sustainability

MDPI

Article

Dust Retention Effect of Greenery in Typical Urban Traffic Landscapes of Nanjing—In the Case of Xuanwu Avenue in Nanjing City

Qianqian Sheng [1,2,3,4,*], Xiangyi Zhang [1,2], Chen Meng [1], Xiru Zhang [1,2], Weizheng Li [5], Ruizhen Yang [6] and Zunling Zhu [1,2,3,4,7,*]

1 College of Landscape Architecture, Nanjing Forestry University, Nanjing 210037, China; zhangxiangyi@njfu.edu.cn (X.Z.); meganchenmc88@gmail.com (C.M.); xiru@njfu.edu.cn (X.Z.)
2 Co-Innovation Center for the Sustainable Forestry in Southern China, Nanjing Forestry University, Nanjing 210037, China
3 Jin Pu Research Institute, Nanjing Forestry University, Nanjing 210037, China
4 Research Center for Digital Innovation Design, Nanjing Forestry University, Nanjing 210037, China
5 Advanced Analysis and Testing Center, Nanjing Forestry University, Nanjing 210037, China; gisplayer@gmail.com
6 Nanjing Sky Hunt Data Technology Co., Ltd., Nanjing 210037, China; yangruizhen@foxmail.com
7 College of Art and Design, Nanjing Forestry University, Nanjing 210037, China
* Correspondence: qqs@njfu.edu.cn (Q.S.); zhuzunling@njfu.edu.cn (Z.Z.)

Abstract: With the accelerated process of urbanization, air pollution has become increasingly severe. Garden plants can trap atmospheric particulate matter, which is of great significance for improving the urban ecological environment and promoting sustainable development. To investigate the dust retention effect of typical transportation green spaces in Nanjing, this study focuses on thirteen garden plants on Xuanwu Avenue in Nanjing. The dust retention capacity of these plants was determined using the wash-off method, while the microstructure of their leaf surfaces was observed using scanning electron microscopy. The results are as follows: Firstly, per unit leaf area, *Liriope spicata*, *Ophiopogon japonicus*, and *Viburnum odoratissimum* demonstrate solid dust retention abilities. Additionally, *Viburnum odoratissimum*, *Prunus serrulata* var. *Lannesiana*, and *Liriope spicata* show strong dust retention abilities per single leaf. Moreover, *Platanus acerifolia*, *Viburnum odoratissimum*, and *Cinnamomum camphora* have strong dust retention abilities per plant. *Viburnum odoratissimum*, *Platanus acerifolia*, and *Prunus serrulata* var. *Lannesiana* exhibit the most substantial dust retention capacities. Secondly, there is a significant negative correlation between dust retention per plant and the potassium content, while a significant positive correlation is observed with plant height, canopy height, and leaf width. Furthermore, there is a highly significant positive correlation between dust retention per unit leaf area and stomatal length and a highly significant negative correlation with leaf length. The surface microstructure of the blade mainly increases the dust retention capacity of the blade by increasing the friction of the leaf surface. Lastly, specific leaf surface microstructures, such as grooved epidermis and trichomes, enhance plants' dust retention capacity. Consequently, for the future configuration of road green spaces in Nanjing, a mixed planting mode of trees, shrubs, and grass is recommended. Priority should be given to selecting plants with strong overall dust retention capabilities, such as *Platanus acerifolia*, *Viburnum odoratissimum*, and *Prunus serrulata* var. *Lannesiana*, to alleviate air pollution, improve the urban ecological environment, and achieve sustainable development.

Keywords: road green spaces; dust retention amount; particulate matter; leaf surface microstructure

check for updates

Citation: Sheng, Q.; Zhang, X.; Meng, C.; Zhang, X.; Li, W.; Yang, R.; Zhu, Z. Dust Retention Effect of Greenery in Typical Urban Traffic Landscapes of Nanjing—In the Case of Xuanwu Avenue in Nanjing City. *Sustainability* **2024**, *16*, 917. https://doi.org/10.3390/su16020917

Received: 27 November 2023
Revised: 12 January 2024
Accepted: 16 January 2024
Published: 22 January 2024

1. Introduction

With accelerated urbanization and rapid economic development, the particulate matter pollution from many urban areas has caused severe environmental problems. Currently, the issue of particulate matter pollution cannot be resolved solely by controlling the pollution sources [1]. Particulate matter pollution severely threatens human health [2,3], and the smaller the particle diameter, the greater the harm [4]. The sources of atmospheric particulate matter can be divided into natural and anthropogenic sources. Natural sources refer to particles generated naturally, such as plant pollen; fungal spores; and particles from soil weathering, volcanic eruptions, and forest fires. On the other hand, anthropogenic sources refer to various particle pollutants produced by human activities, mainly including coal combustion emissions, vehicle exhaust, industrial waste gas, energy consumption pollutants, and construction dust [5,6].

The *2023 Agenda for Sustainable Development* proposes global sustainable development goals and indicators, which provide important guidance for the planning and management of urban road green spaces. As an important part of the urban ecosystem, urban road green space has a significant dust retention effect, which is of great significance for improving air quality and achieving urban sustainable development goals. At present, there are mainly sweepers and high-pressure cleaning vehicles for road dust reduction operations, but this requires a lot of manpower, material, and financial resources. Nowak et al. [7] found that the total amount of air pollutants in urban trees in the United States was 711,000 metric tons, worth USD 3.8 billion, which shows the economic value of plant dust retention. Therefore, road green spaces are receiving wide attention as an essential means to mitigate atmospheric particulate matter pollution [8]. The dense canopy of garden plants can effectively reduce wind speed, causing some particulate matter in the atmosphere to settle, and the particles are fixed and intercepted by leaf surface characteristics such as leaf texture, trichomes, oils, and moisture [9,10]. Rainwater, strong winds, and leaf fall help plants renew the retained atmospheric particulate matter. Different plants' surface structure, texture, leaf area, and morphological features, such as plant height, crown size, and branch angles, affect their ability to retain and purify particulate matter [11–14]. Chen et al. [15] believe that conifers have a thicker waxy layer on their leaves and a compact crown structure, so they have a stronger dust retention effect than broad-leaved trees. Studies by Weerakkody et al. [16] have shown that leaves of smaller size have a more vital ability to retain dust due to their more significant edge effect. Sabin [17] found that leaves with trichomes, grooves, protrusions, or shorter petioles can adsorb more $PM_{2.5}$, and rougher leaves can adsorb more particles. Dzierzanowski et al. [18] found that the wax layer on plant leaf surfaces can adsorb particles and improve dust retention capacity. Sæbø [19] also believes that the leaf surface hairs of plants can improve their ability to retain dust. Perini's findings, however, were the opposite, suggesting that leaves with more fluff had a lower ability to retain dust [20]. Wang Lei et al. [21] found that the ability of particles to adhere to the leaf surface is in the order of protrusions < crypts < veins + crypts < grooves, with the lower leaf surface having less dust retention capacity than the upper surface. Pal et al. [22] found that leaf folds, grooves, and other features can affect the dust retention ability of plants. Xie Binze et al. [23] suggested that the width of grooves on the leaf surface is the main factor affecting the differences in particle adsorption among different plants, and the dust retention capacity of leaves is also related to the number of stomata, with a decrease in stomata corresponding to a decrease in the dust retention capacity of plants. Ming-Yeng Lin et al. [24] conducted studies on removing ultrafine particles by plants using wind tunnel experiments, indicating a strong correlation between capture efficiency and particle size, with higher capture rates for smaller particle sizes, which decrease with increasing wind speed and decreasing leaf area density.

