UAV ELECTROSTATIC SPRAY DEPOSITION ON APPLE TREES: A STUDY ON DROPLET DISTRIBUTION DURING BLOOMING STAGE
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苹果树花期无人机静电喷雾液滴沉积分布研究

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ABSTRACT
This study investigates the effect of electrostatics in UAV spraying to enhance droplet deposition efficiency during the blooming stage of apple trees. Experiments were conducted under two operating conditions - electrostatic spraying and non-electrostatic (conventional) spraying - at UAV flight heights of 1.0 m, 2.0 m, and 3.0 m above the apple tree canopy. Spray deposition was measured by placing test paper on the upper, middle, and lower canopy layers, on both the front and the back sides of the leaves. The results show that, compared with conventional UAV spraying, electrostatic force increased droplet number density by 17.6% and reduced droplet size by 25.3%, thereby improving overall spray performance. This provides notable advantages for pollination and pest control during the early growth stage of apple trees. The electrostatic charge generates an attractive force between charged droplets and the target surface, enhancing droplet adhesion and deposition on the back side surfaces of lower leaves and flowers. However, this advantage is not significant on the back sides of upper and middle canopy leaves due to limited recirculating airflow reaching those locations. These findings support the application of electrostatic technology to improve pollination efficiency and precision pesticide spraying during the early developmental stage of apple trees.

摘要
本研究旨在探究苹果树花期无人机喷雾中静电效应对提升雾滴沉积效率的作用。试验设置静电喷雾与非静电（常规）喷雾两种工况，并在距离苹果树冠层上方 1.0 m、2.0 m 和 3.0 m 的不同无人机飞行高度下进行试验。通过在冠层上、中、下不同层次的叶片正反面布设喷雾采样纸，对雾滴沉积分布进行测定。结果表明，与常规无人机喷雾相比，静电力可使雾滴数密度提高 17.6%，雾滴粒径减小 25.3%，从而提高喷雾效果，在苹果树生长早期的授粉及病虫害防治方面具有明显优势。静电作用在带电雾滴与靶标之间产生吸引效应，可增强雾滴在下层叶片背面或花朵的黏附与沉积。然而，由于回流气流难以到达冠层上部和中部叶片背面，该静电优势在这些部位并不显著。上述研究结果为在苹果树生长早期利用静电技术提升授粉效率或开展精准农药喷施提供了支撑。

INTRODUCTION
Efficient and rapid pollination is crucial for ensuring apple's yield (*Olhnuud et al., 2022; Wu et al., 2024; Manzoor et al., 2025)*. However, the apple pollination process faces multi-source risks from prolonged rainy weather, frost, and sudden natural disasters (*Broussard et al., 2023*). As shown in Fig. 1, pollination in apple trees is the process by which pollen is transferred from the stamen of the pollen donor to the pistil of the pollen recipient. There are mainly three pollination methods, bee, manual (handheld pollinator) and UAV spraying. UAV-assisted pollination serves as an important supplement to manual and bee pollination (*Miyoshi et al., 2025*). Previous reports have demonstrated the successful application of agricultural UAVs in pesticide spraying, fertilizer and seed broadcasting, and agricultural supply transportation, showcasing their strong adaptability to complex terrains and high efficiency *(Lan et al., 2017; Pathak et al., 2020; Daniel et al., 2025)*.

The development of new UAV-based systems is an interesting and challenging topic. Electrostatic spray with UAVs is a novel spray technique aimed at optimizing spray quality. Traditional UAV spray systems often use larger droplet sizes to reduce drift caused by environmental wind *(Wang et al., 2019; Paul et al., 2024; Gatkal et al., 2025)*, but in fruit tree pollination, the specificity of the process requires pollen droplets to have a more suitable biological size. Smaller, more numerous droplets can increase pollination chances *(Nepi et al., 2009)*. Droplet density (number) is the most important parameter in UAV liquid pollination, that is because, in the process of liquid pollination by UAVs, the droplets produced by the spraying system need to deposit on the stigma of the recipient to achieve effective pollination. As shown in Fig. 2, the relationship between droplet volume and droplet number was analyzed, revealing a negative functional relationship between droplet size and droplet count. However, because the stigma is very small, larger droplets are prone to off-target deposition, making it necessary to optimize spraying by increasing droplet density (droplet number) to improve the on-target rate of pollen droplets. Electrostatic spraying shows potential for achieving this. Nevertheless, unlike ground-based electrostatic spraying, the influence of UAV propeller airflow on the behavior of electrostatically charged droplets remains insufficiently understood.

