B), sPM2.5–10 (5.13 ± 0.38 $\mu g\ cm^{-2}$) (Figure 1C), and sPM0.2–2.5 (1.33 ± 0.15 $\mu g\ cm^{-2}$) (Figure 1D). In addition, the adsorption of PM2.5–10 was significantly higher ($p < 0.05$) in *F. pumila* at the overpass than in *E. fortunei*, and the adsorption of PM0.2–2.5 was significantly higher ($p < 0.05$) in *E. fortunei* than in *F. pumila*.

The maximum retention of the different particle sizes by *H. nepalensis* in summer at the overpass was sPM (15.94 ± 1.67 $\mu g\ cm^{-2}$) (Figure 2A), sPM10–100 (11.99 ± 0.75 $\mu g\ cm^{-2}$) (Figure 2B), sPM2.5–10 (2.60 ± 0.13 $\mu g\ cm^{-2}$) (Figure 2C), and sPM0.2–2.5 (1.35 ± 0.11 $\mu g\ cm^{-2}$) (Figure 2D). Campus *H. nepalensis* adsorbed significantly more sPM and sPM10–100 than the other two climbers, and campus *H. nepalensis* and *E. fortunei* adsorbed significantly more sPM0.2–2.5 than *F. pumila* ($p < 0.05$) There was no significant difference in the adsorption of sPM2.5–10 among the three plants. The adsorption of sPM and the different particle size classes by *H. nepalensis* at the overpass was significantly higher than that by *E. fortunei* ($p < 0.05$). There was no significant difference between the adsorption of sPM, sPM10–100 and sPM2.5–10 by *H. nepalensis* and *F. pumila*, but the adsorption of sPM0.2–2.5 by the three climbing plants was significantly different ($p < 0.05$).

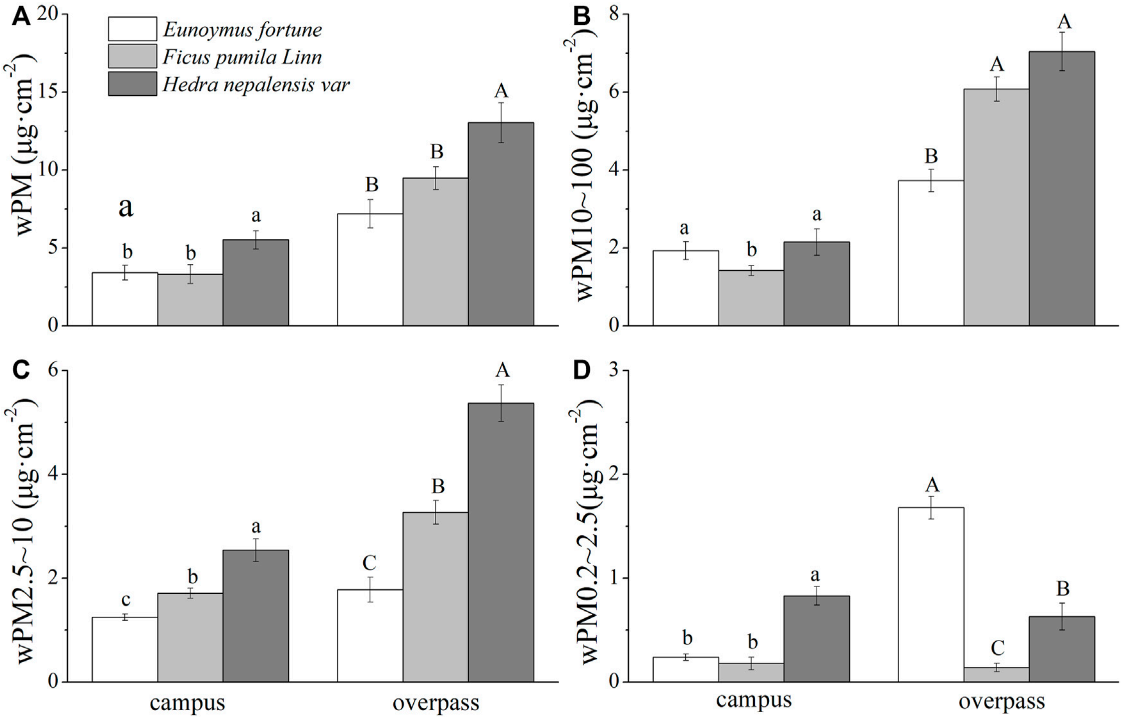


FIGURE 5
The mass of retained particulate matter on the leaf wax layer in spring (mean ± SE). **(A)** The total mass of particulate matter. **(B)** The mass of PM10–100. **(C)** The mass of PM2.5–10. **(D)** The mass of PM0.2–2.5.*Bars with different letters indicate signigicant differenc (p < 0.05) between the sites at a specific season. The same below.

In autumn, *H. nepalensis* at the overpass had the highest adsorption among the particles of different particle sizes, sPM (14.41 ± 2.14 μg cm^{-2}) (Figure 3A), s PM10–100 (9.29 ± 1.97 μg cm^{-2}) (Figure 3B), sPM2.5–10 (3.50 ± 0.45 μg cm^{-2}) (Figure 3C), and sPM0.2–2.5 (1.61 ± 0.13 μg cm^{-2}) (Figure 3D). A one-way ANOVA showed that there was no significant difference in sPM adsorption by the three climbers at the campus. The adsorption of sPM10–100 and sPM2.5–10 by *H. nepalensis* was significantly higher than that of *F. pumila* and *E. fortunei* (p < 0.05), and the adsorption of sPM0.2–2.5 by *H. nepalensis* and *F. pumila* was significantly higher than that of *E. fortunei* (p < 0.05). The adsorption of sPM and sPM2.5–10 by *H. nepalensis* and *F. pumila* at the overpass was significantly higher than that of *E. fortunei* (p < 0.05). The adsorption of sPM10–100 by all three plants at the overpass was significantly different (p < 0.05), and the adsorption of sPM0.2–2.5 by *F. pumila* was significantly higher than that of *E. fortunei* (p < 0.05).

The maximum adsorption of the different particle sizes in winter at the overpass for *H. nepalensis* was: sPM (21.35 ± 2.01 μg cm^{-2}) (Figure 4A), sPM10–100 (14.99 ± 1.36 μg cm^{-2}) (Figure 4B), sPM2.5–10 (3.49 ± 0.31 μg cm^{-2}) (Figure 4C), and sPM0.2–2.5 (2.87 ± 0.15 μg cm^{-2}) (Figure 4D). The adsorption patterns of the three climbers for sPM and sPM10–100 were consistent across sampling sites, with all having a significantly higher adsorption of sPM and sPM10–100 by *H. nepalensis* than by *F. pumila* and *E. fortunei* (p < 0.05). The adsorption of sPM2.5–10 and sPM0.2–2.5 at the campus by *H. nepalensis* and *F. pumila* was significantly higher than that of *E. fortunei* (p < 0.05). The adsorption of sPM2.5–10 by the three climbers at the overpass was not significantly different, and the adsorption of sPM0.2–2.5 by *H. nepalensis* was significantly higher than that of the other two climbers (p < 0.05).

