

Article

A Case Study of Leaf Wettability Variability and the Relations with Leaf Traits and Surface Water Storage for Urban Landscape Plants

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Abstract: Leaf wettability, the affinity of a leaf surface to water droplets, affects the interactions between leaves and external environments. This study aimed to determine the interspecific and seasonal variabilities of leaf wettability across 30 common landscape plants, and their relationships with leaf functional traits, surface micromorphology and rainfall interception in Hefei city, China. Results indicated that leaf wettability was species-specific, and the adaxial and abaxial contact angles ranged from 63° to 134° and 66° to 134°, respectively, with the adaxial surface proving more wettable. Leaf wettability gradually increased from spring to winter. Classification of life forms revealed that there were no significant wettability differences among trees, shrubs and herbs, and between evergreen and deciduous plants, but deciduous plants' wettability increased more significantly in winter. Leaf wettability was not significantly correlated with any leaf functional traits. Single surface microscopic parameters also had low correlations with leaf wettability. Instead, the low-wettability species were found to possess more prominent epidermis cells, dense waxy layers or trichomes on leaf surfaces. Leaf wettability was the best predictor of surface rainwater storage within all functional traits. Our results highlighted that leaf wettability was variable between different species and growth periods due to micromorphological differences, and significantly affected rainfall interception at the leaf scale, which may have great significance for evaluating plant hydrological function in urban areas.



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Keywords: leaf wettability; seasonality; leaf functional traits; surface micromorphology; urban hydrology

1. Introduction

Leaf wettability reflects the repellency of a leaf surface to water droplets, atmospheric pollutants or pathogenic microorganisms, thus affecting the interactions and ecological functions of the leaf surface in regard to the external environment. In natural conditions, leaf wetting occurs frequently as a result of rainfall and dew, and the extent and duration of wetting are closely related to leaf wettability and plant ecohydrological effects [1]. Surface wetting can have both positive and negative effects for individual plants and regional ecosystems. The water droplets or films on leaf surfaces can be absorbed to alleviate leaf drought stress in water-limited areas [2]. Conversely, the blocked gas exchange on the stomates may suppress leaf photosynthesis and normal growth [3]. For excessively wetted leaves, nutrient leaching and adhesion of pathogens and particulate pollutants are more likely to occur and to be harmful [4,5]. In particular, leaf surface retention of rainwater greatly alters rainfall redistribution characteristics by reducing the net rainfall amount to the ground and weakening raindrop kinetic energy and splash [6,7]. These rainfall cycle changes dramatically affect water balance and water-resource management in certain regions [8]. Thus, leaf wettability may be an important functional trait to be studied for evaluating vegetation's environmental and hydrological effects.

Leaf wettability is expressed by the contact angle between the water droplet and leaf surface, with the larger the contact angle, the lower the wettability of the leaf surface to the droplet [4]. Leaf surfaces were found to range from completely wettable to virtually non-wettable for different plant species [4]. For instance, *Nelumbo nucifera* has a surface contact angle of up to 150° and is highly hydrophobic with self-cleaning properties [9]. Extremely hydrophilic leaf surfaces are also common in various habitats, and their specific surface properties have attracted great interest in material and biological sciences [10]. Gramineous and Leguminous species were more hydrophobic than Compositae and Rosaceous species in the semiarid Loess Plateau of China [1]. Even the same species can have significantly different leaf wettability after long-term adaption to certain environments. Decreased leaf wettability was considered a selective strategy to either favor leaf water uptake or increase soil water replenishment in drought-prone regions [8,11]. Variability in interspecific or intraspecific leaf wettability was found among different species types, plant growth stages and external habitat conditions [12–14].

These differences in leaf wettability may relate to leaf surface physicochemical properties, including leaf surface wax structure and chemical composition, epidermal cell morphology, trichome morphology and density, stomata size and distribution, etc. [15–17]. The high hydrophobicity of tender and mature *N. nucifera* leaves was mainly caused by the presence of dense waxy crystals and microbumps on their surface [18]. When leaf surface wax was removed or the leaf senesced, the contact angle decreased significantly and the leaf became easily wettable [18,19]. The presence of trichomes or a high trichome density on leaf surfaces tended to reduce their wettability [12]. These leaf surface properties are variable during plant growth and are strongly influenced by external environmental factors such as rainfall, air temperature and humidity [20,21]. Leaf morphological features, such as leaf area, leaf thickness and leaf dry matter content, also respond markedly to these variations [22], and, thus, may affect leaf wettability. However, few studies have examined the variation range and influence factors of leaf wettability in urban landscape plants; in particular, the integrated impact of leaf functional traits and surface microscopic parameters on wettability are still worth further investigating.

The rapid development of urbanization has greatly changed urban land utilization types, with decreased natural vegetation and increased prevalence of impervious underlying surfaces, which aggravates urban flood disaster and water security risks under changing global rainfall patterns [23]. Landscape plants are the key component of urban green space ecosystems, and the canopy rainfall interception they provide significantly affects the hydrologic cycle and urban surface runoff [6]. Interception loss refers to the amount of rainfall that evaporates back into the atmosphere after being retained on plant leaf, stem or branch surfaces, accounting for 10–50% of gross rainfall [7]. Changes in leaf wettability may affect plant rainfall interception and the generation of surface runoff [24]. Determining the variability in leaf wettability and the relationship with plant rainfall interception contributes to the selection and introduction of landscape plants, thereby improving natural-based solutions for urban water systems management.

Hefei city is one of the first “National Garden Cities” of China, and the main landscape plants include *Magnolia grandiflora*, *Cinnamomum camphora*, *Platanus orientalis*, etc., which provide important ecosystem services such as rainfall interception, carbon fixation, oxygen release and environmental improvement. In this study, 30 common urban landscape plants (including trees, shrubs and herbs, evergreen and deciduous, broadleaved and coniferous plants) were selected in Hefei city, China. The adaxial and abaxial leaf contact angles, common leaf functional traits, leaf surface microstructure and wax content and leaf surface water storage were systematically measured throughout the whole growing season. The main objectives of this study were (1) to quantify the variation range of leaf wettability and the interspecific differences in landscape plants; (2) to analyze the variation trends in leaf wettability of leaf sides, growth seasons and life forms; (3) to investigate the relationships between leaf wettability and leaf functional traits and surface micromorphology, and examine whether leaf wettability can affect leaf surface water storage. The study hypotheses

were (1) there are significant interspecific and seasonal differences in leaf wettability due to different surface micromorphology; (2) leaf wettability can determine the magnitude of leaf rainfall interception in urban green spaces.

2. Materials and Methods

2.1. Site Description

This study was conducted at the campus of Anhui Agricultural University ($31^{\circ}85'85''$ – $31^{\circ}87'10''$ N, $117^{\circ}24'54''$ – $117^{\circ}25'84''$ E; 30 m a.s.l.) in Hefei city, Anhui Province, China (Figure 1). Hefei is characterized by a northern subtropical monsoon climate, with four distinctive seasons, in which the summer is hot and humid and the winter is dry and cold. The annual average air temperature is 15.7°C and the relative humidity is 77%. The sunshine duration is 2100 h and the frost-free period is 228 days. The average annual rainfall is 1000 mm, mainly distributed in summer (approximately 50% from June to August) [25]. Extreme rainfall events have occurred frequently in recent years; for instance, the bimestrial rainfall reached 820 mm from June to July in 2020, 232% higher than the normal season, resulting in serious urban flooding and ecological damage to urban waterways.

