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A Sustainable Pesticide Application Strategy Based on the Wettability Characteristics of Plant Leaf Surfaces

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Abstract

Due to long-term evolution and adaptation to the natural environment, the surfaces of plant leaves have developed hydrophobic microstructures or functional characteristics around stomata. These adaptations ensure the long-term stability of stomatal function under rainy or highly humid conditions. However, such hydrophobicity also poses challenges for agricultural practices, particularly in pesticide application, where poor wettability of leaf surfaces often reduces droplet adhesion and pesticide efficiency. Therefore, identifying the relatively more hydrophilic regions of plant leaves is essential for improving pesticide deposition and utilization. In this study, we conducted a comparative analysis of the morphology and wettability of both the upper and lower surfaces of *Silver Maple* leaves. The results revealed that the lower surface exhibits significantly stronger hydrophobic properties than the upper surface, which can be attributed to the presence of micro-nano hierarchical roughness on the epidermis. These surface structures effectively enhance water repellency and droplet rolling, thereby protecting the leaves but simultaneously reducing the adhesion of aqueous pesticide solutions. Our findings provide new insights into the relationship between leaf surface microstructure and wettability, and highlight the importance of targeting more hydrophilic sites on leaves for efficient pesticide application. This study not only contributes to improving the precision and effectiveness of pesticide usage but also supports sustainable agricultural development by reducing chemical waste and environmental pollution.

Keywords

Stomata, Wettability, Hydrophobilicity, Pesticide, Agricultural, Sustainable Development

1. Introduction

The distribution and density of stomata on plant leaves are closely related to the specific living environments of plants and play a crucial role in regulating gas exchange and water balance. Traditionally, it has been understood that the majority of plants possess a higher stomatal density on the lower surface of their leaves in order to reduce transpiration, whereas monocotyledonous species often exhibit a more uniform stomatal distribution across both surfaces [1]. Beyond this conventional understanding, recent perspectives suggest that stomatal positioning is also driven by the necessity to avoid blockage by water films, which could otherwise impede respiration and compromise plant survival.

Over the course of long-term natural evolution, plants have developed various adaptive strategies to protect their stomata from environmental challenges. Many species exhibit specialized water-repelling structures or hydrophobic functional surfaces surrounding their stomata. A well-known example is the lotus (*Nelumbo nucifera*), whose leaves display remarkable superhydrophobicity, a property derived from their unique dual-scale micro-nano hierarchical architecture coated with low-surface-energy wax crystals [2] [3]. These structural and chemical adaptations effectively minimize water accumulation, ensuring the sustained functionality of stomata even in rainy or humid conditions. However, such hydrophobicity, while advantageous for plant survival, presents significant challenges in agricultural practices, particularly in pesticide application. When aqueous pesticide solutions encounter highly hydrophobic leaf surfaces, they tend to bead up and roll off instead of spreading and adhering. This leads to substantial pesticide loss, reduced protective efficacy, and excessive chemical runoff into the soil, thereby contributing to environmental pollution. The inefficiency of pesticide deposition not only compromises crop protection but also increases production costs and threatens ecological sustainability.

This challenge is especially critical for China, the world's largest agricultural producer by both volume and value, where balancing crop productivity with sustainable agricultural development is of national importance. To achieve this balance, it is essential to deepen our understanding of plant surface wettability characteristics and identify the regions of leaves that exhibit relatively higher hydrophilicity. By clarifying how microstructural features influence droplet adhesion and infiltration, agricultural spraying practices can be optimized. Specifically, pesticides can be more precisely targeted to areas of leaves that favor better retention, thereby improving efficiency, reducing chemical waste, and minimizing environmental contamination.

- In this context, our research aims to investigate the surface morphology and wettability differences between the upper and lower surfaces of leaves, with *Silver Maple (Acer saccharinum)* as a representative model. Through these findings, we hope to provide both theoretical and practical guidance for improving pesticide application strategies, ultimately contributing to the sustainable development of agriculture and the production of higher-quality crops.

2. Materials and Methods

The plant leaves collected for the experiment were from the park. The contact angle was captured by an iPhone 5. Each wettability test was conducted at least five times, and the average value was taken. The SEM images of the *Silver Maple* leaf were observed by Environmental Scanning Electron Microscopy (ESEM, Quanta FEG 250, FEI) under the voltage of 5 kV.