Furthermore, external environmental factors highly influence the coefficient of variation of dust retention per unit leaf area on plant leaves. Studies have shown that the dust retention of the same plant species is lower in open environments compared to enclosed environments, and the dust retention varies among different heights of the same plant—secondary dust results in lower dust retention on higher leaves than on lower leaves [25]. The dust retention rate of plants can vary with changes in the environment. The amount of dust trapped by plants is also related to the amount of particulate matter in the environment, which varies from environment to environment. Qin Fan [26] studied the $PM_{2.5}$ concentration in Jiaozuo City and found that the concentrations in residential, educational, and commercial areas exceeded the national standard limits by 2.22, 1.02, and 1.66 times, respectively. Sternberg [27] found that the amount of dust trapped in plants increased with the increase in particulate matter in the environment. However, Nanos [28] and Rai et al. [29] believed that with the increase in particulate matter content, the photosynthetic rate, number of stomata, and stomatal conductance of leaves would be affected to a certain extent, thereby reducing the amount of dust retention in plants to a certain extent. Meteorological factors that affect particulate matter concentrations also include humidity, temperature, and wind speed [30]. Within a day, the dust retention of the same plant can change over time. In addition, the dust retention of plants also varies throughout the year. For example, Gao Jinhui [31] found that plants have the highest dust retention capacity during the peak season of vigorous growth in summer and autumn, while Zhu Liqiong et al. [32] found that some plants have higher dust retention in winter than in summer, which may be related to higher wind speeds in summer than in winter [33]. Therefore, it is evident that various internal and external factors influence the dust retention capacity of plants.

Nanjing City has abundant plant resources. Xuanwu Avenue is an important thoroughfare in the main urban area of Nanjing, and its traffic exhaust emissions rank among the highest in the city. Road green spaces can increase the area per unit and reduce dust content in the air, enhancing the dust retention benefits of green spaces. Due to differences in canopy structure and leaf surface characteristics, different types of ornamental plants have varying abilities to retain dust. By measuring the dust retention capacity of various plants, economically practical species can be selected, thus improving the quality of road green belts in limited spaces and land and utilizing the dust retention effect of green belts to reduce dust and purify city roads. In this study, taking Xuanwu Avenue in Nanjing as an example, we measured the dust retention capacity of the leaves in three dimensions, namely unit leaf area, single leaf, and single plant; used a scanning electron microscope to observe the microstructure and stomata of the leaves; and explored the dust blocking effect of traffic green space, so as to screen out the plants with the strongest dust retention ability, aiming to provide a scientific basis for selecting urban landscaping plants. The guidance of the rational allocation of garden plants will give full play to their ecological benefits and achieve the goal of ecological environmental protection and sustainable development.

2. Materials and Methods

2.1. Study Area Overview

Nanjing City is located in the southwestern part of Jiangsu Province, China, in the middle of the fertile region downstream of the Yangtze River. Its geographical coordinates range from $31°14''$ to $32°37''$ north latitude and $118°22''$ to $119°14''$ east longitude [34]. Nanjing City has distinct seasons and abundant rainfall in the North Subtropical Humid Climate Zone. The period from late June to early July is the rainy season in Nanjing City. The annual average temperature in Nanjing City is 15.4 °C, with the highest extreme value of 39.7 °C and the lowest extreme value of −13.1 °C. For this study, Xuanwu Avenue, one of the key construction projects in Nanjing City, was selected as the research object (Figure 1). Xuanwu Avenue is a typical urban traffic artery with an asphalt roadway, located in the main urban area of Nanjing, with a large flow of people and vehicles, and once ranked second in Nanjing with an average daily traffic volume of 131,000 vehicles. It is a road with serious automobile exhaust pollution in Nanjing, and at the same time, the surrounding areas are mostly commercial areas, residential areas, and schools, which reduces the diffusion of atmospheric particulate matter to a certain extent.

Furthermore, Xuanwu Avenue has minimal differences in climate and environmental factors, such as traffic conditions. Its green belt construction is relatively mature, with various vegetation species and good growth conditions, facilitating centralized data collection.

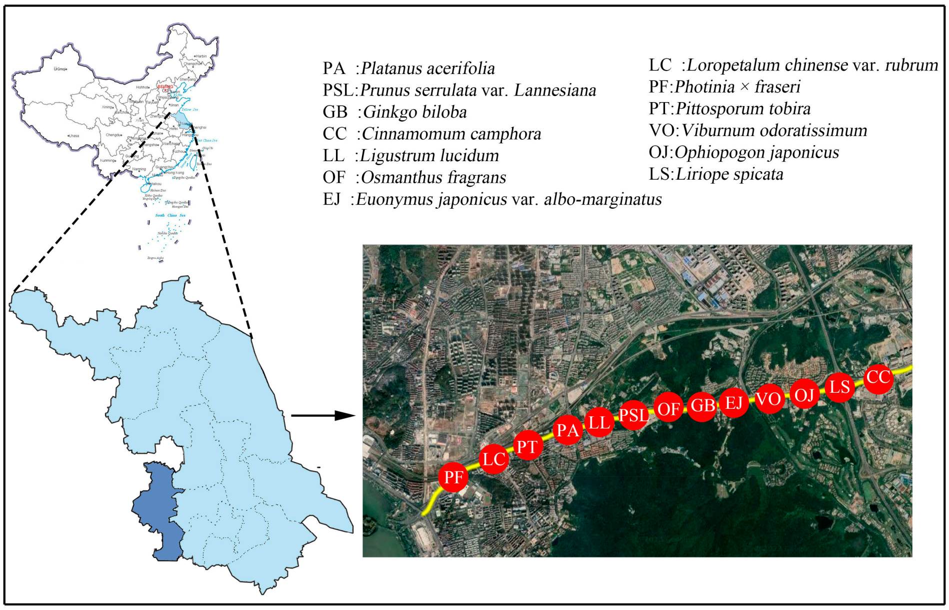

Figure 1. Geographical location of Xuanwu Avenue.

2.2. Experimental Materials

The experiment surveyed the existing tree species in the traffic green spaces of Xuanwu Avenue, Nanjing. Following the principle of typical adaptability, 13 species of plants with high frequency and wide application range in Nanjing were selected, including three deciduous trees, PA, PSL, and GB, along with two evergreen trees, CC and LL. Additionally, six evergreen shrubs were chosen: OF, EJ, LC, PF, PT, and VO. Two types of herbaceous plants, OJ and LS, were also selected. The experiment equipment mainly consisted of a 3-m telescopic branch cutter, a regular branch cutter, disposable rubber gloves, sealed bags, a tape measure, a leaf area meter, an oven, an electronic balance, a spectrophotometer, a flame photometer, volumetric flasks, and beakers.

2.3. Research Methods

2.3.1. Sample Collection

We chose to conduct our sampling during late spring when plants are thriving. Specifically, leaf samples were collected on 12 April 2023. The sampling process was carried out within a single day, during which the weather was sunny every day, without exceptional conditions such as heavy winds or rainfall. Three replicate samples were selected for each plant species under examination, ensuring that the sampled plants were consistent regarding trunk diameter, tree height, tree age, crown width, and overall growth status. Plant height, crown height, and crown width were measured using a measuring tape and a measuring rod, while leaf length and leaf width of the collected plant specimens were recorded using a leaf area meter. Samples were collected uniformly from the peripheral, upper, middle, and lower parts of the tested plants, with 15 to 30 plant leaves being collected at multiple points to ensure sufficient representation of dust deposition.