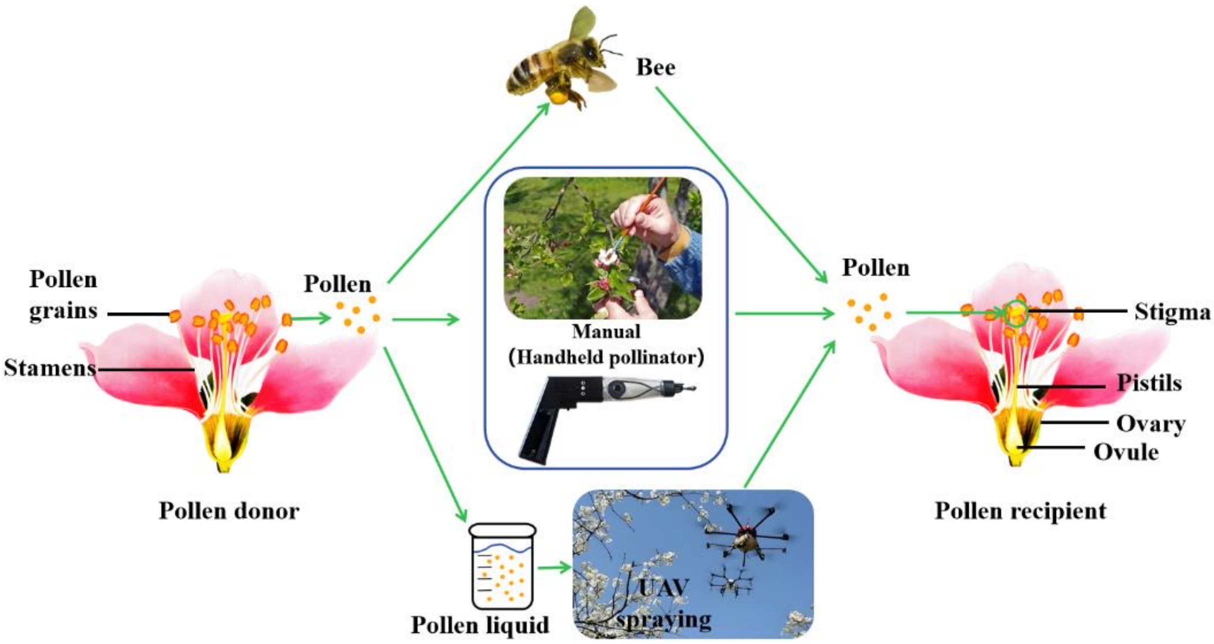


Fig. 1 - Schematic diagram of three pollination methods (cross-pollination)

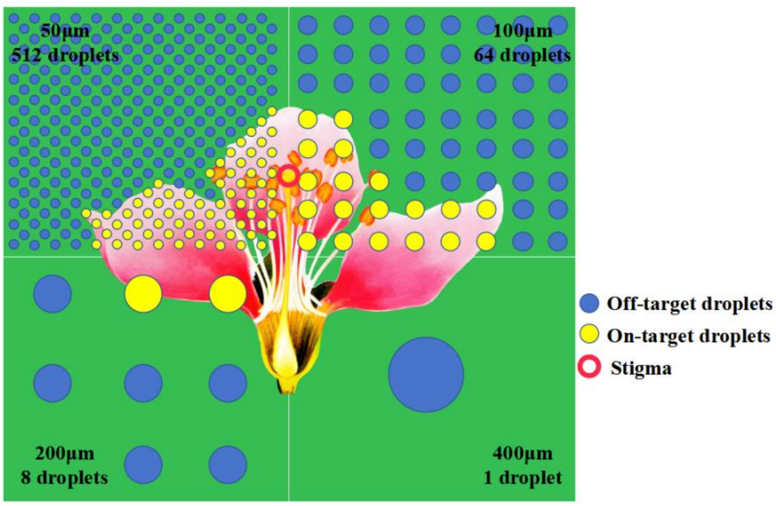


Fig. 2 - The relationship between droplet volume and numbers (droplet on-target rate analysis for stigma)