3.2 The mass of PM retained on the leaf wax layer in different seasons

The adsorption of PM, PM10–100, and PM2.5–10 was highest in the leaf wax layer of *H. nepalensis* in the spring at the overpass, with values of 13.04 ± 2.28 μg cm^{-2} (Figure 5A), 7.05 ± 0.69 μg cm^{-2} (Figure 5B), and 5.37 ± 0.35 μg cm^{-2} (Figure 5C), respectively, and the adsorption of PM0.2–2.5 was highest in the leaf wax layer of *E. fortunei* (1.68 ± 0.3 μg cm^{-2}) (Figure 5D). The adsorption of PM and PM2.5–10 by the waxy layer of *H. nepalensis* leaves in both the campus and overpass was significantly higher than that of the other two climbers (p < 0.05), and the adsorption of

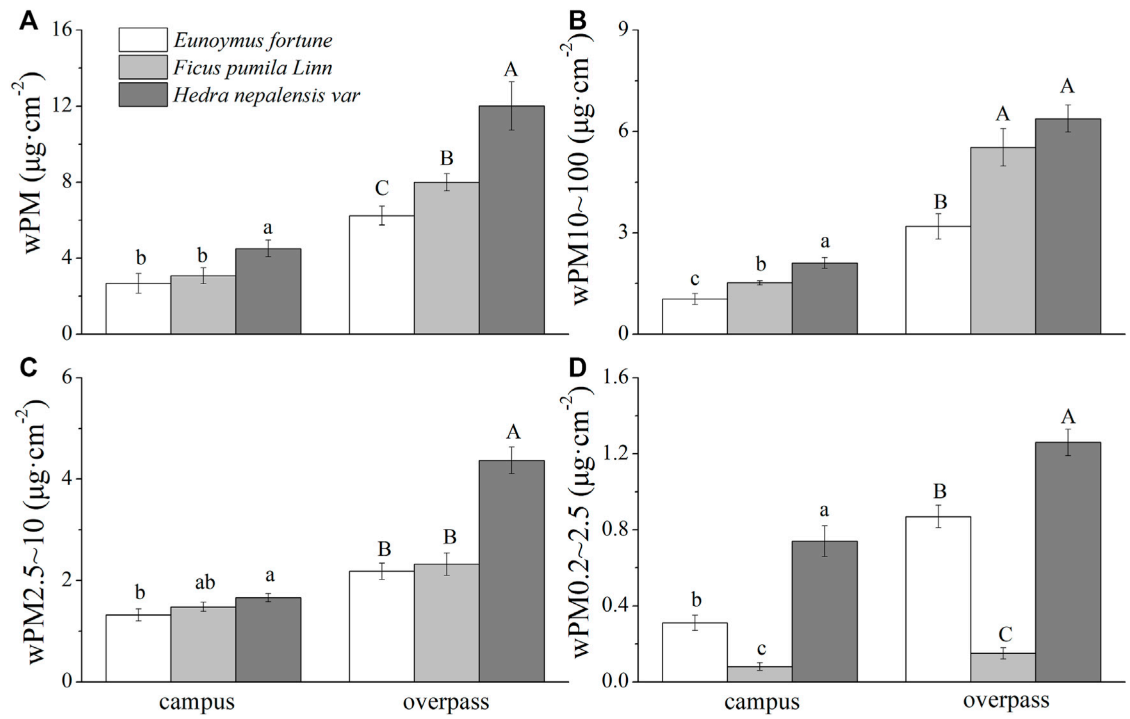


FIGURE 6
The mass of retained particulate matter on the leaf wax layer in summer (mean ± SE). **(A)** The total mass of particulate matter. **(B)** The mass of PM10–100. **(C)** The mass of PM2.5–10. **(D)** The mass of PM0.2–2.5.

PM10–100 by the waxy layer of *H. nepalensis* and *E. fortunei* leaves was significantly higher than that of *F. pumila* ($p < 0.05$). The adsorption of PM0.2–2.5 by the waxy layer of *H. nepalensis* leaves at the campus was significantly higher than that of the other two climbers ($p < 0.05$). The adsorption of PM0.2–2.5 by the waxy layer of the leaves of *E. fortunei* at the overpass was significantly higher than that of the other two climbers ($p < 0.05$).

The adsorption of PM by the waxy layer of H. *nepalensis* leaves at both the campus and the overpass reached a maximum in summer. The adsorption of PM of different particle sizes by the *H. nepalensis* leaves at the overpass was: wPM (10.83 ± 0.52 μg cm^{-2}) (Figure 6A), wPM10-100 (7.93 ± 0.36 μg cm^{-2}) (Figure 6B), and wPM0.2–2.5 (1.03 ± 0.15 μg cm^{-2}) (Figure 6D). Overall, the adsorption of PM, PM10–100 (Figure 5C), and PM0.2–2.5 by the waxy layer of campus *H. nepalensis* leaves was significantly higher than that of the other two climbers ($p < 0.05$), and the adsorption of PM, PM2.5–10, and PM0.2–2.5 by the waxy layer of *H. nepalensis* leaves at the overpass was significantly higher than that of the other two climbers ($p < 0.05$).

The adsorption of PM by the waxy layer of *H. nepalensis* leaves at the overpass reached a maximum in autumn for PM (10.83 ± 0.52 μg cm^{-2}) (Figure 7A), PM10–100 (7.93 ± 0.36 μg cm^{-2}) (Figure 7B), PM2.5–10 (1.87 ± 0.21 μg cm^{-2}) (Figure 7C), and PM0.2–2.5 (1.03 ± 0.15 μg cm^{-2}) (Figure 7D). The adsorption pattern of the leaf wax layer of the three climbing plants at the campus was consistent for PM, PM10–100, and PM0.2–2.5, all of which were significantly higher for *H. nepalensis* than for the other two plants ($p < 0.05$). The adsorption pattern of the three plants at the overpass was consistent for PM and PM10–100, i.e., *H. nepalensis* was significantly higher than the other two plants ($p < 0.05$). The adsorption pattern of the three climbing plants was also consistent for PM2.5–10, while there was no significant difference in the adsorption of PM0.2–2.5 among the three climbers ($p < 0.05$).

The adsorption of different particle sizes of PM by the leaf wax layer of all three plants in the winter at the campus was significantly higher for *H. nepalensis* than for the other two plants ($p < 0.05$). The adsorption of different particle sizes of PM by the leaf wax layer of *H. nepalensis* in the overpass was: wPM (10.83 ± 0.52 μg cm^{-2}) (Figure 8A), wPM10–100 (7.93 ± 0.36 μg cm^{-2}) (Figure 8B), and wPM2.5–10 (7.93 ± 0.36 μg cm^{-2}) (Figure 8C). The adsorption patterns of PM, PM10–100, and PM2.5–10 were consistent among the three plants at the overpass, i.e., *H. nepalensis* was significantly higher than the other two plants ($p < 0.05$), and there were significant differences ($p < 0.05$) in the adsorption of PM0.2–2.5 for all three climbers at the overpass (Figure 8D).