2.3.2. Calculation of Plant Dust Retention Capacity

Three to five evenly sized leaves were selected for each tested plant species. Leaf area was measured, and the leaves were dried and weighed to determine their dry weight. Specific leaf weight was calculated accordingly. The leaves were then washed and dried, and each plant species' total leaf area (S_1) was measured, including both tree and shrub leaves. The dust retention capacity of the plants was assessed using the difference in weight method. Dry filter paper (W_1) was used to filter the suspension fluid, and the filtered paper was then placed in sealed disposable Petri dishes. After being baked in a 60 °C oven for 24 h, the filter paper was weighed using a precision balance (W_2), and the data were recorded. The total dust retention of the leaves was obtained by subtracting the weight measurements before and after filtration, resulting in the total dust retention (C). Ten to twenty mature and intact leaves were selected for each plant species under study to determine the average leaf area (s). The specific formula is as follows:

$$S = \exp(0.631 + 0.2375H1 + 0.6906D - 0.0123S2) + 0.1824 \quad (1)$$

$$S_2 = \pi D(H + D)/2 \quad (2)$$

$$C_1 = C/S_1 \quad (3)$$

$$C_2 = C/S_1 \times s \quad (4)$$

$$C_3 = C_1 \times S \quad (5)$$

In these equations, S represents the total leaf area, H corresponds to the height of the crown, D denotes the crown width, C_1 represents the amount of dust retained per unit leaf area, C_2 represents the dust retained per single leaf, and C_3 represents the dust retained per plant. It should be noted that "exp" refers to the exponential function, while "π" represents the mathematical constant pi. During the experiment, 10 to 20 mature and intact leaves were selected from each plant species to determine the average leaf area (s).

2.3.3. Determination of Nitrogen, Phosphorus, and Potassium Element Content in Plant Leaves

The Kjeldahl method was used to determine plant leaves' nitrogen, phosphorus, and potassium content. The plant samples were digested with concentrated sulfuric acid in the presence of copper sulfate and potassium sulfate. After the digestate was obtained, the nitrogen and phosphorus content of the leaves was measured using the indophenol blue colorimetric method on a spectrophotometer. The potassium content of the leaves was determined using flame photometry with a flame photometer.

The following equation was used to calculate the nitrogen, phosphorus, or potassium content (W):

$$W = c \times V \times t_s \times 1000/m \times 10^5 \quad (6)$$

W represents the total nitrogen content (W_N), total phosphorus content (W_P), or total potassium content (W_K). c represents the concentration of the colored solution of nitrogen or phosphorus obtained from the working curve or the concentration of the colored solution of potassium measured from the flame photometer. V represents the volume of the colored solution. t_s represents the extraction factor. m represents the dried sample mass.

2.3.4. Observation of the Microscopic Structure on the Surface of the Leaves

A piece of each plant leaf was randomly selected, and a sample of 5 mm × 5 mm was cut at the leaf near the main vein of the leaf tip and quickly placed in a glutaraldehyde solution with a volume fraction of 2.5% for fixation. It was dehydrated using an ethanol solution [35]. After the sample was plated, it was fixed on the sample stage using double-sided carbon glue. An environmental scanning electron microscope (Quanta 200, FEI, Eindhoven, the Netherlands) was used to observe sample characteristics and take photos of micro-morphological features such as leaf surface, stomata, and cross-sections to obtain images.

2.4. Data Processing

Microsoft Excel 2007 for was used data statistics and organization. IMB SPSS Statistics 26 was utilized for one-way ANOVA of the differences in dust retention between different plants. The K-means clustering method was applied for systematic clustering analysis of the dust retention capability of the tested plants. Correlation analysis was conducted between plant growth indicators, leaf nitrogen–phosphorus–potassium content, and dust retention capability. Origin 2021 software was used for charting.

3. Results

3.1. Analysis of Plant Dust Retention Capability

3.1.1. The Results of Dust Retention Capacity of Different Garden Plants' Leaves

In this experiment, the dust capture capacity of leaves from 13 species of urban plants along Xuanwu Avenue was measured in three aspects: dust retention per unit leaf area, dust retention per single leaf, and dust retention per single plant (dust retention per single plant was measured for 11 species of urban plants). As shown in Figure 2, GB's dust retention was too low to be reflected in the figure.

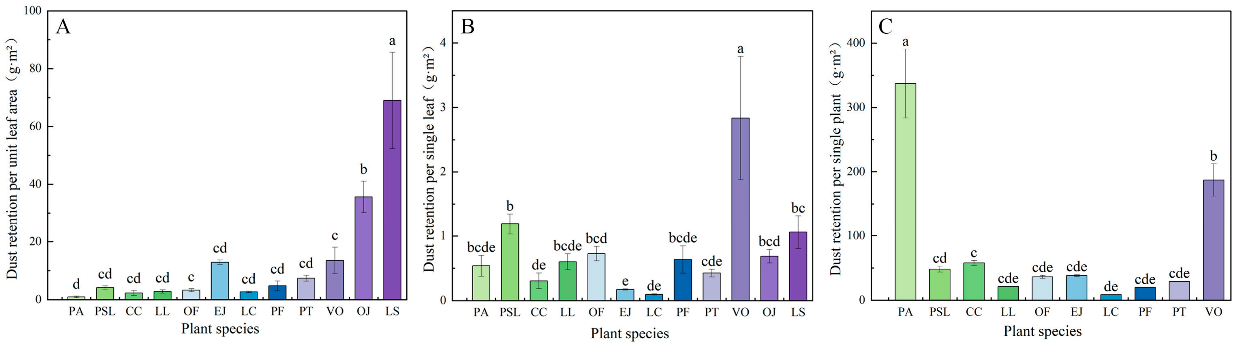

Figure 2. Dust retention per unit leaf area (**A**), per single leaf (**B**), and single plant of different plants (**C**). Different lowercase letters indicate significant differences in dust retention per unit leaf area (**A**), per single leaf (**B**), and single plant of different plants (**C**) among various species at the 0.05 level. PA (*P. acerifolia*); PSL (*P. serrulata* var. *Lannesiana*); GB (*G. biloba*); CC (*C. camphora*); LL (*L. lucidum*); OF (*O. fragrans*); EJ (*E. japonicus* var. *albo-marginatus*); LCt (*L. chinense* var. *rubrum*); PF (*P. fraseri*); PT: Pittosporum tobira; VO (*V. odoratissimum*); OJ (*O. japonicus*); LS (*L. spicata*) (same below).

The order of dust retention per unit leaf area (Figure 2A) of the 13 species of urban plants along Xuanwu Avenue from highest to lowest is as follows: LS > OJ > VO > EJ > PT > PF > PSL > OF > LL > LC > CC > PA > GB. Among them, LS has the highest dust retention per unit leaf area, which is 69.039 $g{\cdot}m^2$, while GB and PA have the lowest, with only 0.15 $g{\cdot}m^2$ and 0.951 $g{\cdot}m^2$, respectively. There are significant differences in dust retention per unit leaf area among different plants, with LS having nearly 40 times the dust retention per unit leaf area of GB.