In the field of UAV-assisted crop pollination, *Li et al. (2015)* developed a device that redirects the downdraft generated by UAV rotors, converting vertical airflow into horizontal airflow to facilitate pollen transfer from male to female rice plants. *Shi et al. (2019)* installed deflectors on both sides of a UAV to change the downdraft flow field, experimentally verifying the potential of UAVs for tomato pollination. The above studies suggest that airflow exerts positive effects on pollen movement. *Wang et al. (2022)* tested optimal operating parameters for a commercial UAV in liquid pollination of Korla pears, indicating that 1.0 m above the canopy achieved the best results, comparable to manual pollination and cost-saving. *Koşar et al. (2023)* conducted UAV pollination on frost-affected walnuts, showing that UAV pollination increased walnut fruiting rates and saving pollen, though it had limitations in uniformity. In previous studies, researchers have tried to develop several UAV electrostatic spray systems *(Zhang et al., 2017; Wang et al., 2020; Zhao et al., 2024)*. However, test on deposition characteristics on different actual crops are very limited or even lacking. Field characteristic testing is essential to advance further research in this area. Therefore, this study employed a self-developed electrostatic spray UAV to evaluate droplet deposition characteristics in a standardized apple orchard, thereby assessing the feasibility of using an electrostatic UAV spraying system for liquid-based pollination.

MATERIALS AND METHODS

Experiment design

The experiment was conducted in a commercial apple orchard located in Zibo City, Shandong Province, China (118.07°E, 36.11°N). The orchard cultivates Fuji apple trees planted at a 2.0 m spacing, with an average tree height of approximately 4.0 m supported by a steel-frame trellis structure with overhead wires. During the test period, the temperature ranged from 8 to 25 °C, wind speed from 0.3 to 1.5 m/s, and relative humidity from 40% to 50%. The experimental platform consisted of a self-developed electrostatic spray UAV, comprising a high-voltage electrostatic generator and a four-rotor UAV (manufactured by Shandong Flight UAV Manufacturing Co., Ltd., Zibo, China). The system adopted a contact-charging method with an applied voltage of ±35 kV. The negative output of the electrostatic generator was connected to two spray tanks, polarizing the liquid with negative charges, while the positive output was exposed to the air for discharge. In UAV electrostatic spraying, the key mechanism is the charging of droplets and the establishment of a spatial electric field. Grounding creates a potential difference between the nozzle and the ground, which strengthens the electric field and enhances droplet adhesion to the target. Preliminary tests showed that the contact-charging method effectively charged the droplets, achieving a charge-to-mass ratio (CMR) of 3.5 mC/kg at 35 kV. The required ‘grounding’ effect is realized through the induced spatial electric field between the charged droplets and the plant canopy.

The high-voltage electrostatic generator unit consists of an adjustable high-voltage electrostatic generator, a 12 V lithium battery, a remote-control relay, and indicator lights. The spray system includes two water tanks, two diaphragm pumps, water pipelines, power supplies, and two pressure nozzles mounted on each side of the UAV, providing a total flow rate of 0.64 L/min. The components of the electrostatic spray system are shown in Fig.3.

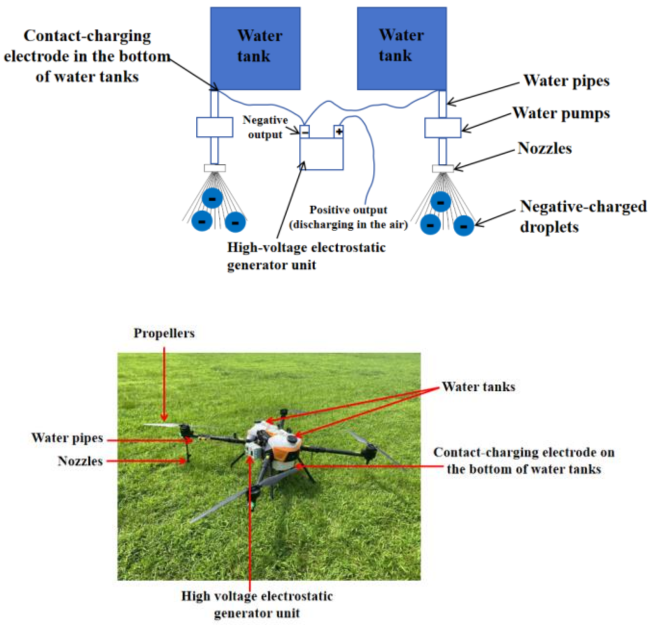


Fig. 3 - Components of the UAV electrostatic spray system

The UAV flight path was planned using the GPS-based A-B point mode, following a route aligned with the apple tree rows (Fig. 4).