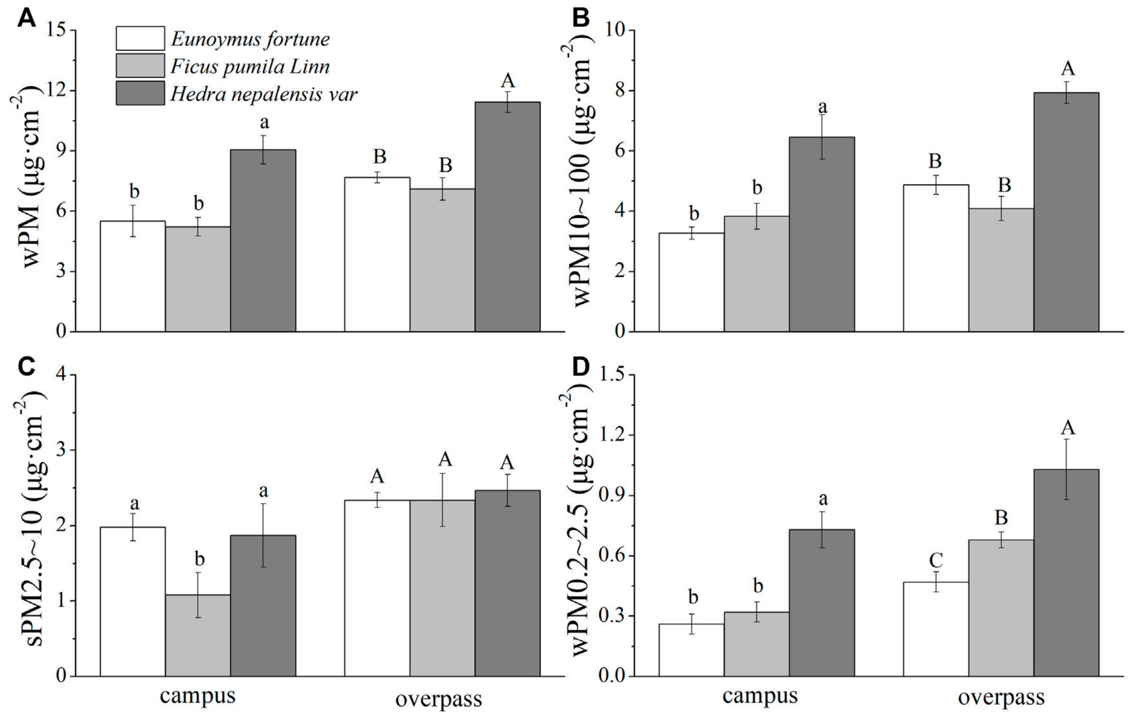


FIGURE 7
The mass of retained particulate matter on the leaf wax layer in autumn (mean ± SE). **(A)** The total mass of particulate matter. **(B)** The mass of PM10–100. **(C)** The mass of PM2.5–10. **(D)** The mass of PM0.2–2.5.

3.3 The photosynthetic gas exchange paremeters response of climbing plants to different levels of PM pollution

The P_n, C_i, and T_r of *F. pumila* leaves on campus were significantly higher than those of the other two climbers in spring. The G_s of *H. nepalensis* leaves reached a maximum on campus, which was significantly higher than that of *E. fortunei*. On the overpass, the P_n of *F. pumila* leaves was significantly higher than that of *E. fortune*. The Gs and Tr of *F. pumila* and *H. nepalensis* leaves were significantly higher than those of *E. fortunei*. The C_i of *H. nepalensis* leaves was significantly higher than that of *E. fortune* (Table.1).

As can be seen from Table 1, the P_n, C_i, and T_R of *E. fortunei* leaves at the campus were significantly higher than for the other two climbers in summer. Additionally, the P_n, T_R, G, and C_i of *E. fortunei* leaves all reached a maximum in the summer. The P_n, G_s, and T_R of the *H. nepalensis* and *F. pumila* leaves at the interchange were significantly higher than those of *E. fortunei*.

The P_n, G_s, C_i, and T_R of *H. nepalensis* and *F. pumila* leaves were significantly higher than those of *E. fortunei* in autumn. The P_n, and G_s of *H. nepalensis* leaves reached a maximum at the overpass, where the P_n, of *H. nepalensis* leaves was significantly higher than those of the other two plants. The C_i and T_R of *H. nepalensis* and *E. fortunei* leaves were significantly higher than those of *F. pumila* at the overpass, and the G_s of the three plants was not significantly different.

The P_n of *F. pumila* leaves was significantly higher than that of *E. fortunei* and *H. nepalensis* leaves in winter at the campus. The C_i of both *E. fortunei* and *H. nepalensis* leaves was significantly higher than that of *F. pumila*. The G_s and transpiration rate of *H. nepalensis* leaves reached a maximum in winter, while the G_s of *H. nepalensis* and *F. pumila* leaves was significantly higher than that of *E. fortunei*, and the T_R of *H. nepalensis* leaves was significantly different. The T_R of *H. nepalensis* leaves was significantly higher than that of the other two plants.

3.4 The physiological and biochemical responses of climbing plants to different levels of PM pollution

3.4.1 Seasonal changes of total SOD activity of plants under different levels of PM pollution

As can be seen from Figure 9, the SOD activity of *H. nepalensis* leaves was significantly higher than that of the other two plants in summer (Figure 9B) and autumn (Figure 9C). The SOD activity of *F. pumila* leaves was significantly higher than that of the other two plants in winter

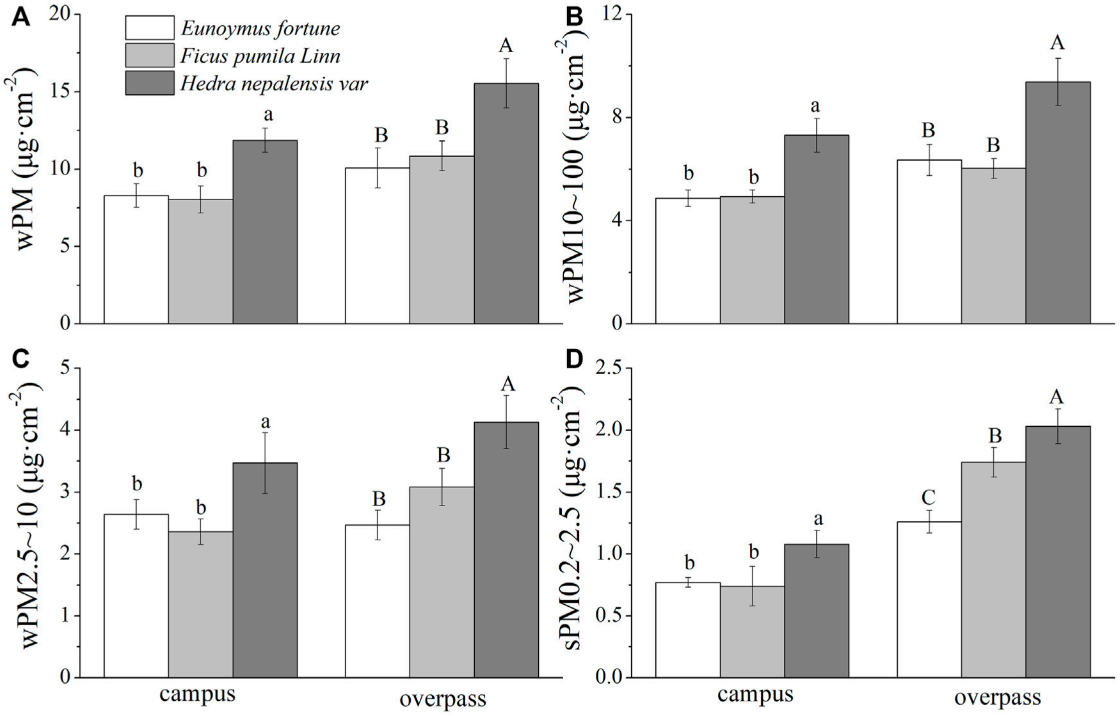


FIGURE 8
The mass of retained particulate matter on the leaf wax layer in winter (mean ± SE). **(A)** The total mass of particulate matter. **(B)** The mass of PM10–100. **(C)** The mass of PM2.5–10. **(D)** The mass of PM0.2–2.5.

at the campus (Figure 9D). At the overpass, the SOD activity of *H. nepalensis* leaves in spring (Figure 9A)and autumn was significantly higher than that of the other two plants, and the SOD activity of *H. nepalensis* and *F. pumila* leaves in summer was significantly higher than that of *E. fortunei* leaves ($p < 0.05$) (Figure 9B). The SOD activity of *F. pumila* leaves in winter at the overpass reached a maximum and was significantly higher than that of the other two plants.

3.4.2 Seasonal changes of plant POD activity under different levels of PM pollution

As can be seen from Figure 10, the POD activity of E. fortunei leaves at the campus reached a maximum in spring (Figure 10A), summer (Figure 10B), and winter (Figure 10D). The POD activity of *E. fortunei* leaves at the campus was significantly higher than that of the other two plants in spring and winter. The POD activity of *E. fortune* and *F. pumila* leaves was significantly higher than that of H. nepalensis leaves in summer, and there was no significant difference in the POD activity of the leaves of the three plants in autumn (Figure 10C). The leaf POD activity of *E. fortunei* was significantly higher than that of the other two plants, and the leaf POD activity of all three plants at the overpass was higher than that at the campus in all four seasons.