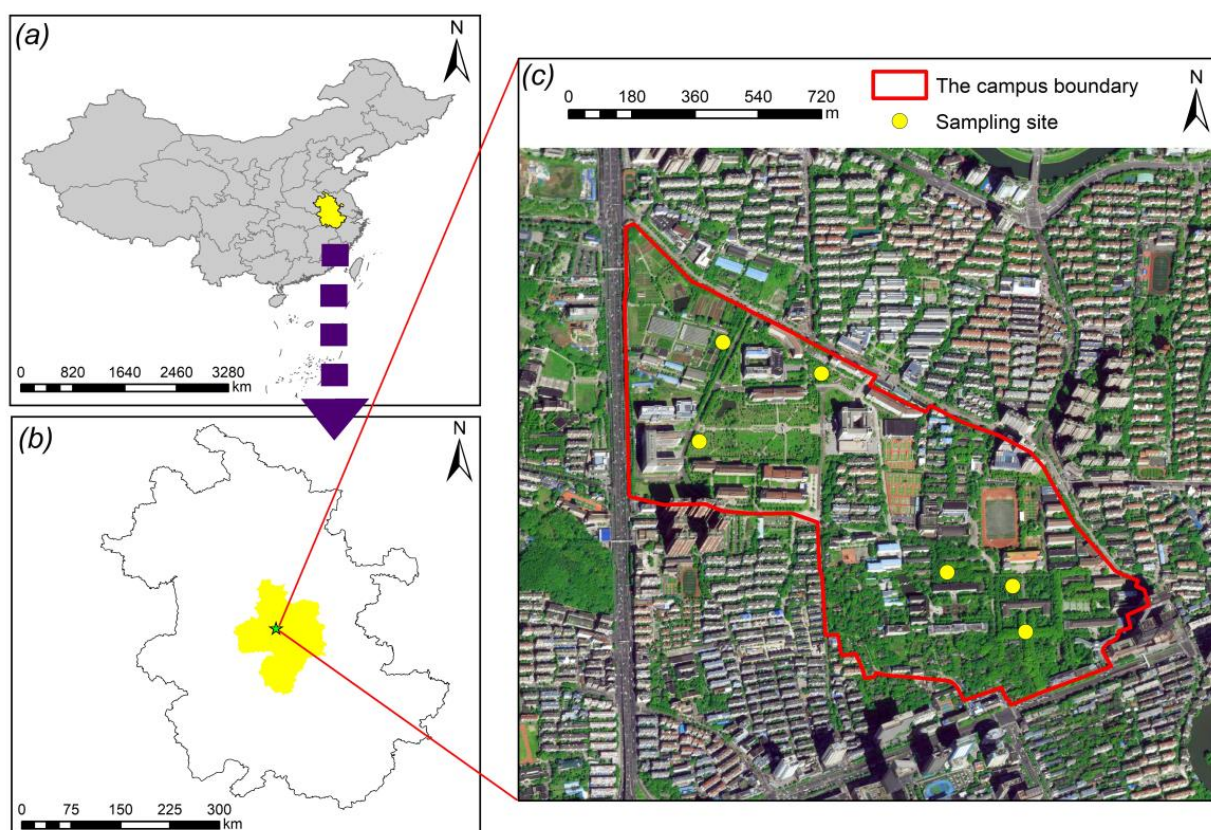


Figure 1. The location of sampling sites on the campus of Anhui Agricultural University (c), Hefei city, Anhui Province (b), China (a).

Until the end of 2020, the built-up area of Hefei city was 528.5 km², with 46% green coverage ratio, 40.3% green land ratio and 13 m² public green area per capita in the urban area. The university is located in Shushan District, with a campus area of 93.7 hm², of which 21.3 hm² is green space. The campus has great garden landscape and plant diversity, with approximately 168 landscape species, including 146 woody species, 16 herbaceous species and 6 species of vines and aquatic plants. Common urban landscape plants are included in the campus, and effective conservation management ensures plant growth and development.

2.2. Experimental Design and Plant Sampling

The experiment was conducted during the whole plant-growing season (spring: April to May 2021, summer: July to August 2021, autumn: October to November 2021 and winter: January to February 2020). After investigating the distribution status and biological characteristics of common landscape plants in Hefei, 30 widely distributed species of different life forms with different canopy structures and leaf traits were selected, including 15 trees, 12 shrubs and 3 herbs, or 13 evergreen broadleaved, 12 deciduous broadleaved, 1 evergreen coniferous and 1 deciduous coniferous species (Table 1, Figure S1). Six sampling sites with areas from 500 to 2500 m² were determined according to the actual site conditions in the campus. At least five individual plants were selected for each tree and shrub, and five 1 × 1 m quadrats were set for each herb. A total of 30–60 healthy, fully developed and representative leaves were collected from each species in each season. For trees and shrubs, leaves were collected from different directions and plant heights, i.e., upper, middle and lower points [26]. Herbaceous leaves were collected from the upper and middle parts. Plant leaves were sampled in the morning (8:00–9:00 am) and placed in a portable cool box, then were immediately transported to the laboratory and stored in a freezer at 4 °C [27]. All the sample processing and analyses were completed within 1 day after sampling. The collected samples were then used to measure leaf wettability, functional traits and surface water storage (each species with 5 to 10 replicates) for all four seasons, and leaf surface micromorphology and wax content were determined only for the summer season.

Table 1. The Latin names, abbreviations, families, life forms and leaf adaxial/abaxial contact angles of 30 common urban landscape plants.

Species	Abbreviations	Families	Life Forms	Leaf Contact Angle (°, Mean ± SE)	
				Adaxial	Abaxial
<i>Acer palmatum</i>	AP	Aceraceae	D-B-T	82 ± 6 a	93 ± 4 a
<i>Albizia julibrissin</i>	AJ	Leguminosae	D-B-T	120 ± 3 a	132 ± 1 a
<i>Buxus sinica</i>	BS	Buxaceae	E-B-S	79 ± 6 a	91 ± 5 a
<i>Chimonanthus praecox</i>	CP	Calycanthaceae	D-B-S	78 ± 5 a	91 ± 5 a
<i>Cinnamomum camphora</i>	CC	Lauraceae	E-B-T	82 ± 2 b	126 ± 2 a
<i>Gardenia jasminoides</i>	GJ	Rubiaceae	E-B-S	83 ± 4 a	77 ± 6 a
<i>Ginkgo biloba</i>	GB	Ginkgoaceae	D-C-T	88 ± 12 b	123 ± 5 a
<i>Hypericum monogynum</i>	HM	Guttiferae	E-B-S	122 ± 4 a	134 ± 1 a
<i>Ligustrum lucidum</i>	LL	Oleaceae	E-B-S	89 ± 4 a	94 ± 9 a
<i>Liriodendron chinense</i>	LCs	Magnoliaceae	D-B-T	102 ± 12 b	128 ± 6 a
<i>Loropetalum chinense</i>	LCr	Hamamelidaceae	E-B-S	110 ± 8 b	133 ± 3 a
<i>Magnolia grandiflora</i>	MG	Magnoliaceae	E-B-T	78 ± 7 b	121 ± 9 a
<i>Malus halliana</i>	MH	Rosaceae	D-B-T	83 ± 5 a	92 ± 2 a
<i>Nandina domestica</i>	ND	Berberidaceae	E-B-S	102 ± 5 a	114 ± 6 a
<i>Osmanthus fragrans</i>	OF	Oleaceae	E-B-S	83 ± 4 a	87 ± 2 a
<i>Photinia serratifolia</i>	PSk	Rosaceae	E-B-S	76 ± 4 a	88 ± 3 a
<i>Phyllostachys sulphurea</i>	PSv	Gramineae	E-B-T	75 ± 2 b	131 ± 1 a
<i>Pinus parviflora</i>	PP	Pinaceae	E-C-T	74 ± 5 a	66 ± 5 a
<i>Pittosporum tobira</i>	PT	Goodeniaceae	E-B-S	71 ± 7 a	90 ± 4 a
<i>Platanus orientalis</i>	PO	Platanaceae	D-B-T	84 ± 4 a	86 ± 6 a
<i>Prunus cerasifera</i>	PC	Rosaceae	D-B-T	69 ± 7 b	94 ± 4 a
<i>Salix babylonica</i>	SB	Salicaceae	D-B-T	73 ± 4 b	120 ± 5 a
<i>Sapindus mukorossi</i>	SM	Sapindaceae	D-B-T	78 ± 6 a	83 ± 6 a
<i>Sophora japonica</i>	SJ	Leguminosae	D-B-T	89 ± 14 b	126 ± 3 a
<i>Spiraea salicifolia</i>	SS	Rosaceae	D-B-S	98 ± 10 a	111 ± 9 a
<i>Ulmus pumila</i>	UP	Ulmaceae	D-B-T	69 ± 4 a	78 ± 3 a
<i>Viburnum odoratissimum</i>	VO	Caprifoliaceae	E-B-S	88 ± 6 a	82 ± 5 a
<i>Cynodon dactylon</i>	CD	Gramineae	Perennial herb	125 ± 4 a	119 ± 5 a
<i>Ophiopogon bodinieri</i>	OB	Liliaceae	Perennial herb	63 ± 5 a	76 ± 3 a
<i>Oxalis corniculata</i>	OC	Oxalidaceae	Perennial herb	134 ± 1 a	79 ± 5 b

Note: In the column “life forms”, E and D represent evergreen and deciduous plants; B and C represent broadleaves and conifers; T and S represent trees and shrubs, respectively. Different small letters within a row indicate significant differences between leaf abaxial and adaxial contact angles.