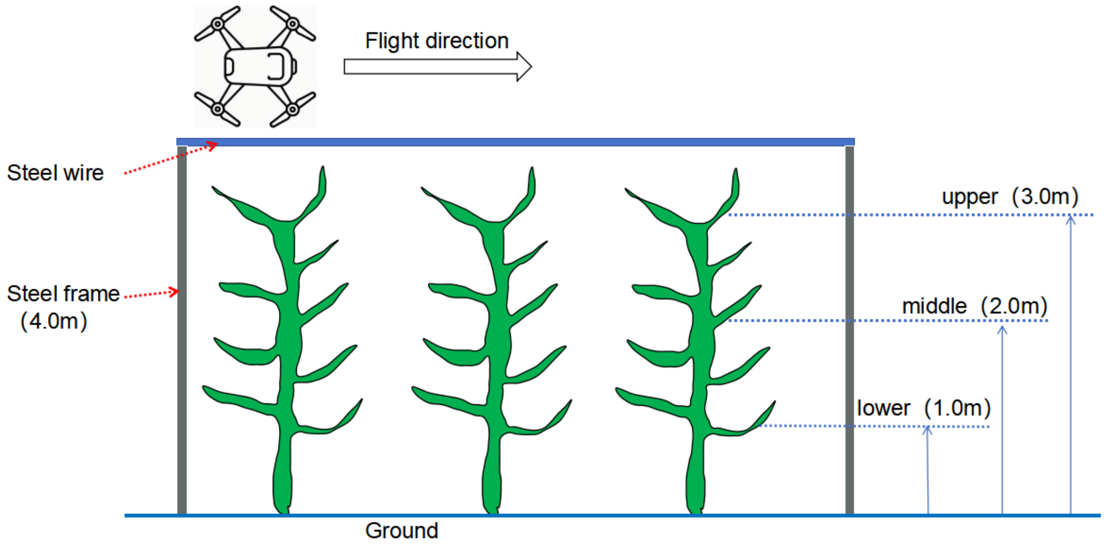


Fig. 4 - Experimental design

The spray solution consisted of water mixed with 0.5% Temptation Red dye, which served as a tracer to simulate the behavior of pollen droplets. Photographic paper strips (7 cm × 3 cm) were used as deposition collectors. Flight heights were set to 1.0 m, 2.0 m, and 3.0 m above the apple tree canopy. Based on pilot experience and preliminary tests, the UAV flight speed was fixed at 1.5 m/s, and the application rate was 14.2 L/ha. Water-sensitive paper cards were placed at three canopy levels - upper (3.0 m), middle (2.0 m), and lower (1.0 m) - with three sampling points randomly arranged at each level across three replicate trees. At each sampling point, two paper cards were fixed back-to-back with paper clips to measure droplet deposition on both the front and back side leaf surfaces. Four treatments were tested: T1 - 1.0 m flight height, conventional mode (C); T2 - 1.0 m, electrostatic mode (E); T3 - 2.0 m, E; and T4—3.0 m, E. After field spraying, all paper cards were scanned at 400 dpi as grayscale images using an HP scanner and analyzed with ImageJ software developed by USDA/ARS (ATRU, Wooster, Ohio, USA). The software automatically quantified key spray deposition parameters, including volume median diameter (VMD), coverage, and droplet density. Data were log(x + 1) transformed to meet normality requirements. Treatment and canopy-level effects were assessed using analysis of variance (ANOVA), and Tukey's honest significant difference (HSD) test was used for multiple comparisons at a significance level of $\alpha = 0.05$. For factorial comparisons, means were evaluated using t-tests at the 5% probability level *(Wang et al., 2019)*. The orchard test site and layout of the sampling cards are shown in Fig. 5.