The order of dust retention per single leaf (Figure 2B) from highest to lowest is as follows: VO > PSL > LS > OF > OJ > PF > LL > PA > PT > CC > EJ > LC > GB. Among them, VO has the highest dust retention per single leaf, which is 2.836 $g{\cdot}m^2$, while EJ, LC, and GB have a dust retention per single leaf ranging from 0.004 $g{\cdot}m^2$ to 0.172 $g{\cdot}m^2$, indicating the weakest dust retention per single leaf. There are significant differences in dust retention per single leaf among different plants, with VO having nearly 30 times the dust retention per single leaf of LC.

Based on the dust retention per unit leaf area and the leaf area per plant, the dust retention per single plant (Figure 2C) for the 11 species of trees and shrubs along Xuanwu Avenue can be calculated. The order of dust retention per single plant from highest to lowest is as follows: PA > VO > CC > PSL > EJ > OF > PT > LL > PF > LC > GB. Among them, PA has the highest dust retention per single plant, 337.141 $g{\cdot}m^2$, while LC and GB have a dust retention per single plant of 8.62 $g{\cdot}m^2$ and 0.45 $g{\cdot}m^2$, respectively, indicating the weakest dust retention per single plant. There are significant differences in dust retention per single plant among different plants, with PA having nearly 40 times the dust retention per single plant of LC.

The analysis of the dust retention data obtained in this experiment led to the following results (Table 1): Among the three categories (per unit leaf area, per single leaf, and individual plant), herbaceous plants demonstrated significantly higher dust retention than shrubs, while shrubs showed better dust retention than trees. Regarding dust retention per single leaf, herbaceous plants performed the best, followed by shrubs, and trees had the lowest retention capacity. Trees showed the highest effect on dust retention per individual plant, while shrubs exhibited significantly better dust retention than herbaceous plants.

Table 1. Statistics of dust adhered to different plants per individual plant.

The Species of Plants	Dust Trapping Amount per Unit Leaf Area (g·m^2)	Dust Trapping Amount per Single Leaf (g·m^2)	Single Plant Dust Retention Quantity (g·m^2)
Deciduous tree	2.072	0.5274	92.959
Shrub	7.432	0.8153	53.194
Herb	52.327	0.874	/

3.1.2. Cluster Analysis of Plant Dust Retention Capacity

After conducting cluster analysis on the dust retention capacities of different tree and shrub units, we referred to Aliya Baidourela's method [36] and refined the classification on its basis. Including unit leaf area dust retention capacity, single leaf dust retention capacity, and single plant dust retention capacity, the tested plants can be divided into five categories based on their comprehensive dust retention capacities (Figure 3). Category 1 includes VO, PA, and PSL with strong comprehensive dust retention capacity. Category 2 consists of LL, OF, and CC with relatively strong comprehensive dust retention capacity. Category 3 comprises EJ with moderate comprehensive dust retention capacity. Category 4 includes LC, PT, and PF with relatively weak comprehensive dust retention capacity. Category 5 consists of GB with weak comprehensive dust retention capacity.

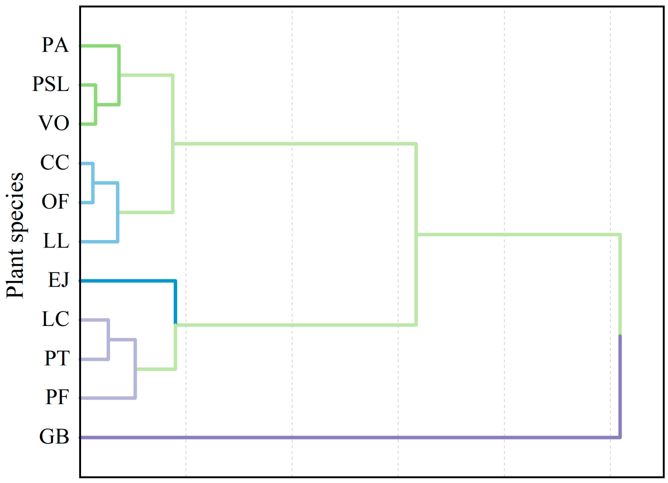

Figure 3. Cluster analysis of dust retention quantity per unit leaf area, per leaf, and per plant in woody and shrubby plants.

3.2. Measurement Results of Nitrogen, Phosphorus, and Potassium Elements in Plant Leaves

According to the values obtained from spectrophotometer measurements of the nitrogen and phosphorus standard solution, a nitrogen and phosphorus calibration curve (Figure 4A) was plotted. The concentrations of nitrogen and phosphorus in the colorimetric solution were determined from the calibration curve. Using a flame photometer to measure the potassium content and applying the formulas for total nitrogen, total phosphorus, and total potassium content, the nitrogen, phosphorus, and potassium elements in the tested plant leaves can be calculated. From Figure 4B, it can be seen that the nitrogen content in the plant leaves, from highest to lowest, is PA > PSL > PF > LL > EJ > GB > OJ > CC > LS > PT > VO > OF > LC. From Figure 4C, it can be seen that the phosphorus content in the plant leaves, from highest to lowest, is PA > GB > OF > LS > LL > OJ > PSL > CC > PF > PT > VO > LC > EJ. From Figure 4D, it can be seen that the potassium content in the plant leaves, from highest to lowest, is PA > PT > LC > GB > EJ > LL > PF > OJ > PSL > CC > VO > OF > LS.