Results and Discussion

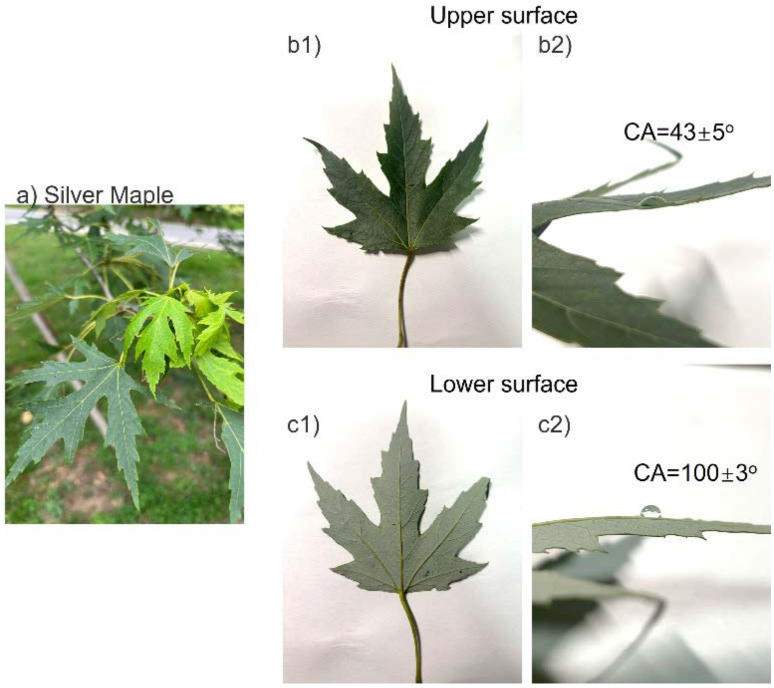

Figure 1. The optical images and contact angle (CA) of the *Silver Maple*. The CA on the upper surface and lower surface is 43˚ ± 0.5˚ (hydrophilic) and 100˚ ± 0.3˚ (hydrophobic), respectively.

Silver Maple (Figure 1) has been widely introduced and planted as an ornamental tree in urban landscapes due to its excellent adaptability. It demonstrates ease of transplanting and establishment, tolerance to diverse site conditions, rapid growth, and aesthetically pleasing form. Beyond ornamental use, the species has also been applied in ecological restoration, including vegetative rehabilitation of surface-mined lands and bottomland reforestation. Additionally, the sap of *Silver Maple* can be processed into a light-flavored syrup; however, its sugar content is among the lowest when compared to other maple species traditionally used in syrup production [4].

Those who study the field of surface wettability all know a concept: the critical value between hydrophilic and hydrophobic is 90˚. When the contact angle of a droplet is less than 90˚, it is defined as hydrophilic. When the contact angle of a droplet is greater than 90˚, it is defined as hydrophobic. In the present study, both optical imaging and contact angle (CA) measurements were performed to characterize the wettability of *Silver Maple* leaves. The results reveal a distinct difference between the adaxial (upper) and abaxial (lower) surfaces. The upper leaf surface exhibited a contact angle of approximately 43˚, which is less than 90˚; thus, it can be classified as hydrophilic, favoring the spreading and retention of aqueous droplets. In contrast, the lower leaf surface exhibited a significantly higher contact angle of about 100˚, which exceeds the 90˚ threshold and therefore indicates hydrophobic behavior. This finding demonstrates a clear polarity in wettability between the two sides of the leaf.

From a stomatal distribution perspective, *Silver Maple* leaves are generally amphistomatous, meaning that stomata are present on both surfaces. Nevertheless, their density tends to be higher on the abaxial side. Interestingly, our observations indicate that the surface with the greater stomatal density corresponds to the hydrophobic side, rather than being more hydrophilic as might be intuitively expected. This suggests that hydrophobic micro-nano surface structures play a dominant role in regulating wettability and protecting stomatal function, overriding the direct influence of stomatal density alone.

To further explore the underlying mechanism, scanning electron microscopy (SEM) was employed to examine the micro- and nano-scale architecture of *Silver Maple* leaf surfaces. The SEM images reveal the presence of fine epidermal features and cuticular nanostructures that contribute to the enhanced hydrophobicity of the lower surface. These hierarchical surface morphologies likely act as barriers, minimizing water accumulation near stomata and thereby preventing potential obstruction of gas exchange.

Taken together, these findings highlight that in *Silver Maple* leaves, wettability asymmetry is closely linked with surface structural adaptations rather than merely stomatal arrangement. This insight underscores the importance of considering both physiological and structural features when analyzing leaf wettability, particularly in the context of agricultural spraying practices where surface interaction with droplets determines the efficiency of pesticide deposition.