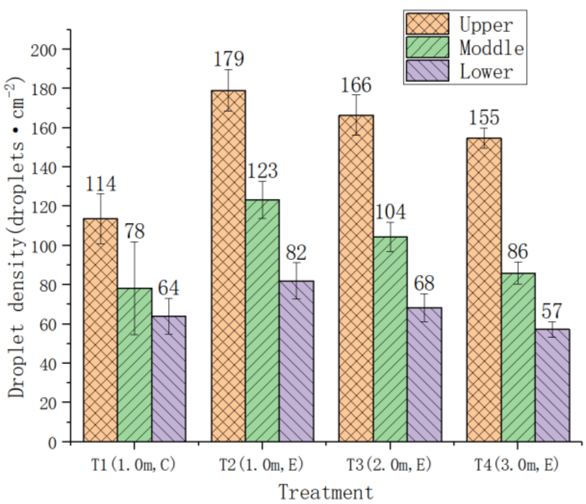
a) Test site ***b) Test paper layout***

Fig. 5 - Test site and test paper layout

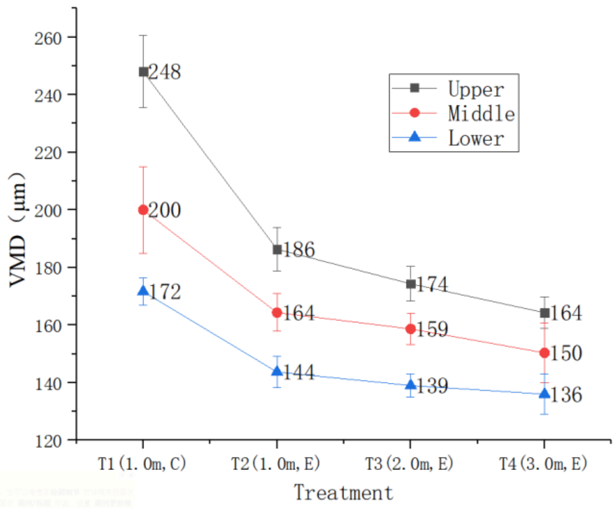
RESULTS

Deposition differences between UAV electrostatic spraying and conventional UAV spraying at different canopy levels

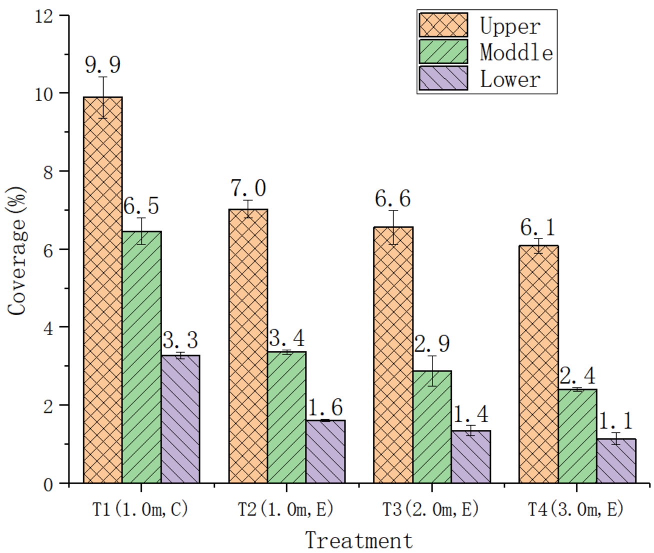
Compared with conventional spraying, activating the electrostatic system produced notable changes in droplet deposition characteristics. As shown in Fig. 6, significant differences were observed in both droplet density and droplet size between electrostatic and non-electrostatic treatments. Analysis of spray mode (T1 vs. T2) showed that electrostatic charging had a significant effect on droplet density ($P < 0.001$, $F = 11.25$). At a flight height of 1.0 m, on the front side of the upper canopy, droplet size (VMD) decreased from 249 μm to 186 μm, while droplet density increased from 136 droplets/cm^2 to 160 droplets/cm^2 - an increase of 17.6%. Similar trends were observed in both the upper and middle canopy layers, where conventional spraying produced larger droplets with lower droplet counts compared with electrostatic spraying. In the lower canopy layer, however, conventional spray produced slightly higher droplet density than the electrostatic mode. This is likely due to the stronger penetration of larger droplets under the downward propeller-induced airflow. For VMD, electrostatic treatment had a significant main effect ($P < 0.001$, $F = 234.83$). Flight height also significantly affected VMD ($P < 0.05$, $F = 249.20$), and there was a significant interaction between flight height and canopy level ($P < 0.001$, $F = 14.12$), indicating that the influence of electrostatics on droplet size varied with vertical canopy position.



a) Droplet density



b) VMD



c) Coverage

Fig. 6 - Front side droplet deposition in different canopy levels

The experiment also examined the deposition characteristics of electrostatic spraying at flight heights of 1.0, 2.0, and 3.0 m above the canopy. Flight height had a significant effect on droplet deposition density ($P < 0.001$, $F = 434.93$), and the interaction between flight height and canopy level also showed a significant effect ($P < 0.001$, $F = 23.69$).

As spray height increased, droplet density on the upper canopy progressively rose to 160, 171, and 183 droplets/cm^2 at 1.0, 2.0, and 3.0 m, respectively. This trend is attributed to the dispersion behavior of the spray flow during UAV application. Near the nozzles, the droplet stream is more concentrated and consists of relatively larger droplets influenced by the UAV's downwash airflow and the electrostatic force. As the droplets move downward, the spray flow expands, covering a larger area. This dispersion increases droplet density while simultaneously reducing droplet size.