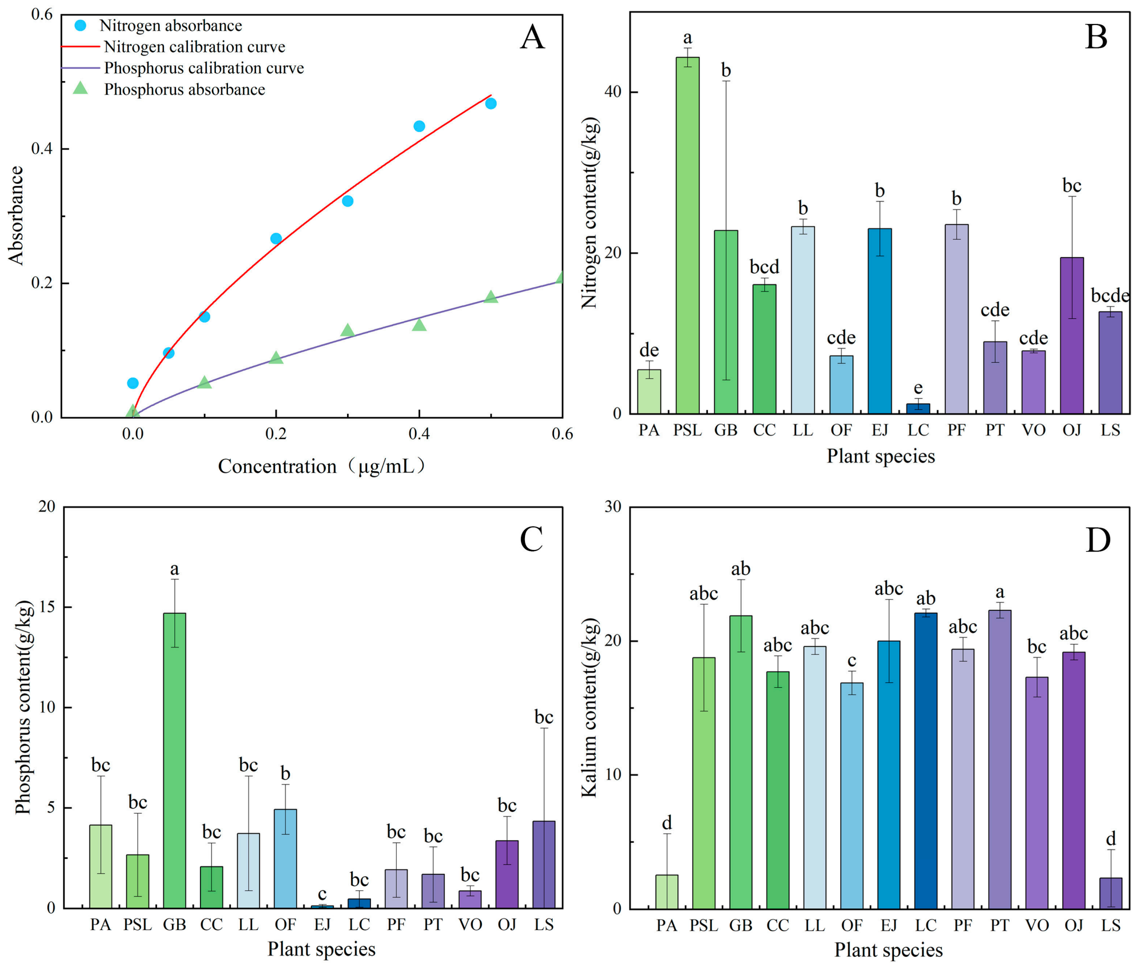

Figure 4. The working curves for nitrogen and phosphorus standard solutions (**A**), as well as the plant nitrogen (**B**), phosphorus (**C**), and potassium (**D**) content. Different lowercase letters indicate that the contents of nitrogen (**B**), phosphorus (**C**) and potassium (**D**) in leaves of different species were significantly different at the level of 0.05.

3.3. Analysis of Leaf Surface Microstructural Characteristics

Scanning electron microscopy was used to scan the cross-sections of leaves, stomata, and leaf surfaces of 13 plant species (Figure 5). The results showed that the leaf surface of PA was rough with star-shaped hairs, and particles were observed surrounding it. PSL had deep grooves around the stomata, and the leaves were hairless, with small particles observed within the grooves. GB leaves have ridges with a regular arrangement, with very few large particles remaining between the ridges; CC leaves are relatively smooth, with pronounced veins, glandular spots at the base, a slight fuzz when young, and a small amount of particles between the defense cells; LL leaf surfaces are smooth and hairless, with slightly concave midveins, and some particles remaining around the stomata; OF leaf surfaces have ridges, and the veins are noticeably concave; EJ has conspicuous veins, smooth and hairless leaf surfaces, and a relatively large amount of particles remaining around the stomata; LC leaf surfaces are rough, with clear veins and star-shaped hairs along the veins; PF leaf surfaces have shallow protrusions, clear prominent veins, serrated edges with glands, and small particles remaining on the leaf surface; PT young leaves have soft hairs, slightly curled edges, and a small amount of particles remaining on the leaf surface; VO leaves are rough and sometimes have star-shaped hairs, with noticeably concave veins and a relatively large amount of particles remaining around the stomata and on the leaf surface; OJ and LS have sunken stomata, deep ridges on the leaf surface, and a large amount of particles remaining in between.

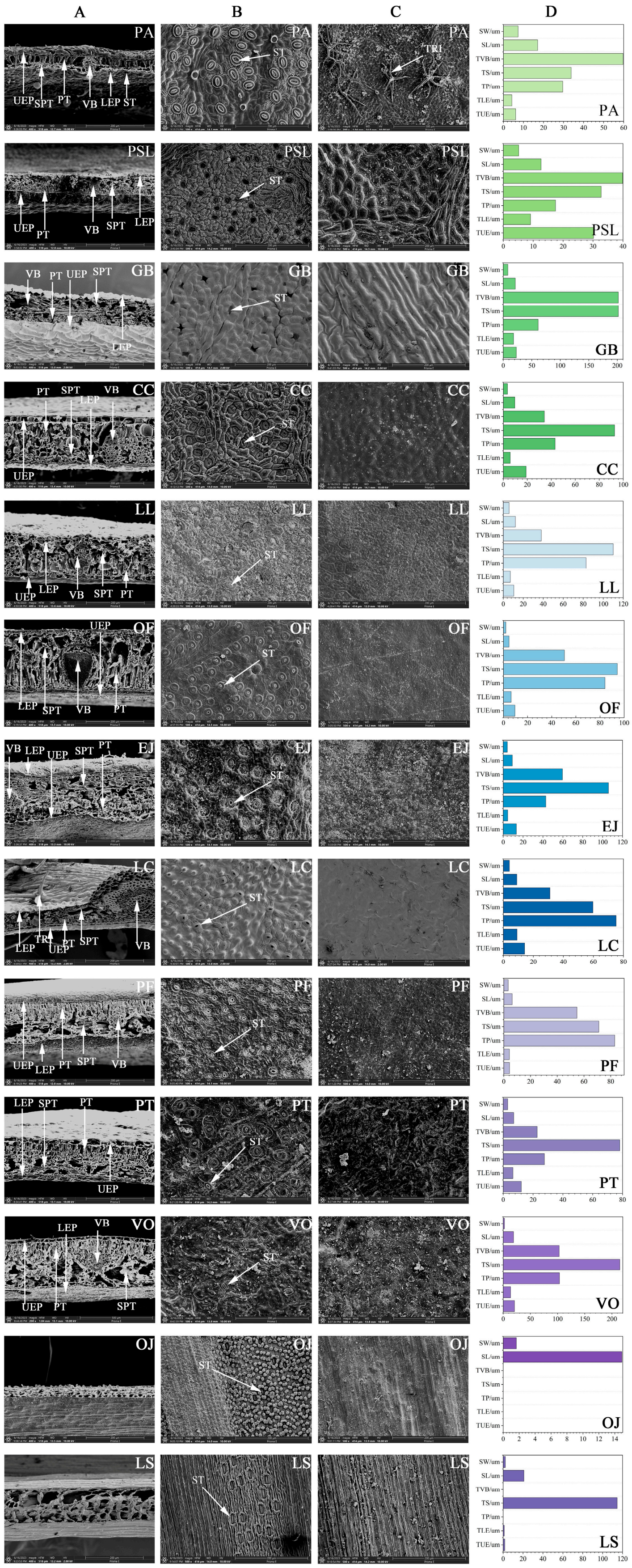

Figure 5. Electron microscope scanning of microstructures on leaf surfaces of 13 types of garden plants. (**A**) Leaf cross-section; (**B**) leaf stomata; (**C**) leaf surface; (**D**) plant microstructural parameters;

UEP: upper epidermis; LEP: lower epidermis; PT: palisade tissue; SPT:s tissue; ST: stomata; VB: vascular bundle; TRI: trichomes. TUE: upper epidermis thickness; TLE: lower epidermis thickness; TP: palisade tissue thickness; TS: spongy tissue thickness; TVB: vascular bundle thickness; SL: stomata length; SW: stomata width; PA leaf is magnified 200 times, while the rest of the blades are magnified 500 times. The cross-section of the VO leaves is magnified 400 times, and the other leaves are magnified 200 times. The stomata are magnified 500 times.