3.4.3 Seasonal changes of the MDA content of plants under different levels of PM pollution

As can be seen from the Figure 11, the MDA content of F. pumila leaves reached a maximum at the campus, where the MDA content of *F. pumila* and *H. nepalensis* leaves was significantly higher than that of *E. fortune* leaves in spring (Figure 11A) and summer (Figure 11B). The MDA content of F. pumila leaves was significantly higher than that of *E. fortunei* and *H. nepalensis* leaves in autumn (Figure 11C) and winter (Figure 11D). At the overpass, the leaf MDA content of *H. nepalensis* and *F. pumila* was significantly higher than that of *E. fortunei* in spring; the leaf MDA content of *E. fortunei* and *F. pumila* was significantly higher than that of *H. nepalensis* in summer; the leaf MDA content of *E. fortunei* was significantly higher than that of the other two plants in autumn; and the leaf MDA content of *F. pumila* was significantly higher than that of *E. fortunei* and *H. nepalensis* in winter.

3.4.4 Seasonal changes of the soluble protein content under different levels of PM pollution

As can be seen from the Table 2, the soluble protein content of *H. nepalensis* and *F. pumila* leaves was significantly higher than that of *E. fortunei* leaves in spring and summer at the

TABLE 1 The photosynthetic gas exchange parameters response of climbing plants to different levels of PM pollution.

Seasons		P_n ($\mu mol \cdot m^{-2} \cdot s^{-1}$)		G_s ($mol \cdot m^{-2} \cdot s^{-1}$)		C_i ($\mu mol \cdot mol^{-1}$)		Tr ($mmol \cdot H_2O \cdot m^{-2} \cdot s^{-1}$)	
		campus	overpass	campus	overpass	campus	overpass	campus	overpass
spring	*E. fortunei*	3.61 ± 0.34b	1.89 ± 0.19B	0.08 ± 0.02b	0.04 ± 0.01B	187.31 ± 22.71b	160.21 ± 27.53B	0.22 ± 0.08c	0.11 ± 0.06B
	F. pumila	5.41 ± 0.48a	3.29 ± 0.58A	0.15 ± 0.03a	0.06 ± 0.01A	284.98 ± 28.54a	190.16 ± 26.18AB	1.75 ± 0.24a	0.58 ± 0.06A
	H. nepaensis	4.01 ± 0.52a	2.65 ± 0.45AB	0.17 ± 0.04a	0.07 ± 0.001A	201.18 ± 23.17b	229.33 ± 22.37A	1.02 ± 0.31b	0.54 ± 0.07A
summer	*E. fortunei*	6.32 ± 0.59b	2.09 ± 0.22B	0.04 ± 0.01b	0.02 ± 0.01A	143.54 ± 20.77b	152.19 ± 17.27A	1.05 ± 0.23b	0.99 ± 0.12A
	F. pumila	7.4 ± 0.43a	2.28 ± 0.08B	0.06 ± 0.01ab	0.02 ± 0.01A	179.06 ± 25.78ab	96.05 ± 15.27B	1.92 ± 0.46a	0.54 ± 0.07B
	H. nepaensis	8.93 ± 0.26a	3.74 ± 0.03A	0.10 ± 0.002a	0.04 ± 0.01A	213.17 ± 29.64a	135.35 ± 14.7A	2.43 ± 0.37a	0.93 ± 0.16A
autumn	*E. fortunei*	4.9 ± 0.25c	2.55 ± 0.21C	0.05 ± 0.01b	0.05 ± 0.01B	211.68 ± 26.73a	219.81 ± 25.29A	0.33 ± 0.02b	0.59 ± 0.12B
	F. pumila	6.51 ± 0.21a	3.58 ± 0.36A	0.07 ± 0.01ab	0.05 ± 0.02A	182.23 ± 26.73a	206.87 ± 16.82A	0.35 ± 0.08ab	0.44 ± 0.12A
	H. nepaensis	4.74 ± 0.49b	3.05 ± 0.27B	0.08 ± 0.03a	0.04 ± 0.01AB	261.2 ± 27.92a	180.22 ± 33.48A	0.69 ± 0.14a	0.34 ± 0.11B
winter	*E. fortunei*	2.61 ± 0.36b	2.38 ± 0.38B	0.04 ± 0.01b	0.03 ± 0.01A	193.81 ± 36.23a	180.85 ± 26.99A	1.06 ± 0.12b	0.32 ± 0.08A
	F. pumila	7.81 ± 0.66a	5.62 ± 0.55A	0.07 ± 0.02ab	0.06 ± 0.02A	193.44 ± 19.01b	180.71 ± 19.85A	1.78 ± 0.42b	1.62 ± 0.24A
	H. nepaensis	4.39 ± 0.47b	4.03 ± 0.39AB	0.12 ± 0.04a	0.04 ± 0.01A	248.43 ± 23.67a	147.72 ± 10.91A	2.39 ± 0.42a	0.61 ± 0.15A

Note: *Different lowercase letters indicate significant differences in data within the campus, different capital letters indicate significant differences in data within the overpass.

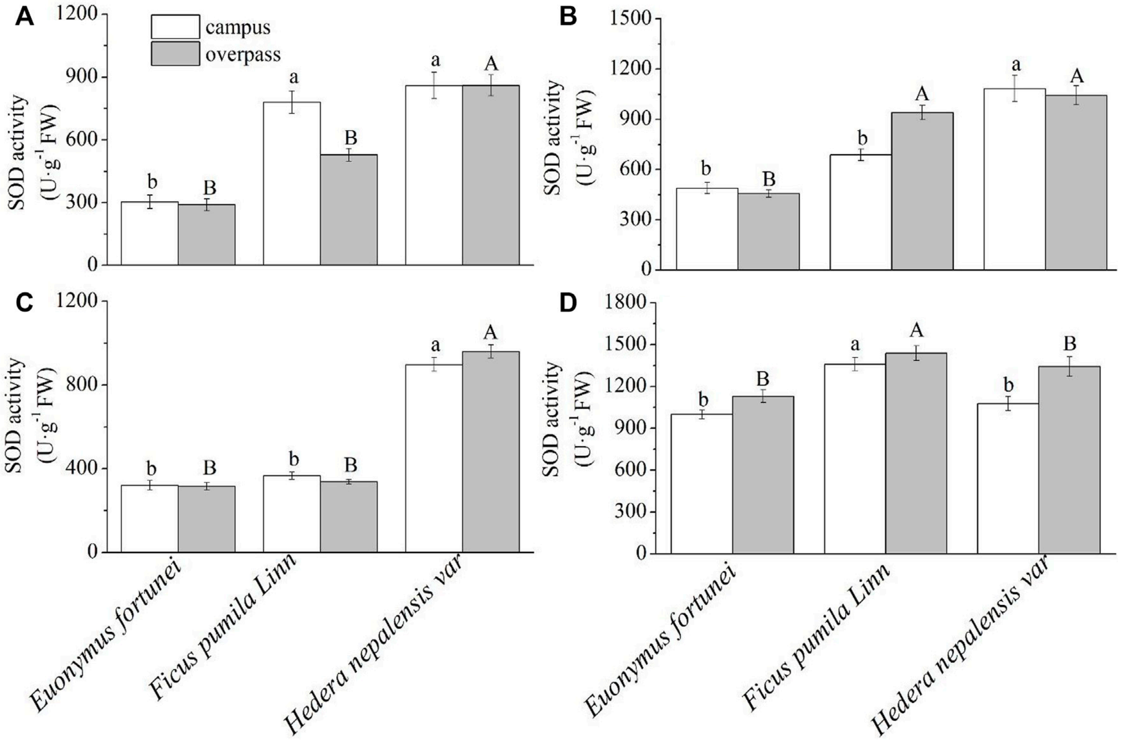


FIGURE 9
Effects of different levels of particulate pollution on SOD activities in plant leaves (mean ± SE). **(A)** spring, **(B)** summer, **(C)** autumn, **(D)** winter.