In terms of droplet deposition coverage, the electrostatic treatment produced lower values than the conventional spray. At a flight height of 1.0 m, the deposition coverage of the electrostatic spray was 29.2% lower than that of the conventional treatment. Due to the presence of electrostatic repel forces, the droplet group tends to spread over a larger spatial extent and spray width rather than concentrating within a fixed deposition area (*Zhao et al., 2024*), which reduces droplet accumulation per unit area and therefore leads to a lower measured droplet coverage.

This finding indicates that the advantage of UAV electrostatic spraying lies not in increasing deposition coverage, but in enhancing droplet density. Consequently, the high droplet density achieved by electrostatic spraying is better suited for applications such as liquid pollination and contact insecticide treatments, where droplet number is critical. In contrast, for operations that require high coverage, such as herbicide application, UAV electrostatic spraying provides no clear advantage.

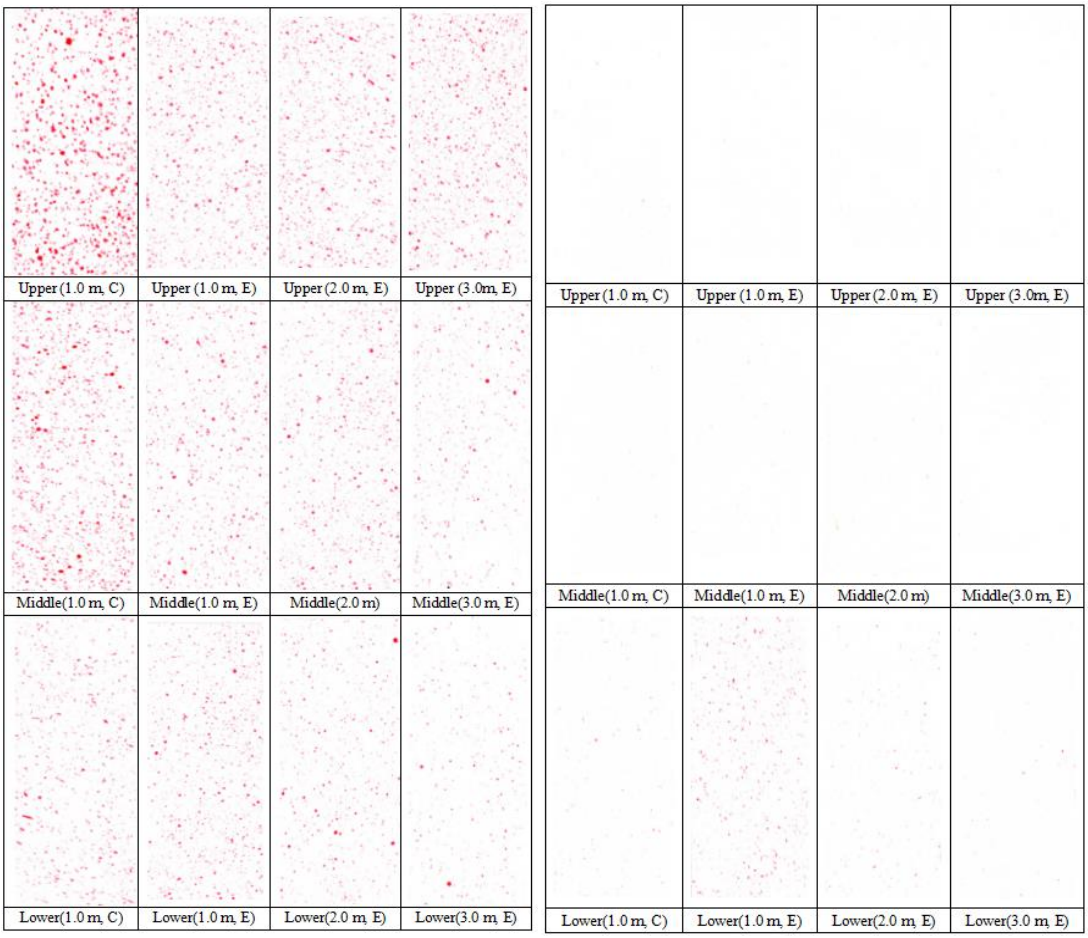
Effective pollination requires direct contact between pollen and the stigma, yet the stigma is a very small floral organ. Increasing droplet number improves the probability that pollen-bearing droplets will reach and contact the stigma, thereby enhancing pollination success. However, the reduction in droplet size observed in the results does not perfectly correspond with the increase in droplet count. This discrepancy suggests that a portion of the smaller droplets may have evaporated during transport. Even so, electrostatic charging still positively influences droplet quantity, and the presence of more fine droplets can promote better adhesion of the pollen-containing liquid to the stigma. This study was conducted in a standardized apple orchard with a high density of flower buds distributed across the upper, middle, and lower canopy layers. In orchards with different planting structures, particularly those in which flower buds are concentrated in the upper canopy, spraying from a slightly higher flight altitude, further above the canopy top, may provide more effective pollination performance.