2.3. Measurement of Leaf Wettability

Leaf wettability was determined by measuring the contact angle (CA, °) between the water droplets and the adaxial/abaxial surfaces. Leaf surfaces with a CA < 40° are generally classified as super-hydrophilic, 40° < CA < 90° as highly wettable, 90° < CA < 110° as wettable, 110° < CA < 130° as nonwettable, 130° < CA < 150° as highly nonwettable and CA > 150° as super-hydrophobic [4]. Leaves were sectioned into 5 × 5 mm samples to avoid leaf veins and margins, and then fixed horizontally on a glass slide with double-sided tape. A 6 µL droplet of distilled water (for broadleaves) and 2 µL droplet (for conifers) was deposited on leaf surfaces with a micropipette (50–100 µL). The contact angle was obtained in accordance with the photoconductive method based on charge-coupled-device imaging (magnification rate: 266 Pixel MM⁻¹) and calculated by the average value of the tangential angles on two sides of the water droplet. Each measurement was completed within 2 min using a contact angle goniometer (FCA2000A2, Shanghai Ifesi Precision Instrument Co., Ltd., Shanghai, China).

2.4. Measurements of Leaf Functional Traits

Leaf samples were wiped lightly using tissue paper to remove surface contaminants, and then spread out on white hardboard and covered with a transparent plastic sheet. A portable leaf area meter (Yaxin-1241, Beijing Yaxin Liyi Technology Co., Ltd., Beijing, China) was used to fully scan the sample, and the leaf area (LA, m²), leaf perimeter (LP, m), leaf length (LL, m) and leaf width (LW, m) were accurately determined. The petiole length (PL, m) was measured with a steel ruler at an accuracy of 0.1 mm. Leaf thickness (LT, mm) was measured with a digital vernier caliper at an accuracy of 0.01 mm. Leaf fresh weight (LFW, g) and dry weight (LDW, g) were measured with an electronic balance at an accuracy of 0.0001 g (FA2004, Shanghai Sunny Hengping Instrument Co., Ltd., Shanghai, China). The leaves were dried in an oven at 75 °C for 48 h to a constant weight for determining the dry weights. The specific leaf area (SLA, m² g⁻¹) was calculated as LA divided by LDW, and leaf dry matter content (LDMC, g g⁻¹) was calculated as LDW divided by LFW.

2.5. Measurements of Leaf Wax Content and Surface Micromorphology

The collected leaf samples were washed with running distilled water and gently dried with paper towels. After measuring the leaf area, each leaf was cut into pieces and placed in a beaker, which was weighed with an electronic balance at an accuracy of 0.0001 g. The sample in the beaker was immersed in 20–30 mL of chloroform depending on the sample size and shaken for 1 min at a speed of 120 rpm to fully extract surface wax. The leaves were picked out carefully with tweezers, and the beaker was placed in a fume hood until the chloroform evaporated completely. The beaker was reweighed, and leaf wax content (g) was calculated as the difference before and after the extraction [28]. For each species, the treatment was replicated 10 times.

Leaf adaxial and abaxial epidermal microstructure were both observed using a scanning electron microscope (Zeiss Gemini 300, Carl Zeiss Co., Ltd., Shanghai, China). Samples of 5 mm × 5 mm size were cut from both the leaf adaxial and abaxial surfaces for each species. The samples were placed in 1.5 mL centrifuge tubes and fixed with 2.5% glutaraldehyde for 12 h at 4 °C. The fixative was poured off and the samples were rinsed 3 times with phosphate buffer (0.1 mL, pH 7.0) for 15 min each time. After fixing the samples with 1% osmic acid solution for 1–2 h, the osmic acid waste solution was removed, and the previous step was repeated. Six ethanol solutions including 30%, 50%, 70%, 80%, 90% and 95% concentrations were used to dehydrate the samples for 15 min each, followed by two treatments of 100% ethanol for 20 min each. The samples were treated with a mixture of ethanol and isoamyl acetate (V/V = 1/1) for 30 min, and then treated with pure isoamyl acetate for 1 h or left overnight. After drying and gilding the samples, the leaf surface micromorphology was observed using SEM under vacuum conditions [5,29]. For each species, thirty-six images (eighteen images each for the adaxial and abaxial surfaces) were acquired with 200×, 500×, 1000×, 3000×, 5000× and 10,000× magnifications. The stomata

length, width, number and guard cell length were calculated by processing the images using Image J (National Institutes of Health, Bethesda, MD, USA).

2.6. Measurement of Leaf Surface Water Storage

Water-immersion and -spraying methods were used to determine leaf surface water storage (LSW, g m^{-2}). The water-immersion method required completely immersing the leaf in a basin filled with collected rainwater for 5 min, and then picking up the leaf carefully with tweezers. The completely wetted leaf was held stationary in the air and re-weighed when there was no water dripping off for 20 s. The weight difference of the leaf sample before and after water immersion was recorded [30]. The water-spraying method required spraying water onto the leaves with an artificial sprayer until water flowed down the leaves in a line. Leaves were left in the air until water stopped dripping and weighed again. Immersed (ILSW) and sprayed (SLSW) surface water storages were calculated as the increased weight (g) divided by the leaf area (m^2). All the samples were weighed with the electronic balance (accuracy: 0.0001 g).

2.7. Statistical Analysis

An independent-samples *t*-test was used to compare the differences between leaf adaxial and abaxial contact angles of the same species. One-way analysis of variance (ANOVA) followed by Duncan's multiple-range test was performed to compare the differences of leaf contact angles among leaf sides, seasons and life forms. Pearson correlation analysis was used to determine the relationships between leaf contact angle and leaf functional traits, wax content, surface micromorphology and surface water storage. Statistical analyses were performed with SPSS Statistics 26.0 (SPSS Inc. Chicago, IL, USA), and the graphs were created in SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA) and the 'ggplot2' package in R statistical software (version 4.2.2, R Development Core Team 2022, New Zealand). Differences were considered significant for all statistical tests at $p < 0.05$.

3. Results

3.1. Variability in Leaf Wettability of 30 Common Landscape Plants

The leaf adaxial and abaxial contact angles (CA_{ad} , CA_{ab}) of 30 landscape plants ranged from $63\text{--}134^\circ$ and $66\text{--}134^\circ$, respectively. The highest CA_{ad} and CA_{ab} were found in *Oxalis corniculata* (OC) and *Hypericum monogynum* (HM), and the lowest were found in *Ophiopogon bodinieri* (OB) and *Pinus parviflora* (PP). CA_{ad} was lower than CA_{ab} for 26 species, and the differences were significant ($p < 0.05$) for 9 species (Table 1). In spring, summer, autumn and winter, the ranges of CA_{ad} and CA_{ab} were $61\text{--}137^\circ$ and $42\text{--}136^\circ$, $60\text{--}135^\circ$ and $70\text{--}136^\circ$, $69\text{--}137^\circ$ and $65\text{--}138^\circ$, $46\text{--}131^\circ$ and $54\text{--}134^\circ$, respectively. The average CA ranking in four seasons (Figure 2) and cluster analysis (Figure 3) indicated that HM, *Albizia julibrissin* (AJ), *Cynodon dactylon* (CD), *Loropetalum chinense* (LCr) and *Liriodendron chinense* (LCs) were the species with the highest CA, and their CA_{ad} and CA_{ab} were 122° and 134° , 120° and 132° , 125° and 119° , 110° and 133° , 102° and 128° , respectively. The lowest CA species were recorded in OB, *Ulmus pumila* (UP), PP, *Gardenia jasminoides* (GJ) and *Pittosporum tobira* (PT), with the values of 63° and 76° , 69° and 78° , 74° and 66° , 83° and 77° , 71° and 90° .

3.2. Leaf Wettability Varied with Growth Season and Life Form

During the whole growth period, CA_{ad} was lower than CA_{ab} , and the differences were significant ($p < 0.05$) in summer, autumn and winter. CA gradually decreased from spring to winter, and the CA_{ad} and CA_{ab} were 96° and 104° , 92° and 106° , 88° and 102° , 76° and 97° in four seasons, respectively. In winter, CA_{ad} was significantly ($p < 0.05$) the lowest compared to other seasons, and CA_{ab} was also the lowest but not significantly (Figure 4).