campus, and there was no significant difference in the soluble protein content of the leaves of all three plants in autumn. The soluble protein content of *F. pumila* leaves was significantly higher than that of *H. nepalensis* and E. fortunei leaves in winter. At the overpass, the soluble protein content of *H. nepalensis* leaves was largest in spring and autumn, with the soluble protein content of *H. nepalensis* leaves in spring being significantly higher than that of the other two plants. In summer, the plant soluble protein of *F. pumila* leaves was significantly higher than that of *E. fortune* leaves. In autumn, the soluble protein of *H. nepalensis* leaves was significantly higher than that of *E. fortune* leaves. In winter, the plant soluble protein of *F. pumila* leaves was significantly higher than that of the other climbers.

3.4.5 Seasonal changes of plant soluble sugar content under different levels of PM pollution

As can be seen from the Table 3, the soluble sugar content of *E. fortunei* leaves at the campus reached a maximum in spring, summer, and autumn, and the soluble sugar content of *E. fortunei* leaves and *H. nepalensis* leaves was significantly higher than that of *F. pumila* leaves in spring. The soluble sugar content of *E. fortunei* leaves was significantly higher than that of the other two plants in summer and autumn. The soluble sugar content of *H. nepalensis* and *E. fortunei* leaves at the campus was significantly higher than that of *F. pumila* leaves in winter. At the overpass, the soluble sugar content of *E. fortunei* leaves was significantly higher than that of *F. pumila* leaves in spring. At the overpass, the soluble content of *H. nepalensis* leaves was significantly higher than the other two plants in spring, the soluble sugar content of *E. fortunei* and *F. pumila* leaves was significantly higher than that of *H. nepalensis* leaves in summer, the soluble sugar content of *E. fortunei* leaves was significantly higher than that of the other two plants in autumn ($p < 0.05$), and the soluble sugar content of *H. nepalensis* leaves was significantly higher than that of the other two plants in winter.

3.5 Two-factor ANOVA

As shown in Table 4, the interaction of tree species and sampling site had highly significant effects ($p < 0.001$) on the sPM, sPM10–100, sPM2.5–10, wPM, wPM10–100, POD activity, MDA content, P_n, and G_s of climbing plants. The effect of tree species on the wPM2.5–10 and wPM0.2–2.5 of all climbing plants was highly significant ($p < 0.01$). Sampling site had a highly significant effect on the sPM0.2–2.5 and T_r of

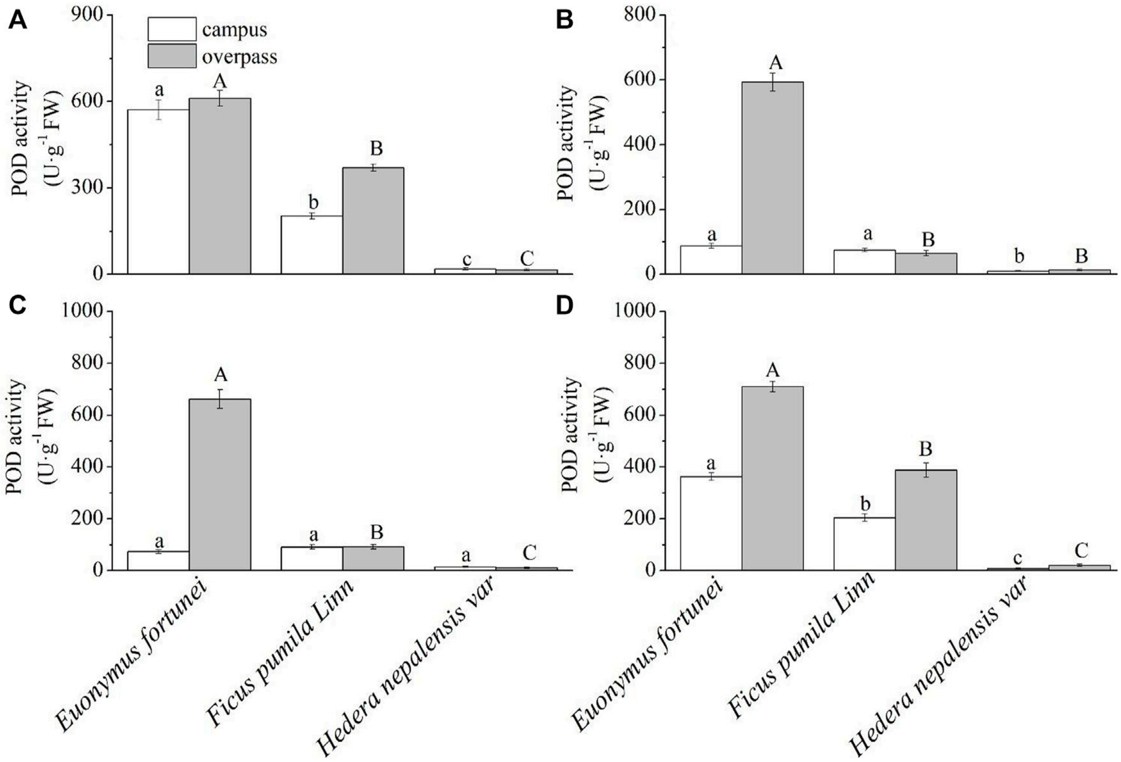


FIGURE 10
Effects of different levels of particulate pollution on POD activities in plant leaves (mean ± SE). **(A)** spring, **(B)** summer, **(C)** autumn, **(D)** winter.

climbing plants ($p < 0.01$). Tree species had a highly significant effect on the soluble protein content, C_i, and T_r of climbing plants ($p < 0.001$). The interaction of tree species and sampling site had highly significant effects on the POD activity ($p < 0.001$), soluble sugar content ($p < 0.01$), and sPM10–100, wPM2.5–10, wPM0.2–2.5, MDA, G_s, and T_r ($p < 0.05$).

3.6 Relationship between particulate matter, photosynthesis and biochemistry by leaves of climbing plants

AS shown in Figure 12, the SOD activity was positively correlated with MDA content, cell concentration ($p < 0.01$), G_s, sPM, sPM10–100, wPM, wPM10–100 ($p < 0.05$), and negatively correlated with the POD activity and soluble sugar content ($p < 0.05$). The POD activity was positively correlated with the MDA content ($p < 0.05$), and negatively correlated with the soluble protein content, P_n, G_s ($p < 0.01$), and T_R and wPM2.5–10 ($p < 0.05$). The MDA content was positively correlated with the soluble protein content, sPM, and sPM0.2–2.5 ($p < 0.01$), and sPM10–100 and sPM2.5–10 ($p < 0.05$), and negatively correlated with the total soluble sugar content ($p < 0.01$), and G_s and C_i ($p < 0.05$). The soluble protein content was positively correlated with the T_R ($p < 0.01$) and P_n ($p < 0.05$), and negatively correlated with the C_i ($p < 0.01$). The soluble sugar content was negatively correlated with the P_n ($p < 0.01$). The P_n was positively correlated with G_s and the T_r ($p < 0.01$), and negatively correlated with sPM, sPM10–100, sPM2.5–10, wPM, and wPM10–100 ($p < 0.01$), and sPM0.2–2.5 ($p < 0.05$). G_s was positively correlated with C_i and the T_r ($p < 0.01$), and negatively correlated with sPM, sPM10–100, and wPM10–100 ($p < 0.05$). The sPM was positively correlated with sPM10–100, sPM2.5–10, sPM0.2–2.5, wPM, wPM10–100, wPM2.5–10, and wPM0.2–2.5 ($p < 0.01$). The sPM10–100 was positively correlated with sPM2.5–10, 1 sPM0.2–2.5, wPM, wPM10–100, wPM2.5–10, and wPM0.2–2.5 ($p < 0.01$). The sPM2.5–10 was positively correlated with sPM0.2–2.5, wPM, wPM10–100, wPM2.5–10, and wPM0.2–2.5 ($p < 0.01$). The sPM0.2–2.5 was positively correlated with wPM, wPM10–100, wPM2.5–10, and wPM0.2–2.5 ($p < 0.01$). The wPM was positively correlated with wPM10–100, wPM2.5–10, and wPM0.2–2.5 ($p < 0.01$). The wPM10–100 was positively correlated with wPM2.5–10 and wPM0.2–2.5 ($p < 0.01$). The wPM2.5–10 value was positively correlated with wPM0.2–2.5 ($p < 0.01$).