Effect of electrostatics and downwash airflow on droplet penetration characteristics

Fig. 7 shows the droplet deposition patterns on the front and back sides of the sampling papers. At the middle and lower canopy levels, as the UAV flight height increased, droplet size gradually decreased, and droplet density declined correspondingly. This is mainly because greater spray height causes the downwash airflow to become more diffuse, weakening its ability to penetrate the internal canopy structure. At a flight height of 1.0 m, effective droplet deposition of 68.3 droplets/cm^2 was detected on the backside surfaces in the lower canopy layer. This confirms the presence of recirculating airflow: the downward rotor airflow transports droplets toward the ground and then generates an upward return flow that carries droplets onto the underside of leaves and flowers in the lower layer. In contrast, for conventional spraying, almost no droplets were detected on the backside surfaces, indicating that the finer, charged droplets in electrostatic spraying exhibit better adhesion and deposition efficiency. At flight heights of 2.0 m and 3.0 m, only minimal droplet deposition (less than 10 droplets/cm^2) was observed on the backside of the lower canopy. Therefore, controlling flight height is essential for achieving effective droplet penetration and enhancing deposition on the lower-layer flowers.

For the lower canopy layer, the combined effects of electrostatics and rotor-induced airflow create noticeable differences in deposition characteristics. In conventional spraying at a flight height of 1.0 m, droplets primarily deposited on the front side of the lower-layer sampling cards due to the strong downward airflow, while very few droplets reached the backside. This may be related to insufficient kinetic energy in the airflow to transport droplets around the leaf surfaces. The difference in droplet size between treatments - 177 μm in T1 versus 138 μm in T2 - indicates that larger droplets in conventional spraying require greater momentum to reach and deposit on the backside surfaces.

In the electrostatic spraying treatments (T2, T3, and T4), as the flight height increased, only small numbers of droplets were detected on the backside (T3 and T4), suggesting that increased flight height weakens the recirculating airflow. Moreover, on the backside of the upper and middle canopy papers, droplet deposition was nearly zero across all treatments. Under the influence of the UAV rotors, both airflow and droplets move predominantly downward. While the recirculating airflow can facilitate deposition on the backside of the lower canopy, this upward return flow is not strong enough to transport droplets to the backside of the middle or upper canopy layers.



a) front sides test paper; *b) back sides test paper*

Fig. 7 - Droplet deposition color images of front and back sides test papers

Fig. 8 - Droplet deposition in apple flowers (red points are the pollen droplets)

Thus, low flight heights help generate recirculating airflow, but for taller crops, droplet deposition on the backside of the middle and upper canopy layers remains limited. Fig. 8 shows droplet deposition on petals; however, it is important to note that the stigma has a much smaller surface area compared with the petals.

Therefore, the advantage of electrostatic spraying in increasing droplet density becomes particularly significant: a greater number of fine droplets increases the likelihood that droplets will contact the stigma, thereby enhancing pollination effectiveness. As illustrated, electrostatic spraying produced substantial droplet coverage on petals, and the higher droplet count further improves the probability of successful stigma contact.