There were no significant differences in CA among trees, shrubs and herbs. They varied with the seasons and decreased significantly in winter, having a larger reduction in CA_{ad} than CA_{ab} . CA also displayed no significant differences between evergreen and deciduous plants on the whole. However, evergreen broadleaved plants (E-B) had lower

CAs than deciduous broadleaved plants (D-B) in spring, whereas they had higher CAs in summer, autumn and winter. From spring to winter, the CAs of deciduous broadleaved and coniferous plants (E-C) decreased more obviously than evergreen broadleaved and coniferous plants (D-C), respectively. This means that deciduous plants experienced greater changes in CA than did evergreen plants during the growth period. Moreover, species' life forms, such as tree, shrub and herb, or evergreen and deciduous plants, or broadleaved and coniferous plants, cannot be used to directly judge leaf-wetting properties (Figure 5).

3.3. The Relationships between Leaf Wettability and Leaf Functional Traits and Surface Micromorphology

CA_{ad} and CA_{ab} were significantly positively correlated ($r = 0.501$, $p < 0.001$), whereas they had no significant correlations ($p > 0.05$) with all measured leaf functional traits, i.e., leaf area (LA, m^2), leaf perimeter (LP, m), leaf length (LL, m), leaf width (LW, m), petiole length (PL, m), leaf thickness (LT, m), leaf fresh weight (LFW, g) and dry weight (LDW, g), specific leaf area (SLA, $m^2 g^{-1}$) and leaf dry matter content (LDMC, $g g^{-1}$) (Figure 6).

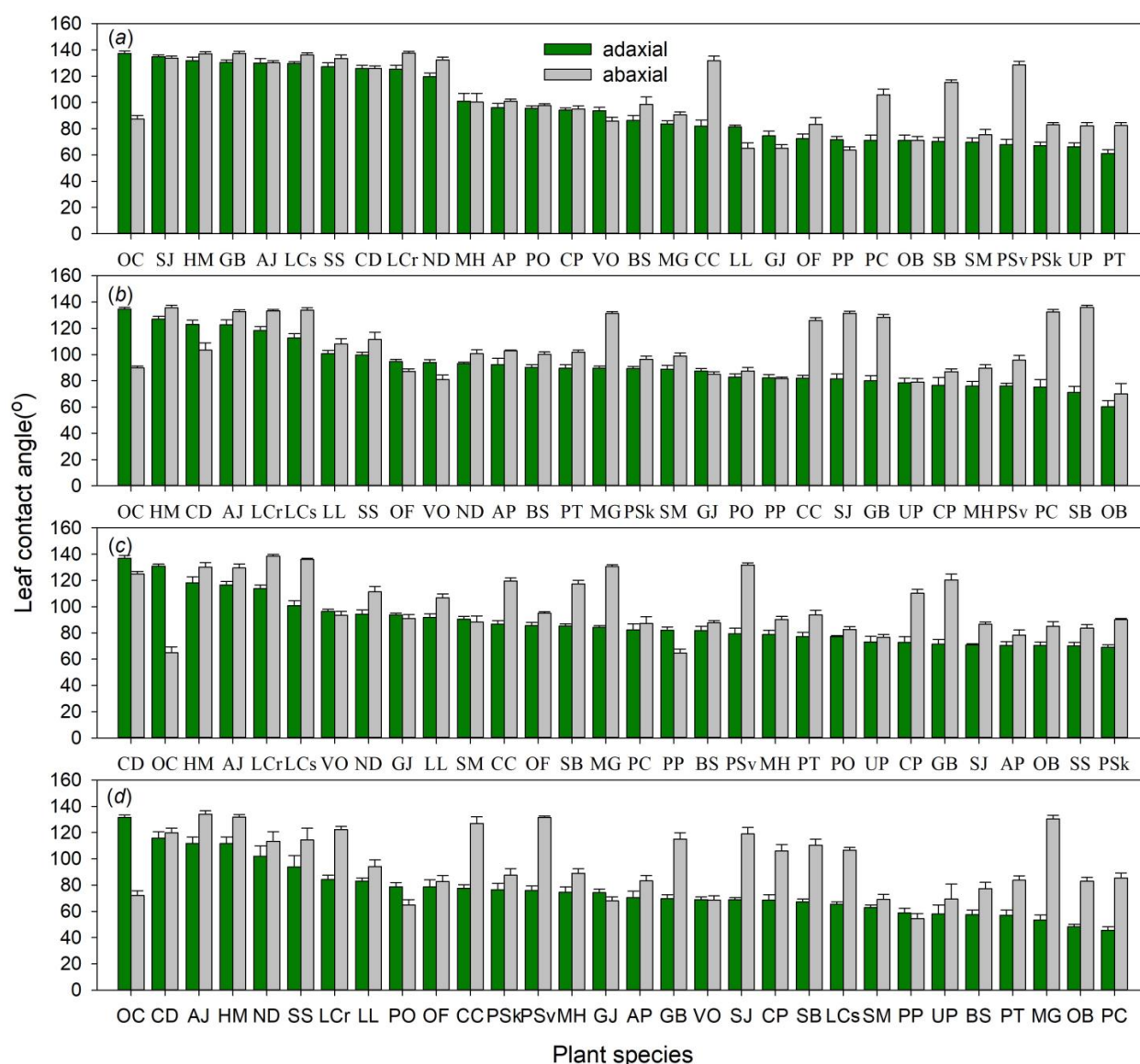


Figure 2. Leaf adaxial and abaxial contact angles of 30 common urban landscape plants in four seasons (a: spring; b: summer; c: autumn; d: winter; Mean \pm SE).

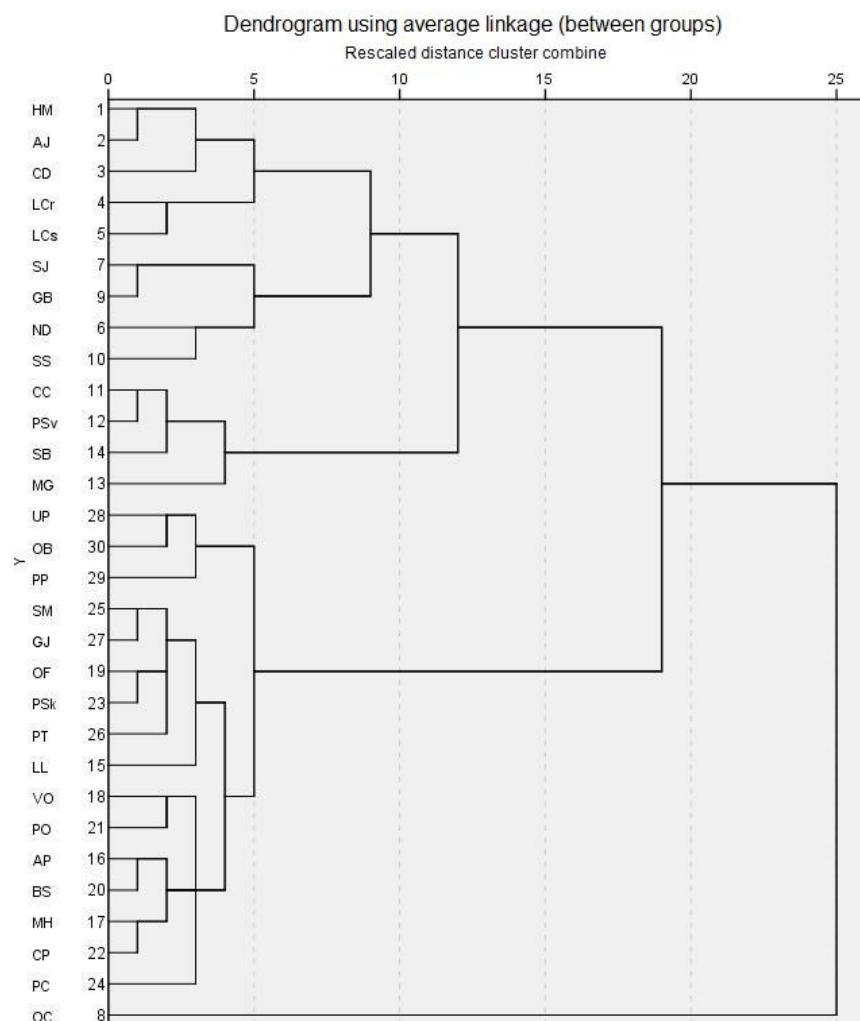


Figure 3. Cluster analysis of leaf contact angle by average-linkage method (between groups).