The upper surface is smooth (**Figure 2(a)**). The lower surface is rough (**Figure 2(b)**). The hydrophobic performance of the lower surface is induced by the rough nano-petal topography. Over the course of long-term natural evolution, plants have gradually developed diverse adaptive structures to ensure their survival and reproduction in complex environments. Among these, the hydrophobic structures on the lower surfaces of leaves represent a typical and critical adaptive strategy. These specialized micro-nano scale architectures significantly enhance the water repellency of the leaf surface, making it difficult for water droplets to adhere or remain for extended periods. Instead, the droplets quickly roll off, thereby effectively preventing the formation of water films that could cover stomata under conditions of high humidity or rainfall. If stomata were to be blocked by water, gas exchange would be hindered, photosynthesis and transpiration would be negatively affected, and localized hypoxia could occur, posing a serious threat to the plant's normal physiological processes. Thus, the hydrophobic structures of the lower leaf surface play an essential role in keeping stomata unobstructed and maintaining their normal function.

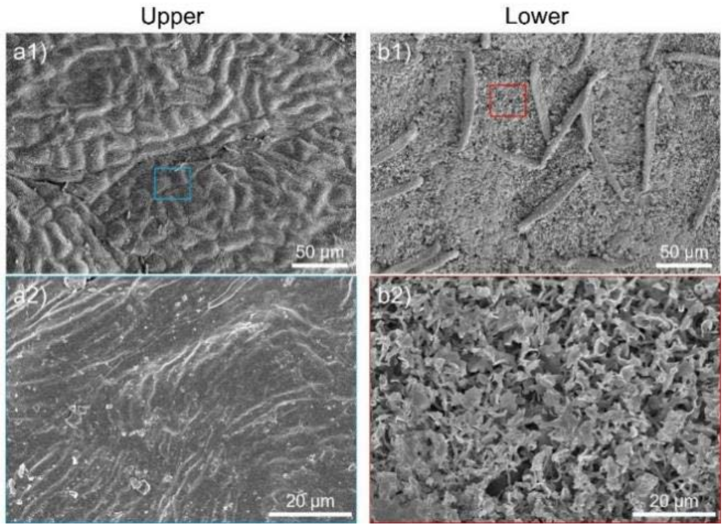

Figure 2. The SEM images of the leaf surfaces. The upper (a) surface is smooth and lower (b) surface is rough.

At the same time, this hydrophobic property reflects a delicate balance in plant strategies for water regulation and energy utilization. By reducing water retention on the surface, plants not only decrease the risk of pathogen colonization and invasion but also improve their adaptability to adverse environmental conditions. This structural advantage is particularly significant in ecosystems characterized by frequent rainfall or high atmospheric humidity, where it ensures that stomata can continue stable gas exchange even under unfavorable conditions, thereby supporting the overall vitality of the plant.

However, from the perspective of agricultural applications, the strong hydrophobicity of the lower leaf surface also presents certain challenges. For example, during pesticide spraying, solutions often fail to spread evenly or adhere effectively on hydrophobic surfaces, causing substantial droplet runoff. This not only reduces the efficacy of pest control but also increases the risk of environmental pollution. Therefore, gaining a deeper understanding of the formation mechanisms of hydrophobic structures on the lower leaf surface and their relationship with stomatal function is of great significance. Such knowledge not only reveals the evolutionary wisdom of plant adaptation to the environment but also provides important theoretical guidance and practical strategies for optimizing pesticide use, reducing resource waste, and promoting sustainable agricultural development.

Figure 3 shows the sketch of the wetting state of the S*ilver Maple* leaf surface. In the upper surface, the surface is relatively smooth with fewer stomata, the leaf can absorb water and pesticide more easily. In the lower surface, with the most arrangement of stomata and the rough nano-petal topography, water and pesticide is less easy to get into and absorb by the leaves.

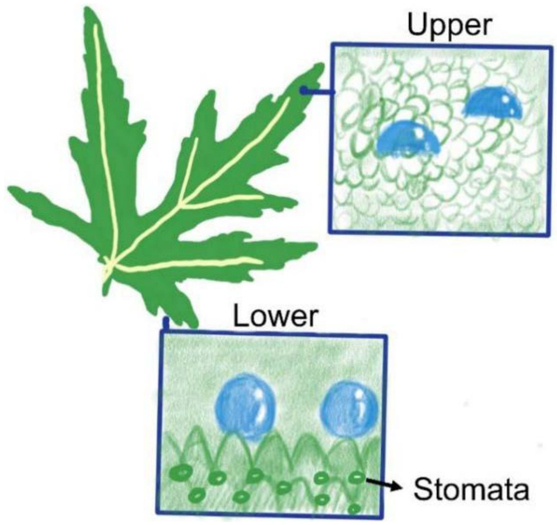

Figure 3. The sketch of the wetting state of leaf surface.