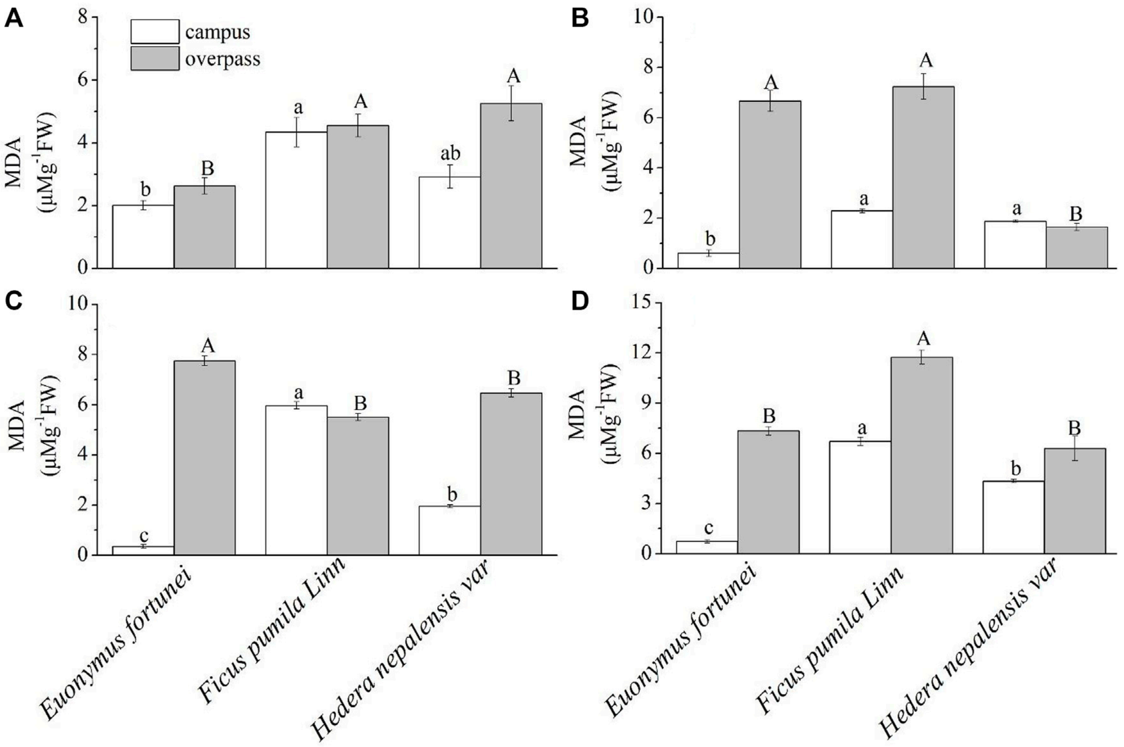


FIGURE 11
Effects of different levels of particulate pollution on MDA content in plant leaves (mean ± SE). **(A)** spring, **(B)** summer, **(C)** autumn, **(D)** winter.

TABLE 2 Effects of different levels of particulate pollution on soluble protein content in plant leaves (g·100 g^{-1} FW).

Plant species	Spring		Summer		Autumn		Winter	
	Campus	Overpass	Campus	Overpass	Campus	Overpass	Campus	Overpass
E. fortunei	0.22 ± 0.07b	0.04 ± 0.0063C	0.13 ± 0.074a	0.13 ± 0.074B	0.89 ± 0.067a	0.53 ± 0.085B	0.09 ± 0.0036b	0.39 ± 0.042B
F. pumila	0.59 ± 0.09a	0.34 ± 0.08B	0.27 ± 0.04a	0.27 ± 0.04A	1.19 ± 0.085a	0.91 ± 0.066AB	0.34 ± 0.015a	0.74 ± 0.027A
H. nepaensis	0.78 ± 0.11a	0.51 ± 0.06A	0.32 ± 0.036a	0.32 ± 0.036AB	0.82 ± 0.076a	1.31 ± 0.084A	0.18 ± 0.007b	0.52 ± 0.018B

TABLE 3 Effects of different levels of particulate pollution on total soluble sugar content in plant leaves (g·100 g^{-1}FW).

Plant species	Spring		Summer		Autumn		Winter	
	Campus	Overpass	Campus	Overpass	Campus	Overpass	Campus	Overpass
E. fortunei	5.66 ± 0.73a	0.55 ± 0.07C	6.19 ± 0.21a	4.35 ± 0.15A	6.56 ± 0.17a	6.54 ± 0.19A	4.27 ± 0.21a	3.11 ± 0.18B
F. pumila	1.42 ± 0.89b	2.63 ± 0.12B	2.48 ± 0.14c	3.48 ± 0.16A	3.58 ± 0.11c	3.77 ± 0.16B	2.09 ± 0.13b	3.28 ± 0.25B
H. nepaensis	5.01 ± 0.63a	4.79 ± 0.17A	3.49 ± 0.11b	0.35 ± 0.15B	5.09 ± 0.19b	3.73 ± 0.15B	5.01 ± 0.32a	4.76 ± 0.28A

TABLE 4 Effect of tree species and sampling sites on the adsorption particulate matter, photosynthesis and biochemistry by leaves of climbing plants.

Index	sPM	sPM10~100	sPM2.5~10	sPM0.2~2.5	wPM	wPM10~100	wPM2.5~10	wPM0.2~2.5	SOD
Areas (A)	0.000***	0.000***	0.000***	0.003**	0.000***	0.000***	0.000***	0.000***	0.000***
Tree species (T)	0.000***	0.000***	0000***	0.000***	0.000***	0.000***	0.002**	0.001**	0.658
A×T	0.114 ns	0.033*	0.352 ns	0.045	0.111 ns	0.209	0.029 *	0.002*	0.947
Index	POD	MDA	Soluble protein	Total soluble sugar	P_n	G_s	C_i	T_r	
Areas (A)	0.000***	0.000***	0.004*	0.000***	0.000***	0.000***	0.544 ns	0.002**	
Tree species (T)	0.000***	0.000***	0.000***	0.597	0.000***	0.000***	0.000***	0.000***	
A × T	0.000***	0.020*	0.171	0.001**	0.171 ns	0.020*	0.422 ns	0.041*	

***indicated significant correlation at $p < 0.001$, ** indicated significant correlation at $p < 0.01$, * indicated significant correlation at $p < 0.05$.