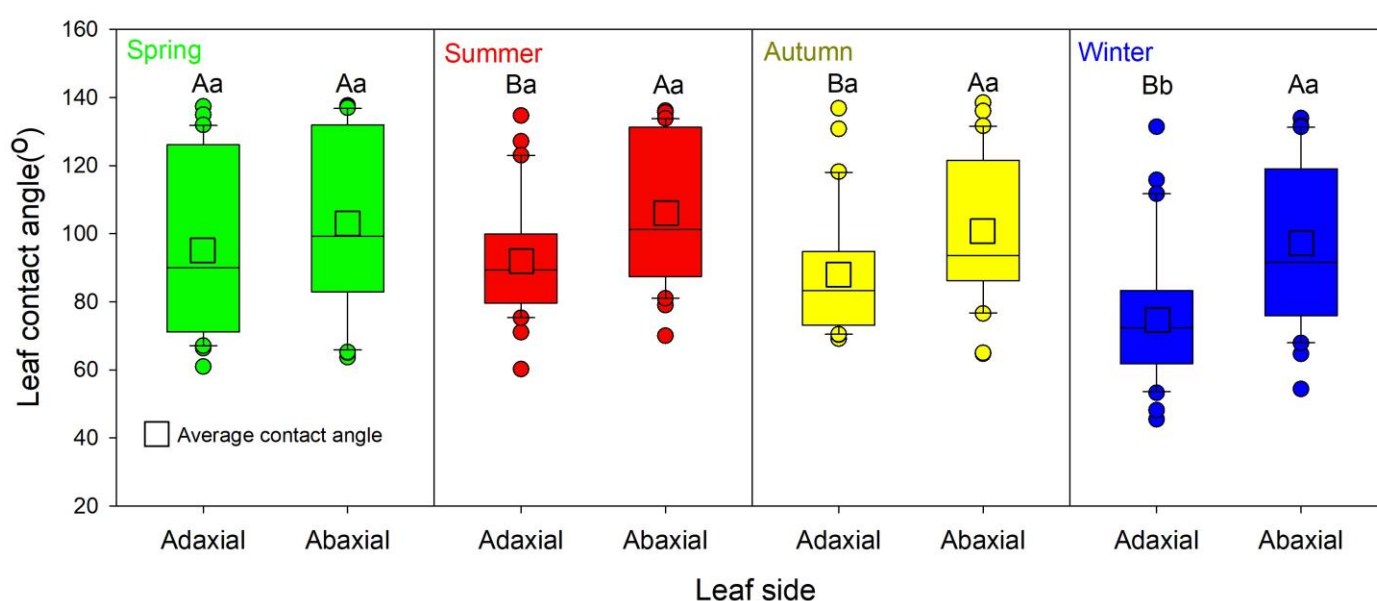


Figure 4. Variations in leaf contact angles on different leaf sides over four seasons (different capital and small letters indicate significant differences between leaf sides and between seasons, respectively).

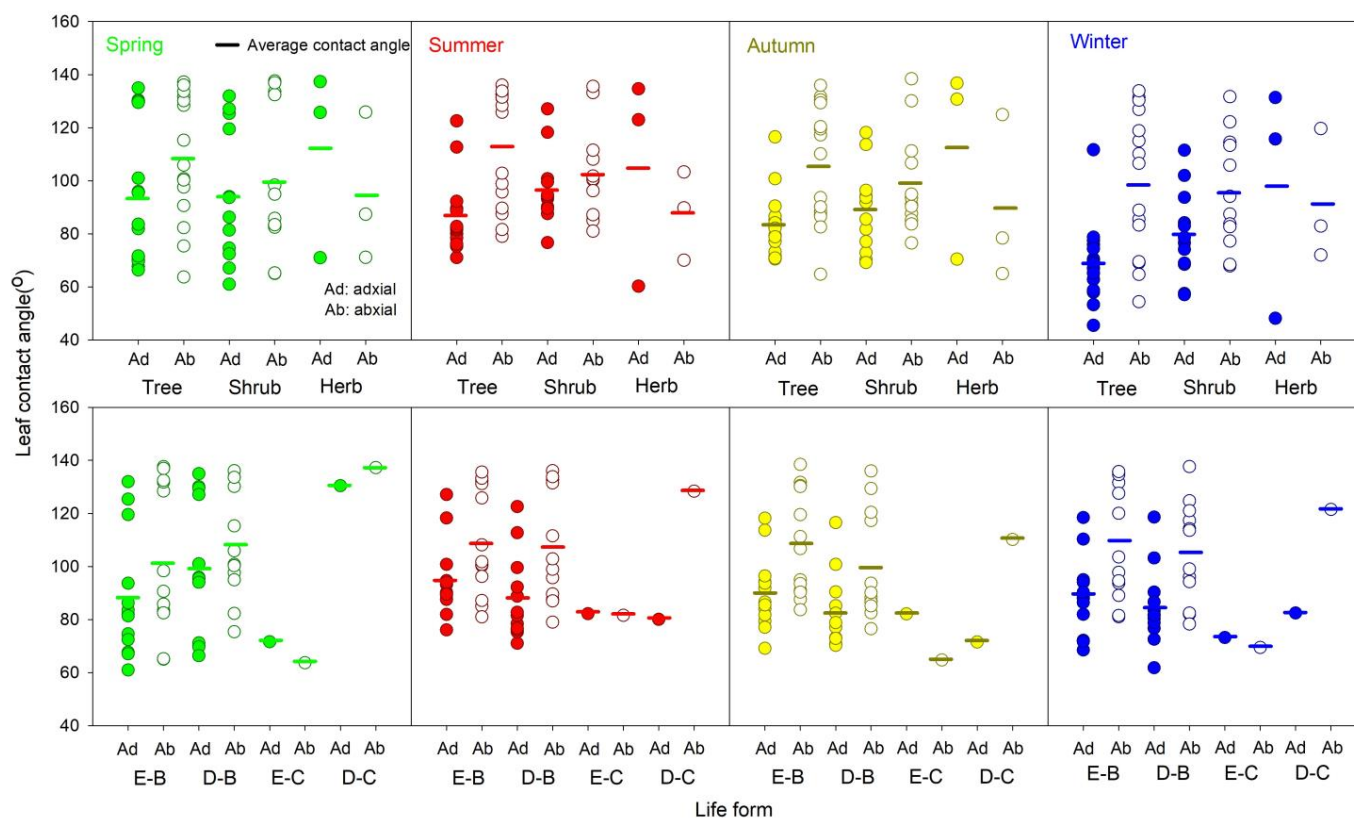


Figure 5. Variations in leaf contact angles of different life forms over four seasons (the abbreviations in X-axis are shown in Section 3.2; the solid symbols represent the adaxial contact angle of each species under the same life form, and the hollow symbols are the abaxial.).

CA_{ad} and CA_{ab} were positively correlated with epidermal wax content ($LWC, g\ m^{-2}$), and the Pearson correlation coefficients were 0.347 and 0.167, respectively. They were negatively correlated ($r = -0.310, -0.205$) with guard cell length ($GCL, \mu m$), but the correlations of wax content and guard cell length both failed to reach significant levels ($p > 0.05$). CA was negatively correlated with stomatal length ($SL, \mu m$), and the adaxial correlation was significant ($r = -0.414, p < 0.05$). Stomatal number (SN, n), stomatal width ($SW, \mu m$) and stomatal density ($SD, \mu m$) all had no obvious influence on determining the interspecies differences of CA in this study (Figure 6). Leaf wettability was affected by the comprehensive properties of leaf surface micromorphology, and individual microscopic parameters could not accurately judge surface wettability.

The leaf surface micromorphology of the species with the lowest (HM, AJ, CD, LCr, LCs) and highest (OB, UP, PP, GJ, PT) wettability is shown in Figures 7 and 8, respectively. HM, CD and LCs exhibited rough leaf surfaces with numerous irregular grooves and protrusions, and dense waxy layers were observed. The leaf surfaces of AJ and LCr were uneven and displayed flocculent and stellate trichomes. Other low-wettability species, such as *Magnolia grandiflora* (MG), *Sophora japonica* (SJ) and *Spiraea salicifolia* (SS), also possessed trichomes on the surfaces. These micromorphological characteristics may lead to highly hydrophobic leaf surfaces. Highly wettable species, such as UP, PP, PT, *Osmanthus fragrans* (OF) and *Photinia serratifolia* (PS), typically possessed smoother leaf surfaces and fewer epidermal cell protrusions. Meanwhile, trichomes were not found on leaf surfaces of these species (Figures 6, 7 and S2–S5).