The research on the efficient and precise target deposition mechanism and general technology of chemical pesticides is one of the key development objects. The behavioral process of pesticide droplets colliding on the leaf surface of target crops is rather complex. The bouncing, splashing and rolling of pesticide droplets are the main ways for pesticide loss. How to regulate the deposition behavior of pesticides on the leaves of target crops and reduce the loss of pesticides due to unwanted bouncing and splashing behavior on the leaves, as well as effectively alleviate the bouncing behavior of pesticide droplets, is a key node for achieving efficient utilization of pesticides. Bottom-up pesticide spraying is the most direct and effective method for dealing with diseases and pests on the underside of leaves, but the downward rebound of droplets and gravity makes deposition extremely difficult, especially on the underside of hydrophobic/superhydrophobic leaves. This has greatly exacerbated the waste of agricultural chemicals, caused soil or water pollution, and threatened ecological security and human safety. Therefore, pesticide carriers urgently need to overcome springback and gravity to achieve efficient deposition and retention on both the near and far axes of the leaves after high-speed spraying. There are a few methods nowadays that can help deal with the problem to a certain degree.

1) Professor Liu Feng's team from the College of Plant Protection at Shandong Agricultural University has proposed a simple and universal strategy that can effectively suppress the bouncing and splashing of pesticide droplets on the surface of diseased leaves (cucumber powdery mildew). Based on the impact dynamics of droplets, the dynamic transformation direction of droplet bouncing is determined, the pinning points formed by droplets on the surface of cucumber powdery mildew leaves are identified, and the trajectory of droplet rebound is initially determined [5].

2) Delay droplet retraction through polymer additives or enhance interaction with surface micro/nano structures through appropriate surfactant self-assembly structures. In particular, these surfactant aggregates, which are used to inhibit droplet rebound, effectively seal and penetrate pesticides [6].

3) The traditional emulsifiable concentrates (EC) were initially addressed by dissolving hydrophobic pesticides and emulsifiers in organic solvents, which usually led to severe soil leaching and volatile organic compound (VOC) pollution, causing serious harm to the ecological society Over the past few decades, a large number of water-based formulations have been developed to replace EC, in order to reduce the usage of organic solvents and enhance the control efficacy of hydrophobic pesticides, such as water emulsions (EW) and suspensions (SC). The dispersibility and wettability of these formulations can be appropriately adjusted according to the application scenario or target performance, which depends on the formulation of the surfactant. It is worth noting that although commercial water-based formulations can significantly reduce the harm of VOCs and enhance the applicability of hydrophobic pesticides, they still have the problems of high processing energy consumption and insufficient dispersion. More importantly, the problem of excessive 1 μm and surfactants is that they do not adopt precise delivery, such as responsive release and non-targeted biofriendliness, which are becoming inherent weaknesses in sustainable agricultural development [7].

3. Conclusions

Through the systematic study of the relationship between the wettability of the upper and lower surfaces of *Silver Maple* leaves and their corresponding surface morphologies, we have demonstrated that micro-nano structural characteristics exert a decisive influence on leaf wettability. Specifically, the lower surface of the leaf, where micro-nano hierarchical structures are more prominent, exhibits a stronger hydrophobic performance, whereas the upper surface shows relatively weaker hydrophobicity and thus behaves more hydrophilically. This contrast highlights that wettability is not solely determined by stomatal distribution or density, but is more fundamentally governed by surface microstructural organization and the presence of waxy layers.

Such findings carry important implications for both theoretical and practical applications. From a biological perspective, the development of hydrophobic microstructures around stomata represents an adaptive evolutionary strategy, enabling plants to maintain gas exchange efficiency under humid or rainy conditions while simultaneously protecting stomata from blockages and damage. From an agricultural perspective, however, these same hydrophobic properties can reduce the adhesion of pesticide solutions during spraying. Droplets tend to bead up and roll off hydrophobic surfaces rather than spread and remain, resulting in significant pesticide loss, lower efficacy, and increased chemical runoff into the surrounding soil. This not only leads to higher economic costs for farmers but also contributes to environmental pollution.

Therefore, our research provides a valuable theoretical reference for improving the efficiency of pesticide application. By identifying which leaf surfaces or regions possess relatively higher hydrophilicity, targeted spraying strategies can be designed to maximize pesticide retention. For example, pesticide formulations might be adjusted to enhance wettability on highly hydrophobic surfaces, or spraying techniques may be optimized to focus on more hydrophilic regions. These strategies could significantly reduce chemical waste and improve the precision of crop protection.

In the broader context of sustainable development, the insights gained from this study are highly significant. Agriculture remains the backbone of food security worldwide, and reducing the environmental footprint of agricultural inputs is a pressing challenge. By linking plant surface morphology to pesticide application efficiency, our findings contribute to the development of more environmentally friendly and resource-efficient agricultural practices. Ultimately, this research not only advances fundamental understanding of plant surface science but also provides practical guidance for promoting sustainable agricultural development and environmental protection.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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