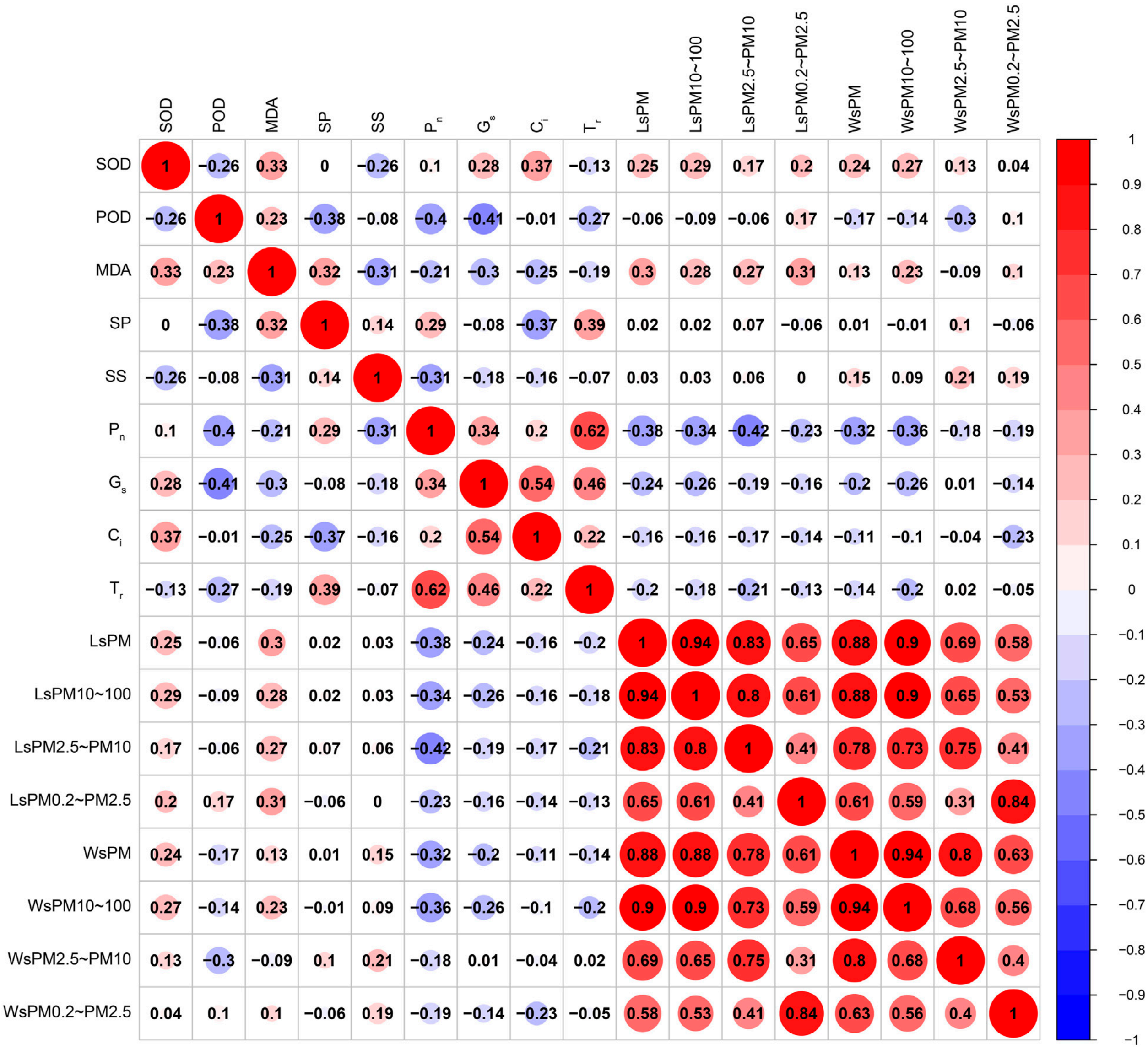
4 Discussion

4.1 Particle adsorption by the leaves of different climbing plants

The adsorption of PM by the three evergreen climbers followed the order of *H. nepalensis* > *F. pumila* > *E. fortunei*, indicating that *H. nepalensis* has a strong adsorption capacity for PM, which is related to its larger individual leaf area, sparsity of scales on the lower surface, and obvious lateral and reticulate veins on the leaf surface. *E. fortunei* has thin leathery leaves with fine lateral veins and inconspicuous veinlets, and displayed the fewest seasonal differences among the three climbers, indicating a consistent ability to adsorb PM. *F. pumila* leaves have a glabrous surface with dorsal short hairs and reticulate veins that protrude in the form of a honeycomb, which is conducive to the adsorption of PM. The roughness of the leaf surfaces of the different plants varied, and these differences had a great influence on the adsorption of PM (Wang et al., 2006; Li M et al., 2021). The ability of plants to adsorb PM is closely related to the micromorphology of the leaf surface, and dense, narrow, and deep grooves on the leaf surface could favor the adsorption of PM by plants (Li et al., 2019; Zha et al., 2019). In this study, the adsorption of PM by all three climbing plants was higher at the overpass than at the campus, which was because the overpass was located in the middle of a road segregation zone that was affected by vehicle exhaust. Atmospheric PM pollution was more serious than in other areas, which was consistent with the findings of Beckett et al., 2000 and Freer-Smith et al., 2005. The amount of PM adsorbed by leaf surfaces and wax for all three climbing plants followed the order of winter > spring > summer > autumn, which may be due to the higher level of atmospheric PM pollution in winter than in other seasons, resulting in plants adsorbing more PM. The occurrence of the maximum dust retention in winter was also reported by other researchers (Prajapati and Tripathi, 2008; Zha et al., 2019).

4.2 The effects of PM pollution on the photosynthetic gas exchange parameters of plants

It was found that PM deposited on the leaf surface increased the leaf temperature and interfered with photosynthetic CO_2 exchange and transpiration rates by shading and impeding diffusion (Gimeno and Deltoro, 2000). Zia-Khan et al. (2015) found that there may be stomatal occlusion on the leaves of plants growing near coal fields, which may result in a decrease in G_s. In this study, it was found that the P_n of the three climbing plants was more strongly affected under the high PM pollution conditions at the overpass (Table 1). Compared to the overpass, at the