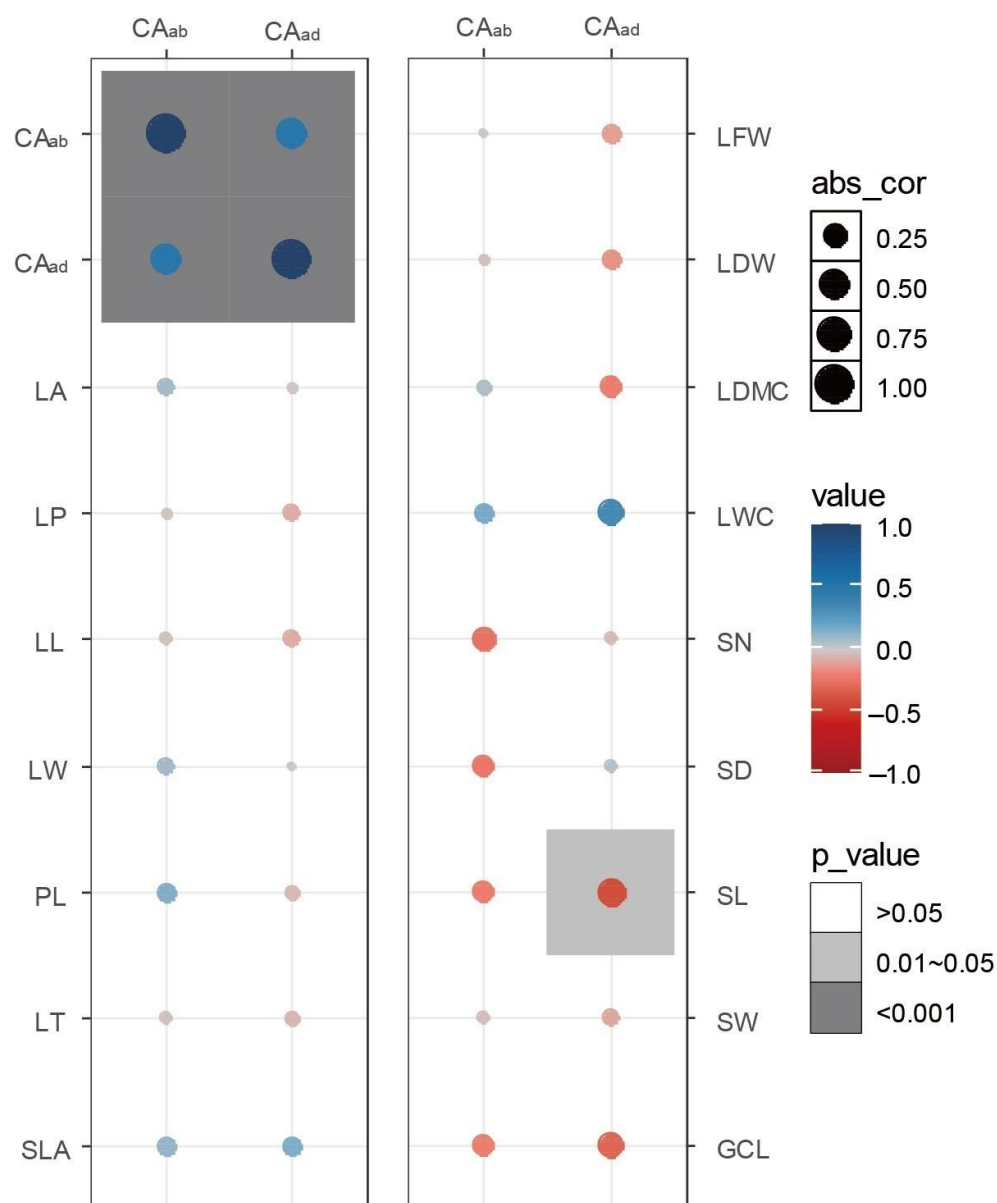


Figure 6. The correlations between leaf contact angle and leaf functional traits and surface microscopic parameters (the abbreviations are shown in Section 3.3).

3.4. The Relationships between Leaf Surface Water Storage and Leaf Wettability and Leaf Functional Traits

Leaf surface water storage was negatively correlated with CA, and the correlations were significant ($p < 0.05$) with CA_{ad} under water-spraying methods ($r = -0.390$), and significant with CA_{ab} under both water-immersion ($r = -0.411$) and -spraying methods ($r = -0.429$). All measured leaf functional traits, leaf area, leaf perimeter, leaf length, leaf width, petiole length, leaf thickness, leaf fresh weight and dry weight, specific leaf area and leaf dry matter content, and surface microscopic parameters, such as leaf wax content, stomatal number, stomatal density, stomatal length, stomatal width and guard cell length had no significant correlations ($p > 0.05$) with leaf surface water storage (Figure 9).

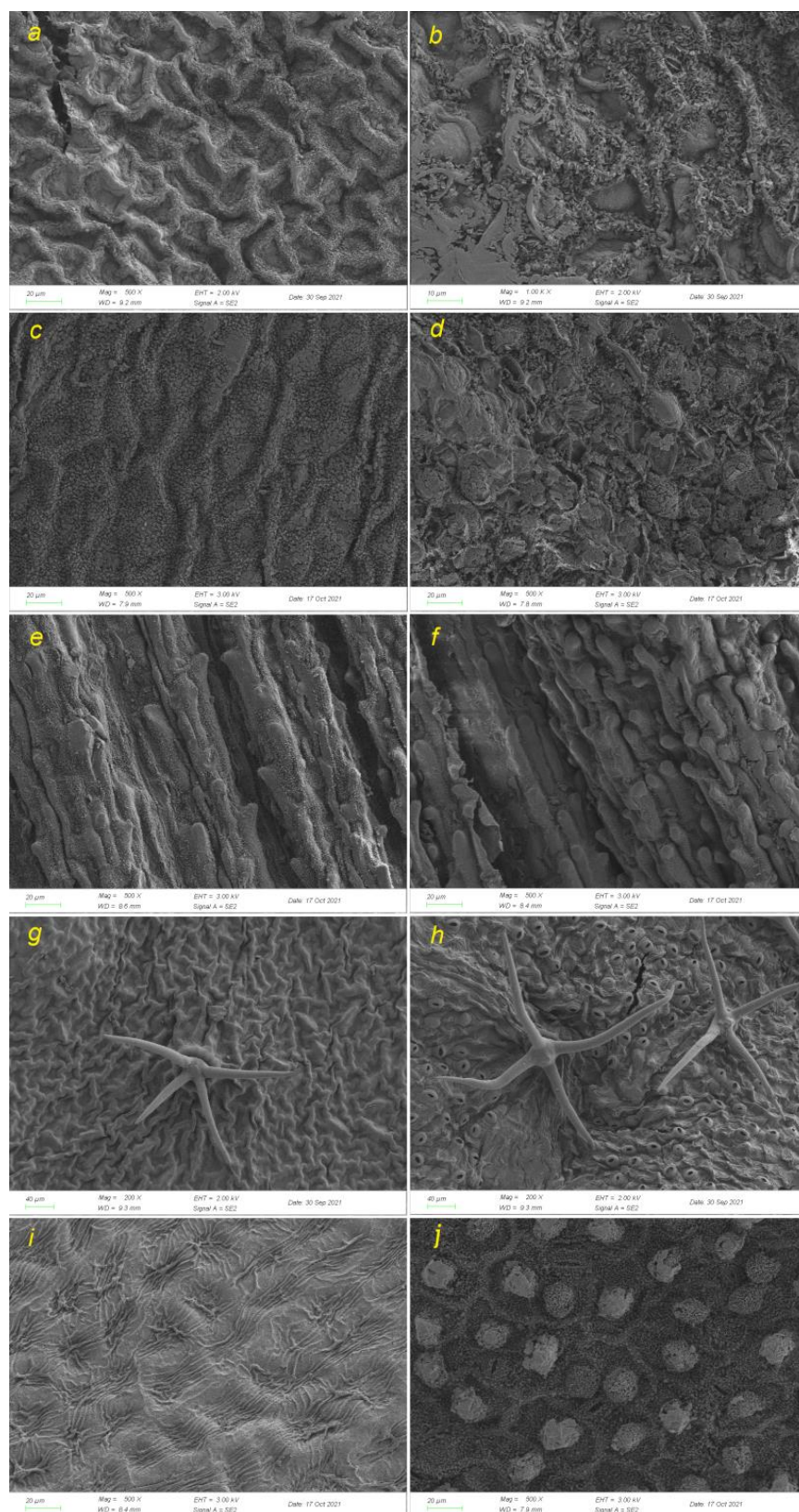


Figure 7. Scanning electron microscopy images of leaf adaxial (a,c,e,g,i) and abaxial (b,d,f,h,j) surfaces of the lowest-wettability species, i.e., *Hypericum monogynum* (a,b), *Albizia julibrissin* (c,d), *Cynodon dactylon* (e,f), *Loropetalum chinense* (g,h) and *Liriodendron chinense* (i,j).