3.4. Results of Correlation Analysis between Plant Growth Indices, Elemental Content, and Dust Retention

By analyzing the correlation between the dust trapping capacity per unit leaf area, per leaf, and per plant with various growth indices of plants; nitrogen, phosphorus, and potassium content; and stomatal characteristics, we can derive the following graph. As shown in Figure 6, the tested plants' dust trapping capacity per unit leaf area shows a significant positive correlation with stomatal length ($p = 0.036$) and a highly significant negative correlation with leaf length ($p = 0.006$). The correlation between the per-leaf dust trapping capacity and the various indices is insignificant. The per-plant dust trapping capacity shows significant positive correlations with plant height ($p = 0.013$), canopy height ($p = 0.022$), and leaf width ($p = 0.011$); a highly significant positive correlation with canopy width ($p = 0.002$); and a highly significant negative correlation with potassium content ($p < 0.01$). (The higher the correlation, the smaller the *p*-value.)

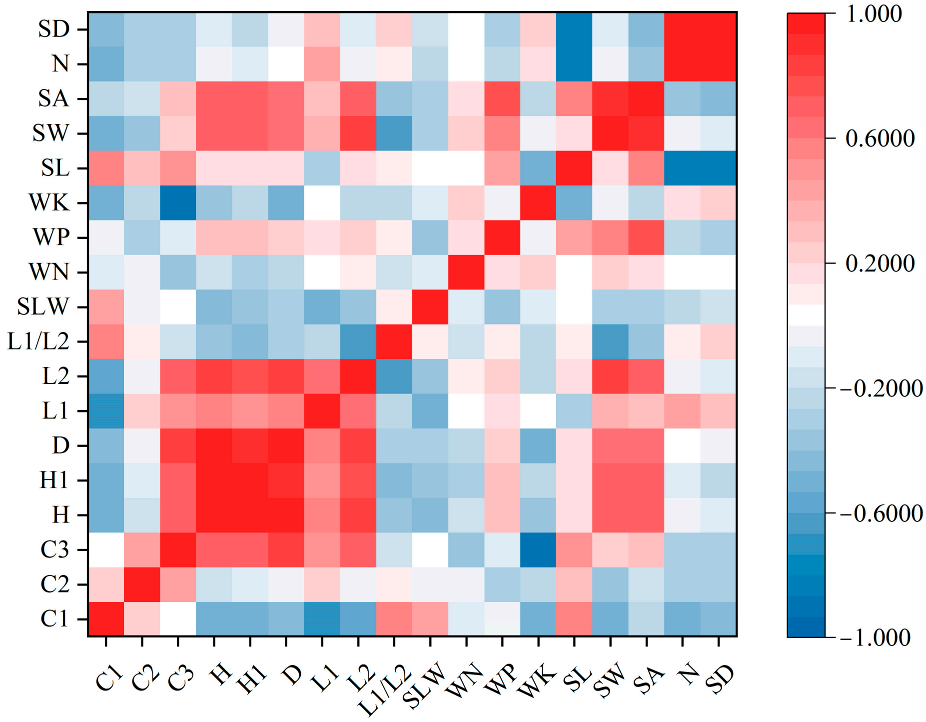

Figure 6. Correlation between dust retention of plants and various indicators. C1: dust retention per unit leaf area; C2: dust retention per leaf; C3: dust retention per individual plant; H: plant height; H1: crown height; D: crown width; L1: leaf length; L2: leaf width; L1/L2: leaf length–width ratio; SLW: specific leaf weight; WN: nitrogen content; WP: phosphorus content; WK: potassium content; SL: stomatal length; SW: stomatal width; SA: stomatal area; N: number of stomata within the field of view; SD: stomatal density.

4. Discussion

4.1. The Influence of Plant Types on Dust Retention Capacity and Its Application in Improving Urban Ecological Environment

The dust retention of different plants varies due to factors such as plant species, level of leaf density, leaf surface microstructure, and leaf texture [33,37,38]. The results of this experiment show that among the tested plants, herbaceous plants have the best dust retention effect in terms of dust retention per unit leaf area and dust retention per single leaf. This is because the surface grooves and stomatal depressions on the leaves of plants like LS and OJ can better block dust particles. Additionally, dust particles can be re-suspended by passing vehicles, but due to gravity, they tend to settle at lower heights. Conversely, trees are more susceptible to wind influence due to their taller canopy, leading to dust particles on their leaves being blown down to shrub and herb layers [39]. Therefore, herbaceous and shrubby plants have more vital dust retention abilities regarding unit leaf area and per single leaf than trees. In terms of individual plants' dust retention capacity, trees have a higher capacity compared to shrubs due to their larger foliage, as in the case of PA, a plant tested in this study with a large leaf area and crown width. It is speculated that the larger the canopy width, the more complex the structure of branches and leaves inside the canopy, and some of the particulate matter retained by the leaves is blown off by the wind, and the other part is intercepted by the rest of the branches and leaves in the canopy, resulting in a more robust individual plant dust retention capacity and overall dust retention ability. A tree–shrub–grass plant structure model can be used when selecting plants for roadside green spaces and gardens. This model has the highest foliage area per unit and can retain relatively more dust particles. It also maximizes the dust retention characteristics of different types of plants and retains dust particles at different heights, thus improving the urban ecological environment.

4.2. Influence of Leaf Surface Structure and Morphology on a Plant's Dust Retention Capacity

The morphology of plant leaf surface structures can affect the plant's dust trapping ability. Dust particles mainly accumulate around trichomes or embed in the grooves between the leaf surface ridges and stomata. Dust also accumulates in the transitional zones with different structures [40,41]. For example, in this study, OJ, LS, and VO leaves were rough on the surface with deep grooves, enabling them to trap a large amount of particles effectively—their dust trapping capacity per unit leaf area ranked the highest among the tested plants. The leaves of CC are relatively smooth and lack prominent grooves, making it difficult for them to trap particles. Therefore, the dust trapping ability per unit leaf area of CC is poor. Despite having deep grooves on the leaf surface, GB has the lowest dust trapping capacity per unit leaf area, possibly due to its hydrophobic surface that is not conducive to trapping particles, as suggested by Neinhuis et al. [42].

On the other hand, Zhou et al. [43] proposed that the depth and width of the grooves on the leaves of GB affect its dust trapping effect. PA has a rough leaf surface with star-shaped hairs, but its dust trapping capacity per unit leaf area is poor, possibly because PA plants are relatively tall and Nanjing City receives ample rainfall, causing particles on the leaf surface to be blown off by wind or washed away by rainwater. PT has young leaves with soft hairs and slightly curled leaf blades, demonstrating a moderate dust trapping ability per leaf. EJ has smooth leaves but a good dust trapping capacity per unit leaf area. LC has rough leaves with star-shaped hairs, but its dust trapping capacity per unit leaf area is poor, possibly due to its growth conditions. Therefore, plants with rough leaf surfaces and trichomes can be chosen when selecting plants for roadside green spaces while ensuring proper maintenance and management to achieve the desired ecological benefits.

4.3. The Impact of Stomata on Dust Retention in Plants

This study found a significant positive correlation between unit leaf area dust retention and stomatal length but not with other indicators such as stomatal area. This is different from the findings of Simon [44]. Zhong Linlin et al. believe that the larger the stomata, the stronger the transpiration of plant leaves, which increases the humidity of the air near the leaves and contributes to the retention of particles on the leaf surfaces [45]. On the other hand, Liu Lu believes that when the stomata are open, particles adhere inside the stomata and are less likely to be blown off by wind or washed away by rainwater [13]. The openness of plant stomata is easily influenced by environmental factors, which may affect the dust retention capacity of plants. In summary, plant height, crown width, leaf surface microstructure, and weather can all impact a plant's dust retention capacity to some extent. Therefore, the strength of a plant's dust retention capacity results from the combined effects of multiple factors.