	SOD	POD	MDA	SP	SS	P_n	G_s	C_i	T_r	LsPM	LsPM10~100	LsPM2.5~PM10	LsPM0.2~PM2.5	WsPM	WsPM10~100	WsPM2.5~PM10	WsPM0.2~PM2.5
SOD	1	−0.26	0.33	0	−0.26	0.1	0.28	0.37	−0.13	0.25	0.29	0.17	0.2	0.24	0.27	0.13	0.04
POD	−0.26	1	0.23	−0.38	−0.08	−0.4	−0.41	−0.01	−0.27	−0.06	−0.09	−0.06	0.17	−0.17	−0.14	−0.3	0.1
MDA	0.33	0.23	1	0.32	−0.31	−0.21	−0.3	−0.25	−0.19	0.3	0.28	0.27	0.31	0.13	0.23	−0.09	0.1
SP	0	−0.38	0.32	1	0.14	0.29	−0.08	−0.37	0.39	0.02	0.02	0.07	−0.06	0.01	−0.01	0.1	−0.06
SS	−0.26	−0.08	−0.31	0.14	1	−0.31	−0.18	−0.16	−0.07	0.03	0.03	0.06	0	0.15	0.09	0.21	0.19
P_n	0.1	−0.4	−0.21	0.29	−0.31	1	0.34	0.2	0.62	−0.38	−0.34	−0.42	−0.23	−0.32	−0.36	−0.18	−0.19
G_s	0.28	−0.41	−0.3	−0.08	−0.18	0.34	1	0.54	0.46	−0.24	−0.26	−0.19	−0.16	−0.2	−0.26	0.01	−0.14
C_i	0.37	−0.01	−0.25	−0.37	−0.16	0.2	0.54	1	0.22	−0.16	−0.16	−0.17	−0.14	−0.11	−0.1	−0.04	−0.23
T_r	−0.13	−0.27	−0.19	0.39	−0.07	0.62	0.46	0.22	1	−0.2	−0.18	−0.21	−0.13	−0.14	−0.2	0.02	−0.05
LsPM	0.25	−0.06	0.3	0.02	0.03	−0.38	−0.24	−0.16	−0.2	1	0.94	0.83	0.65	0.88	0.9	0.69	0.58
LsPM10~100	0.29	−0.09	0.28	0.02	0.03	−0.34	−0.26	−0.16	−0.18	0.94	1	0.8	0.61	0.88	0.9	0.65	0.53
LsPM2.5~PM10	0.17	−0.06	0.27	0.07	0.06	−0.42	−0.19	−0.17	−0.21	0.83	0.8	1	0.41	0.78	0.73	0.75	0.41
LsPM0.2~PM2.5	0.2	0.17	0.31	−0.06	0	−0.23	−0.16	−0.14	−0.13	0.65	0.61	0.41	1	0.61	0.59	0.31	0.84
WsPM	0.24	−0.17	0.13	0.01	0.15	−0.32	−0.2	−0.11	−0.14	0.88	0.88	0.78	0.61	1	0.94	0.8	0.63
WsPM10~100	0.27	−0.14	0.23	−0.01	0.09	−0.36	−0.26	−0.1	−0.2	0.9	0.9	0.73	0.59	0.94	1	0.68	0.56
WsPM2.5~PM10	0.13	−0.3	−0.09	0.1	0.21	−0.18	0.01	−0.04	0.02	0.69	0.65	0.75	0.31	0.8	0.68	1	0.4
WsPM0.2~PM2.5	0.04	0.1	0.1	−0.06	0.19	−0.19	−0.14	−0.23	−0.05	0.58	0.53	0.41	0.84	0.63	0.56	0.4	1

FIGURE 12
Correlations between accumulated particulate matter, photosynthesis and antioxidant enzyme activities by leaves of climbing plants.

campus, the P_n and G_s of the three climbing plants decreased and the C_i concentration increased, indicating that high levels of PM pollution inhibited photosynthesis through its effect on G_s (Guidi et al., 2011; Gajić et al., 2013). The toxic elements from particulate matter can inhibit potosynthetic gas exchange parameters of climbing plants, which consistent with Guidi et al. (2011). The Pearson correlation coefficients between the plant adsorption of different particle sizes and photosynthetic parameters showed that different particle sizes were highly significantly negatively correlated with the net P_n and G_s of plant leaves, i.e., (Table 1). A similar finding was also reported that photosynthesis nad stomatal conductance declined over time at elevated PM2.5, with large variations with PM2.5 concentrations (Yu et al., 2018). The transpiration of stomata was found to make the leaf surface wetter and enhance the deposition of PM. Among the plants investigated in this study *H. nepalensis* was found to have the highest transpiration rate, which is one of the reasons why it had the greatest ability to adsorb PM (Hinds, 1999). Tree species that display resistance to air pollution are reported to have the highest respiration rates (Lorencplucinska, 1980), and an analysis of the three plants in this study showed that *F. pumila* had the highest P_n., indicating a strong resistance to particulate pollution.

4.3 The effects of PM pollution on plant biochemical indicators

The degree of oxidative stress in plants depends on the ability of the plant antioxidant capacity system to inhibit superoxide, hydroxyl, and peroxyl radicals at the cellular level (Mroczek-Zdyrska and Wojcik, 2012; Bisoi et al., 2017). Antioxidant enzymes, such as SOD and POD, are physiological and biochemical indicators that are critical for plant stress resistance and the mitigation of oxidative stress (Radwan and Eldeen, 2012).

The three plant species in this study showed a general trend of higher SOD (Figure 10) and POD levels (Figure 11) in all seasons at the overpass than at the campus, indicating an increase in oxidative stress generated by PM pollution on plants. The increase in SOD and POD enzyme activity indicated an increase in free radicals in plant cells caused by PM pollution, with both SOD and POD scavenging these free radicals to reduce the pollution damage to plants (Verma and Dubey 2003; Xu et al., 2010; Sharma et al., 2012; Panda et al., 2018). In addition, in all three plants there was a general trend for a higher MDA content in all seasons at the overpass than at the campus (Figure 12), which was due to the higher level of cell membrane damage in the overpass plants following their exposure to higher pollution levels than the plants at the campus. The higher leaf SOD activity of the three plant species in the winter at both the overpass and campus in this study may be related to high dust levels, high reactive oxygen species production rates, high atmospheric particulate matter pollutant concentrations, and low available light levels during the winter (Singh et al., 2020).

The soluble protein content of the three climbing plants displayed different trends in each season (Table. 2), and the soluble protein content of *F. pumila* leaves in the summer and winter overpass environments was higher than that of the campus, which may be due to the more extreme weather conditions in summer and winter, when plants actively accumulate soluble proteins to maintain their osmoregulation and sustain higher levels of growth. Kumar and Dubey et al. found that pollutants from automobile exhaust emissions may have an inhibitory effect on protein synthesis (Kumar and Dubey, 1998). The decrease in the foliar protein content in this study may have been due to the breakdown of existing proteins or a decrease in protein synthesis from scratch (Iqba et al., 2000; Singh et al., 1998).

In the three climbing plants investigated in this study there was a general trend for lower soluble sugars in all seasons in the overpass than in the campus, indicating that the three climbing plants were more affected by stress at the overpass (Table. 3). The decrease in the soluble sugar content of damaged leaves may correspond to the photosynthetic inhibition or stimulation of respiration rate (Tzvetkova and Kolarov, 1996). Similarly, Bucker and Ballach et al. found that the level of soluble carbohydrates decreased due to the fumigation of a mixture of O_3, SO_2, and nitrogen dioxide (NO_2) in the leaves, and that the decrease in the soluble sugar content may be the result of increased metabolic depletion under stress (Bücke and Ballach, 2010). Thus, we believe that more particulate matter accumulated in the leaves leads to shade-induced decrease in photosynthetic efficiency, could be responsible for decline in sugar content in the leaves. A similar finding was also reported that heavy metals containing particulate matter can decrease the sugar levels in *pistia stratiotes*, *spirodela polyrrhiza*, *Eichhornia crassipes*, *Lagerstomia speciose* and *Acacia moniliformis* (Mishra and Tripathi, 2008; Gupta et al., 2011).

5 Conclusion

In summary, the ability of the three climbing plants to adsorb PM followed the order of *H. nepalensis* > *F. pumila* > *E. fortunei* and the differences in the adsorption characteristics of the different plant species were mainly caused by the different morphological and structural characteristics of the leaf surface. The greater the roughness of the leaf surface and the higher the density of pileus on the leaf, the greater the ability of plant leaves to adsorb PM. There were seasonal differences in PM adsorption by climbing plants, with a trend of winter > autumn > spring > summer. Particulate pollution is an important factor affecting plant photosynthesis, and the effect of PM on the net P_n varies according to particle size. A comprehensive comparative analysis of the three plants showed that *F. pumila* was the most resistant to PM pollution under the different levels of PM pollution. The three climbing plants actively accumulated biochemical substances in their bodies to regulate osmotic pressure and maintain normal growth when they were exposed to high levels of PM, among which the POD activity and MDA content were the most sensitive indicators of PM stress. Therefore, the identification and assess of the photosynthetic efficacy of these plant species, and their physiological and biochemical responses, may be significant for the selection of climbing tree species for pollution control.

Data availability statement

The original contributions presented in the study are included in the article/Supplymentary Meterial, further inquiries can be directed to the corresponding author.

Author contributions

XL: Conceptualization, writing, and methodology. LC: Data curation. ZL: visualization. JL: writing and investigation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1084902/full#supplementary-material

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