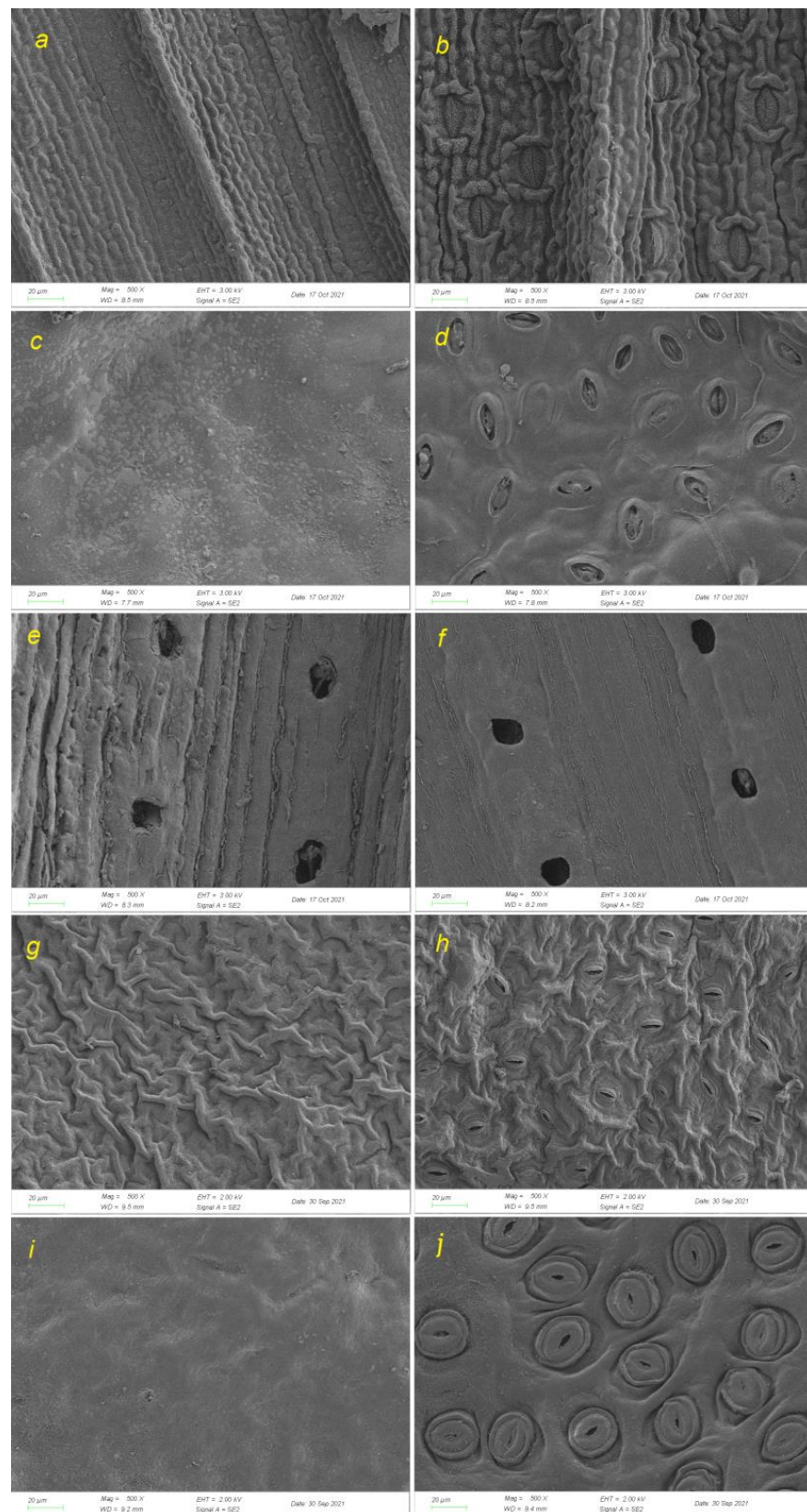


Figure 8. Scanning electron microscopy images of leaf adaxial (a,c,e,g,i) and abaxial (b,d,f,h,j) surfaces of the highest-wettability species, i.e., *Ophiopogon bodinieri* (a,b), *Ulmus pumila* (c,d), *Pinus parviflora* (e,f), *Gardenia jasminoides* (g,h) and *Pittosporum tobira* (i,j).

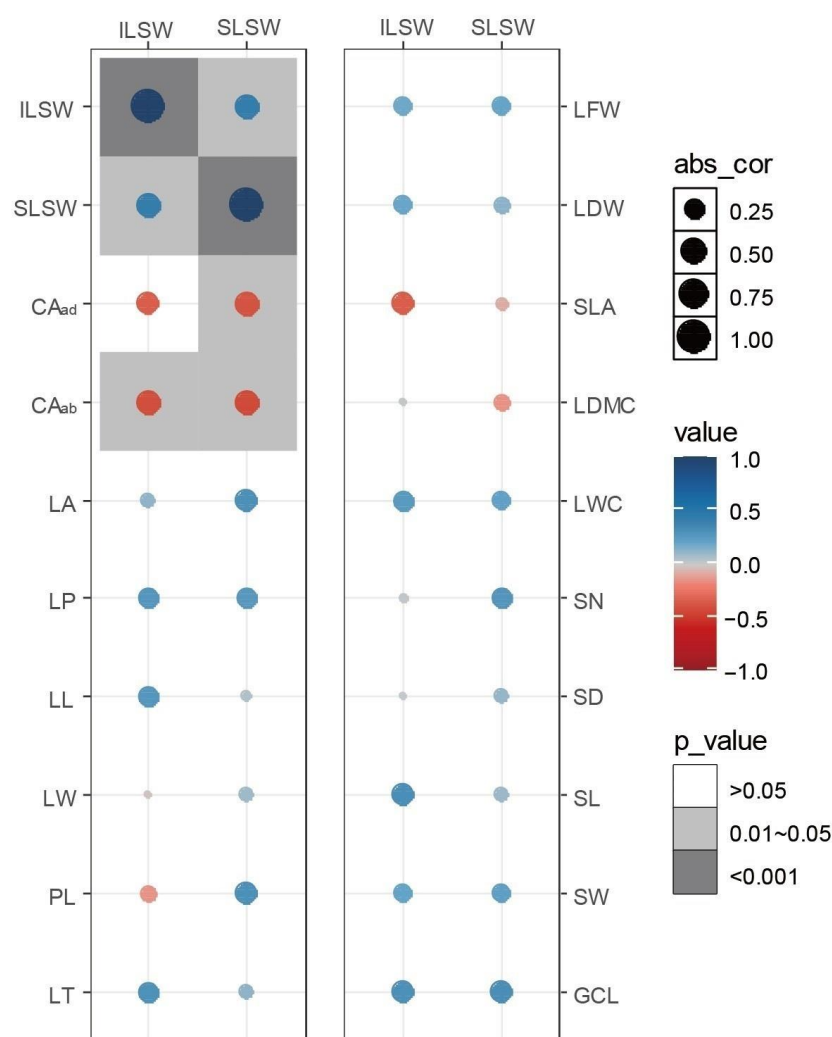


Figure 9. The correlations between leaf surface water storage and leaf contact angle, leaf functional traits and surface microscopic parameters.

4. Discussion

This study highlighted that the leaf wettability of urban landscape plants was species-specific. Leaf adaxial and abaxial contact angles of the 30 investigated common landscape plants ranged from 63° to 134° and 66° to 134°. These variation ranges are similar to previous studies, in which the contact angles ranged from 41° to 144° across 60 plant species at 3 sampling sites in Shaanxi Province, China [26]. The main herbaceous plants (68 species) had contact angles of 27° to 133° in the semiarid Loess Plateau of China [1]. Greater differences in species type or external environments may lead to larger wettability variability among species. Hefei city is located in eastern China with a northern subtropical monsoon climate, which has seldom been studied in relation to the wettability of landscape plants. Meanwhile, this study separately selected five species with the highest and lowest wettability, which may provide basic data for landscape plant selection to improve rainfall management in urban areas.