This study focused on the dust retention capacity of different plants during the peak growth season (late spring and early summer) of Xuanwu Avenue in Nanjing, and other tree species with dust retention ability could be further included in the research scope in the future, while the phenological factors of the same plants also need to be further studied.

5. Conclusions

This study used Xuanwu Avenue in Nanjing as a case study to investigate the dust retention abilities of different plants by quantitatively measuring dust retention. The study examined plant growth indicators, nitrogen–phosphorus–potassium content, and the correlation between leaf surface microstructure and dust retention abilities. The following conclusions were drawn, which can provide a reference for rational planning of urban green space, reducing the cost of air pollution control, improving the quality of human life, maintaining the stability of the ecosystem, and promoting the sustainable development of the city in many aspects:

(1) Regarding dust retention per unit leaf area, herbaceous plants > shrubs > trees, with LS and OJ showing the best dust retention effects. Regarding dust retention per single leaf, herbaceous plants > shrubs > trees, with VO, PSL, and LS showing the best dust retention effects. Regarding dust retention per individual plant, trees > shrubs, with PA showing the best dust retention effect. Among the tested trees and shrubs, VO, PA, and PSL have the best overall dust retention ability and should be considered priority tree species for urban greening.

(2) The potassium element content in the tested plants shows a significant negative correlation with dust retention per individual plant. Therefore, selecting garden plants with lower potassium content, such as PA, is advisable to ensure average plant growth and development.

(3) Plant growth indicators play a significant role in dust retention. Plant height, crown width, and crown height are significantly positively correlated with dust retention per single plant. Therefore, a combination of trees, shrubs, and herbaceous plants, such as PA-VO-LS, can be used in urban roadside green spaces to maximize the ecological value of plants. Leaf stomatal length positively correlates with dust retention per unit leaf area, while leaf surface roughness, grooves, and trichomes also affect a plant's dust retention ability.

Author Contributions: Conceptualization, Q.S.; Methodology, Q.S.; Software, R.Y.; Validation, W.L.; Formal analysis, X.Z. (Xiru Zhang); Investigation, C.M.; Data curation, X.Z. (Xiangyi Zhang) and X.Z. (Xiru Zhang); Writing–original draft, X.Z. (Xiangyi Zhang); Writing–review & editing, X.Z. (Xiangyi Zhang); Visualization, X.Z. (Xiangyi Zhang); Supervision, Q.S.; Project administration, Z.Z.; Funding acquisition, Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Education Humanities and Social Sciences Research "Study on the new mechanism of urban green space ecological benefit Measurement and high-quality collaborative development: A case study of Nanjing Metropolitan Area": grant number 21YJCZH131;Young elite scientist sponsorship program by cast in China Association for Science and Technology: grant number YESS20220054; Social Science Foundation Project of Jiangsu Province: grant number 21GLC002; National Natural Science Foundation of China: grant number 32101582; Natural Science Foundation of Jiangsu Province of China: grant number BK20210613; The Natural

Science Foundation of the Jiangsu Higher Education Institutions of China: grant number 21KJB220008; The National Natural Science Foundation of China: grant number 32071832. "Qing Lan Project" in Jiangsu Province of China: None. And the APC was funded by Qianqian Sheng.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: Author Ruizhen Yang was employed by the company Nanjing Sky Hunt Data Technology Co., Ltd. The remaining 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.

References

1. Bao, H.G.; Wang, C.; Du, W.G. Research progress on dust detention effect of urban trees. *J. Ecol. Rural. Environ.* **2021**, *37*, 1514–1523.
2. Dong, Y.W. Influence of Total Suspended Particulate Matter in Ambient Air on Human Health. *Environ. Sci. Manag.* **2022**, *47*, 93–97.
3. Zhao, H.; Che, H.; Zhang, X.; Ma, Y.; Wang, Y.; Wang, H.; Wang, Y. Characteristics of visibility and particulate matter (PM) in an urban area of Northeast China. *Atmos. Pollut. Res.* **2013**, *4*, 427–434. [CrossRef]
4. Ma, C. Analysis of the Health Impact of Air Suspended Particulate Pollution Concentration on Outdoor Fitness Population. *Environ. Sci. Manag.* **2019**, *44*, 88–91.
5. Du, P.R.; Du, R.; Ren, W.S. Research progress on toxicological characteristics and mechanisms of urban atmospheric particulate matters. *China Environ. Sci.* **2016**, *36*, 2815–2827.
6. Singh, M.; Jaques, P.A.; Sioutas, C. Size distribution and diurnal characteristics of particle-bound metals in source and receptor sites of the Los Angeles Basin. *Atmos. Environ.* **2002**, *36*, 1675–1689. [CrossRef]
7. Nowak, D.J.; Crane, D.E.; Stevens, J.C. Air pollution removal by urban trees and shrubs in the United States. *Urban For. Urban Green.* **2006**, *4*, 115–123. [CrossRef]
8. Wang, Z.Y.; Chen, X.; Hu, X.S.; He, H.D.; Cai, M.; Peng, Z.R. Mechanism and research methods of roadside green barriers affecting the distribution of atmospheric particulate matter: A review. *Ecol. Environ. Sci.* **2022**, *31*, 1047–1058.
9. Zheng, G.; Li, P. Resuspension of settled atmospheric particulate matter on plant leaves determined by wind and leaf surface characteristics. *Environ. Sci. Pollut. Res.* **2019**, *26*, 19606–19614. [CrossRef]
10. Zhou, J.; Wu, Y.; Zhang, L.J.; Pang, M.; Huang, D.Z.; Niu, X.Y. The study of dust-retention ability of some common shurb in Baoding. *For. Ecol. Sci.* **2019**, *34*, 114–120.
11. Beckett, K.P.; Freer-Smith, P.H.; Taylor, G. The capture of particulate pollution by trees at five contrasting urban sites. *Arboric. J.* **2000**, *24*, 209–230. [CrossRef]
12. Li, H.M.; Dang, N.; Yu, L.Q.; Zhang, H.D.; Chen, G.C. Relationship between dust retention capacity and leaf surface morphology and particulate matter size of five garden tree species. *For. Res.* **2021**, *34*, 84–94.
13. Liu, L.; Guan, D.S.; Chen, Y.Q. Morphological structure of leaves and dust-retaining capability of common street trees in Guangzhou Municipality. *Acta Ecol. Sin.* **2013**, *33*, 2604–2614. [CrossRef]
14. Zhang, C.; Song, Y.; Wu, H.; Wu, J.Q.; Jiang, T.T.; Shao, Z.; Li, Y.Y. Research Overview on Dust-retention Ability of Border Trees. *Mod. Agric. Sci. Technol.* **2018**, *8*, 144–146.
15. Chen, L.; Liu, C.; Zhang, L.; Zou, R.; Zhang, Z. Variation in Tree Species Ability to Capture and Retain Airborne Fine Particulate Matter (PM(2.5)). *Sci. Rep.* **2017**, *7*, 3206. [CrossRef]
16. Weerakkody, U.; Dover, J.W.; Mitchell, P.; Reiling, K. Evaluating the impact of individual leaf traits on atmospheric particulate matter accumulation using natural and synthetic leaves. *Urban For. Urban Green.* **2018**, *30*, 98–107. [CrossRef]
17. Sabin, L.D.; Hee Lim, J.; Teresa Venezia, M.; Winer, A.M.; Schiff, K.C.; Stolzenbach, K.D. Dry deposition and resuspension of particle-associated metals near a freeway in Los Angeles. *Atmos. Environ.* **2006**, *40*, 7528–7538. [CrossRef]
18. Dzierzanowski, K.; Popek, R.; Gawrońska, H.; Saebø, A.; Gawroński, S.W. Deposition of particulate matter of different size fractions on leaf surfaces and in waxes of urban forest species. *Int. J. Phytoremediation* **2011**, *13*, 1037–1046. [CrossRef]
19. Sæbø, A.; Popek, R.; Nawrot, B.; Hanslin, H.M.; Gawronska, H.; Gawronski, S.W. Plant species differences in particulate matter accumulation on leaf surfaces. *Sci. Total Environ.* **2012**, *427–428*, 347–354. [CrossRef]
20. Perini, K.; Ottelé, M.; Giulini, S.; Magliocco, A.; Roccotiello, E. Quantification of fine dust deposition on different plant species in a vertical greening system. *Ecol. Eng.* **2017**, *100*, 268–276. [CrossRef]
21. Wang, L.; Gao, S.Y.; Liu, L.Y.; Ha, S. Atmospheric particle-retaining capability of eleven garden plant species in Beijing. *Chin. J. Appl. Ecol.* **2006**, *17*, 4597–4601.
22. Pal, A.; Kulshreshtha, K.; Ahmad, K.J.; Behl, H.M. Do leaf surface characters play a role in plant resistance to auto-exhaust pollution? *Flora—Morphol. Distrib. Funct. Ecol. Plants* **2002**, *197*, 47–55. [CrossRef]