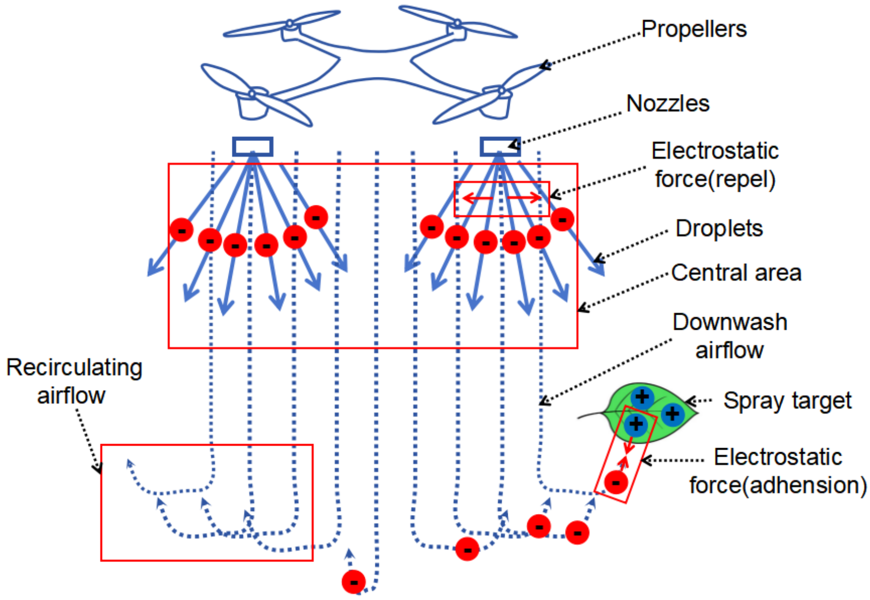


Fig. 9 - Effects of electrostatics and airflow on the motion of pollen droplets

As shown in Fig. 9, the movement of pollen droplets under the combined influence of electrostatic force and rotor-induced airflow was analyzed. Initially, the nozzles generate primary atomization through hydraulic pressure. Under the action of the electrostatic field, secondary atomization occurs: because droplets carry charges of the same polarity, electrostatic repulsion reduces surface tension and promotes the formation of finer droplets. Repulsion among same-polarity droplets also causes the spray flow to expand, increasing the spatial distribution of droplets. These charged droplets then move downward under the downwash airflow produced by the UAV rotors. The airflow supplies kinetic energy, enabling droplets to penetrate the upper, middle, and lower canopy layers. After reaching the ground, droplets encounter the recirculating airflow, which transports them upward toward the backside surfaces of leaves and floral structures. During this process, the increased number of fine droplets, combined with electrostatic attraction between the charged droplets and neutral plant surfaces, results in enhanced deposition on the backside of the targets.

Limitation discussion

This study demonstrates that electrostatic forces promote atomization, reduce droplet size, and increase the proportion of fine droplets, thereby effectively enhancing the likelihood of contact between pollen droplets and stigmas. However, electrostatic charging also reduces droplet coalescence and spreading on the target surface, leading to lower deposition coverage per unit area. This reduced spreading is unfavorable in application scenarios where high surface coverage is required. Therefore, UAV-based electrostatic spraying, as a low-volume spraying technique, is more suitable for applications involving small or discrete targets, such as contact insecticides and liquid pollination. In contrast, for operations that rely on high surface coverage to achieve sufficient pesticide translocation, including systemic herbicides and fungicides, UAV electrostatic spraying provides no clear advantage.

In addition, because the spray output of the system used in this study was relatively low, dense orchards, especially during the later growth stages, may experience droplet shielding by upper canopy leaves. This can hinder droplet penetration and lead to over-deposition in the upper canopy while causing insufficient deposition in the lower canopy. Therefore, stronger rotor-induced airflow is required to enhance penetration, enabling droplets to be transported into the interior of the canopy and deposited on lower leaves. Unlike field crop spraying, orchard applications feature tall, structurally complex canopies, which means that UAV flight speed should not be too high. Reducing flight speed allows better utilization of rotor downwash to generate airflow disturbances, and when combined with electrostatic attraction and fine droplet sizes, can improve overall deposition on leaf surfaces.

For orchards with different planting patterns and canopy architectures, the effectiveness and applicability of UAV electrostatic spraying require further verification, as leaf morphology and canopy structure can markedly influence droplet deposition. In particular, the deposition behavior on broad-leaved species compared with the small leaves of young apple trees requires additional field experimentation to enable a more systematic and comprehensive evaluation.

CONCLUSIONS

This study evaluated the liquid pollination performance of an electrostatic spray UAV using a contact-charging method in an apple orchard. The main conclusions are as follows:

1. Compared with conventional UAV spraying, electrostatic charging increased droplet density by 17.6% and reduced droplet size by 25.3%, thereby improving the efficiency of liquid pollination.

2. The apple tree canopy hinders droplet penetration, and smaller droplets are more likely to reach lower leaves and flowers under the influence of the rotor-generated airflow.

3. Electrostatics enhances the adhesion and deposition of droplets on backside surfaces; however, this advantage diminishes when the airflow direction opposes the electrostatic attraction.

4. UAV flight height is closely associated with deposition performance and should be selected based on horticultural and agronomic considerations, depending on whether pollination is prioritized for the upper or lower canopy. Effective use of rotor-induced airflow is essential: the downwash airflow improves canopy penetration, while the recirculating airflow contributes to backside deposition in the lower canopy.

Based on the results of this study, the recommended operational parameters for UAV electrostatic liquid pollination are: flight height of 1.0 m above the canopy, flight speed of 1.5 m/s, charging voltage of 35 kV, and an application rate of 14.2 L/ha.

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