There were no significant differences in leaf wettability among trees, shrubs and herbs, or among evergreen broadleaved, evergreen coniferous, deciduous broadleaved and deciduous coniferous plants. This suggested that leaf wettability was independent of leaf traits, and could not be accurately estimated by the simple classification of plant life forms. Studies of herbaceous plants in the semiarid Loess Plateau also indicated that there were no significant leaf wettability differences among trees, shrubs and herbs [1]. Instead, leaf wettability was proved to be only partly related to species family; for instance, gramineous and

leguminous species were more hydrophobic than Compositae and rosaceous species. Aryal and Neuner [4] also considered that Oxalidaceae and Fabaceae species showed hydrophobic properties, while Ericaceae and Moraceae species were more hydrophilic. However, the species family may not determine leaf wettability for tropical forest communities in southern Peru, and closely related species did not share similar wettability properties [3]. Despite that, deciduous plants showed a higher wettability increase from spring to winter compared to evergreen plants. Deciduous plants abscise all or most of their leaves in winter, resulting in shorter leaf lifespans, which meant leaf surface micromorphology and ecological functions changed more substantially from spring to winter, exhibiting more variable leaf wettability during the growth period than evergreen plants.

Leaf wettability had obvious seasonal variations, with significant decreases from spring to winter for most species. Surface wettability was determined by the physicochemical properties of the cuticle, serving as the interface between leaves and the surrounding atmosphere. The surface micromorphology is constantly changing during plant growth and development, leading to wettability variations [31]. Newly developed leaves typically possess more dense epicuticular wax layers compared to senescent leaves, and the main components of these waxy layers are hydrophobic [18]. When the degradation of epicuticular wax crystals occurs in senescent leaves, the surfaces tend to become more wettable [32]. Meanwhile, the leaves that have been growing for a long time may be influenced by multiple rainfall events and prolonged exposure to contaminants, causing serious erosion of surface wax crystals [12]. The coverage of epiphytic microorganisms and the distribution of stomates and trichomes may also change with leaf age, thus affecting leaf wettability [33].

The leaf functional traits investigated in this study could not explain the variations in leaf wettability. Holder [34] also proved that leaf water repellency was not correlated with leaf area, leaf thickness, leaf biomass and specific leaf area. Leaf functional traits belong to plant internal features, and are adapted to external environments, such as light, moisture and nutrient levels. However, these variations of leaf traits and surface wettability seemed to be widely different. Overall, leaf wettability was the result of the combined effects of surface microstructure and chemical composition, and it was difficult for a single microscopic parameter to accurately reflect leaf wettability properties. In the present study, leaf wax content had a weak negative correlation with leaf wettability. For a certain species, the artificial removal of cuticle wax had been proved to increase leaf wettability [10,35]. When comparing multiple species, not only the cuticle wax content, but also the epidermal cell morphology may modify leaf wettability. More epidermal cell protrusions mean the gap between adjacent nanopillars is small, and the water droplets can infiltrate only the top of the nanopillars and form air pockets between the nanopillars. Thus, the leaf surface presents the hydrophobic Cassie–Baxter state rather than the hydrophilic Wenzel state because of the reduced contact area between the water droplets and leaf surface [17,36]. Trichomes also play an important role in affecting leaf wettability, and the presence of trichomes reduces the surface wettability of *Loropetalum chinense*, *Magnolia grandiflora* and *Sophora japonica*. Meanwhile, different trichome structure, composition and density may influence surface wettability to varying degrees, which needs to be further studied [33]. There was no significant difference in stomatal density between high- and low-wettability species in this study, and stomatal size was also important in modifying leaf wettability, which was inconsistent with previous studies [12,37]. The leaf surfaces with the highest stomatal density were generally considered the least wettable. However, the leaf wettability was affected by complex surface microstructures, and the investigations of multiple species reduced the predictability of a single parameter. Meanwhile, higher stomatal density, together with lower wettability on the abaxial surface, was recorded compared to the adaxial surface. Low wettability is considered to be an adaption of the abaxial surface against water-film formation above the stomates, which interferes with leaf gas exchange and photosynthetic activity [3].

Leaf wettability was the best predictor of leaf surface water storage among all the investigated leaf traits. A previous study showed that the leaf surface water storage of

Ulmus pumila was 60% higher than that of *Catalpa speciosa*, with the contact angle reported to be half [22]. Different leaf wettability generated different water-droplet retention states on the surface, varying from water film to spherical water droplets [38]. When the contact angle is large, the contact area and affinity between the leaf surface and water droplet are lower due to the epidermal cell protrusions or wax hydrophobic properties, etc. Water droplets can easily drip from the leaf surface by gravity or disturbance, which reduces water storage on the leaf surface [22]. Thus, leaf wettability significantly determined rainfall interception at the leaf scale, which was consistent with our second hypothesis. High-wettability species can be preferentially configured to increase rainfall capture and mitigate surface runoff in areas affected by urban waterlogging. Leaf wettability provides great significance in optimizing urban forestry as a green infrastructure strategy to manage rainwater resources. However, the effects of leaf wettability variations on rainfall interception at the plant or landscape scale still need to be investigated, in order to enhance our understanding of the significance of leaf wettability in ecohydrological research.

5. Conclusions

This study revealed the leaf wettability variations of common landscape plants in Hefei city, China, and explored the factors affecting wettability in terms of leaf traits and surface microstructure. Leaf wettability was species-specific, and the adaxial and abaxial contact angles ranged from 63–134° and 66–134° for 30 landscape plants, respectively. *Ophiopogon bodinieri*, *Ulmus pumila*, *Pinus parviflora*, *Gardenia jasminoides* and *Pittosporum tobira* were the most wettable species, and may be capable of intercepting more rainfall given the same leaf area. Leaf adaxial wettability was significantly higher than abaxial wettability. Leaf wettability reached its maximum in winter, probably because of the surface micromorphological changes taking place during leaf senescence. Although deciduous plants' wettability increased more obviously from spring to winter than that of evergreen plants, the comparison of different life forms, such as trees, shrubs and herbs, evergreen and deciduous, broadleaved and coniferous plants, was not suitable for directly judging leaf wettability. Leaf wettability is the combined effect of surface microstructure parameters, and the surfaces with more epidermal cell protrusions, dense waxy layers and the presence of trichomes tended to be more nonwettable. Within the leaf functional traits, leaf wettability was the best predictor of leaf rainfall interception. Overall, this study ascertained five highly wettable urban species and proved the interspecific and seasonal variations in wettability due to differences in surface micromorphology, emphasizing the significance of leaf wettability in estimating leaf rainfall interception. These findings provide a theoretical basis for using leaf wettability to select high-interception-capacity species, and to evaluate the effects of vegetation changes on urban hydrology. Given the experimental limitations, more comparable studies and field rainfall-monitoring experiments should be conducted to further investigate the role of leaf wettability at the individual plant and landscape scales, so as to effectively quantify the ecohydrological effects of leaf wettability and improve the urban water cycle based on vegetation management.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w15122152/s1>, Figure S1. The photographs of 30 common landscape plant leaves; Figure S2. Scanning electron microscopy images of leaf adaxial (a, c, e, g, i, k) and abaxial (b, d, f, h, j, l) surfaces of *Viburnum odoratissimum* (a, b), *Sapindus mukorossi* (c, d), *Platanus orientalis* (e, f), *Osmanthus fragrans* (g, h) and *Photinia serratifolia* (i, j); Figure S3. Scanning electron microscopy images of leaf adaxial (a, c, e, g, i, k) and abaxial (b, d, f, h, j, l) surfaces of *Prunus cerasifera* (a, b), *Ligustrum lucidum* (c, d), *Acer palmatum* (e, f), *Malus halliana* (g, h) and *Chimonanthus praecox* (i, j) and *Buxus sinica* (k, l); Figure S4. Scanning electron microscopy images of leaf adaxial (a, c, e, g, i) and abaxial (b, d, f, h, j) surfaces of *Oxalis corniculata* (a, b), *Phyllostachys sulphurea* (c, d), *Sophora japonica* (e, f), *Cinnamomum camphora* (g, h) and *Ginkgo biloba* (i, j); Figure S5. Scanning electron microscopy images of leaf adaxial (a, c, e, g) and abaxial (b, d, f, h) surfaces of *Magnolia grandiflora* (a, b), *Salix babylonica* (c, d), *Nandina domestica* (e, f) and *Spiraea salicifolia* (g, h).

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