23. Xie, B.Z. The Retention Capability of PM2.5 and Its Explanation by Leaf Surface Micro-Structure and Configuration of Urban Green Plant. Master's Thesis, Xi'an University of Architecture and Technology, Xi'an, China, 2016.
24. Lin, M.-Y.; Khlystov, A. Investigation of Ultrafine Particle Deposition to Vegetation Branches in a Wind Tunnel. *Aerosol Sci. Technol.* **2012**, *46*, 465–472. [CrossRef]
25. Du, W.G. Research of Change Characteristics Carried by Particulate Matter in Urban Green Lands Under Different Lands Scales and Influencing Factors in Beijing. Ph.D. Thesis, Chinese Academy of Forestry, Beijing, China, 2017.
26. Qin, F. Analysis of Particulate Air Pollution and Preliminary Study on the Pollution Source in Different Function Area of Jiaozuo City. Master's Thesis, Henan Polytechnic University, Jiaozuo, China, 2014.
27. Sternberg, T.; Viles, H.; Cathersides, A.; Edwards, M. Dust particulate absorption by ivy (*Hedera helix* L) on historic walls in urban environments. *Sci. Total Environ.* **2010**, *409*, 162–168. [CrossRef]
28. Nanos, G.D.; Ilias, I.F. Effects of inert dust on olive (*Olea europaea* L.) leaf physiological para. *Environ. Sci. Pollut. Res. Int.* **2007**, *14*, 212–214. [CrossRef] [PubMed]
29. Rai, A.; Kulshreshtha, K.; Srivastava, P.; Mohanty, C.S.J.T.E. Leaf surface structure alterations due to particulate pollution in some common plants. *Environmentalist* **2010**, *30*, 18–23. [CrossRef]
30. Patel, K.; Bhandari, S.; Gani, S.; Kumar, P.; Baig, N.; Habib, G.; Apte, J.; Hildebrandt Ruiz, L. Factors influencing ambient particulate matter in Delhi, India: Insights from machine learning. *Aerosol Sci. Technol.* **2023**, *57*, 546–561. [CrossRef]
31. Gao, J.H. Influence Mechanism and Effectiveness of the Plants on Detaining Dust in Beijing. Master's Thesis, Beijing Forestry University, Beijing, China, 2007.
32. Zhu, L.Q.; Long, M.Y.; Yang, F.L.; Lv, J.J.; Zhao, L.J. Relationship between leaf phenotype, epidermal ultrastructure and dust retaining capability of seven greening shrubs. *Chin. J. Trop. Crops* **2023**, *44*, 1297–1305.
33. Prajapati, S.K.; Tripathi, B.D. Seasonal Variation of Leaf Dust Accumulation and Pigment Content in Plant Species Exposed to Urban Particulates Pollution. *J. Environ. Qual.* **2008**, *37*, 865–870. [CrossRef]
34. Wang, X.; Yang, J.Y.; Yu, Y.C.; Hou, W.J.; Hou, Y.; Yu, J.; Wang, R.H. Concentration and sources of black carbon in urban forest soils in different functional areas of Nanjing, China. *Acta Ecol. Sin.* **2016**, *36*, 837–843.
35. Niu, X.; Wang, B.; Wei, W. Response of the particulate matter capture ability to leaf age and pollution intensity. *Environ. Sci. Pollut. Res.* **2020**, *27*, 34258–34269. [CrossRef]
36. Baidourela, A. Dust Retention Capacity of Common Tree Species for Urban Greening in Aksu City, Northwest China. Ph.D. Thesis, Xinjiang University, Ürümqi, China, 2015.
37. Chai, Y.X.; Zhu, N.; Han, H.J. Dust removal effect of urban tree species in Harbin. *Chin. J. Appl. Ecol.* **2002**, *13*, 1121–1126.
38. Chen, F.; Zhou, Z.X.; Wang, P.C.; Li, H.F.; Zhong, Y.F. Green space vegetation quantity in workshop area of Wuhan Iron and Steel Company. *Chin. J. Appl. Ecol.* **2006**, *17*, 4592–4596.
39. Wang, S.H.; Zhu, X.Y.; Tian, R.N.; Wen, S.S. Comprehensive analysis of dust retention efficiency of six common garden plants in Nanjing. *Chin. Landsc. Archit.* **2021**, *37*, 111–116.
40. Li, H.J.; Xu, A.L.; Qiao, F.L.; Jiang, M.; Song, Q. Micro-morphological characteristics of particles on Holly and Ligustrum leafSurfaces and seasonal changes in bacterial communities. *Environ. Sci.* **2021**, *42*, 3063–3073.
41. Speak, A.F.; Rothwell, J.J.; Lindley, S.J.; Smith, C.L. Urban particulate pollution reduction by four species of green roof vegetation in a UK city. *Atmos. Environ.* **2012**, *61*, 283–293. [CrossRef]
42. Neinhuis, C.; Barthlott, W. Seasonal changes of leaf surface contamination in beech, oak, and ginkgo in relation to leaf micromorphology and wettability. *New Phytol.* **1998**, *138*, 91–98. [CrossRef]
43. Zhou, Y.W.; Tian, Z.P.; Su, X. Relationships between leaf epidermal morphology and dust capacity of common street trees in Harbin Municipality. *J. Northwest For. Univ.* **2017**, *32*, 287–292.
44. Simon, E.; Baranyai, E.; Braun, M.; Cserháti, C.; Fábián, I.; Tóthmérész, B. Elemental concentrations in deposited dust on leaves along an urbanization gradient. *Sci. Total Environ.* **2014**, *490*, 514–520. [CrossRef]
45. Zhong, L.L.; Zheng, L.; Qu, Y.D. The dust-retention capability of street trees and its Mechanism in Zhanjiang, a tropical city. *Ecol. Sci.* **2019**, *38*, 86–93.