Postprint: Comparison of Droplet Deposition Performance Between Ground-Based Mist Sprayers and Six-Rotor Plant Protection UAVs in Mango Canopies

Authors: Li Yangfan, He Xiongkui, Han Leng, Huang Zhan, He Miao, Xiongkui He

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Abstract

To address issues of excessive pesticide usage, uneven application, and low operational efficiency in conventional plant protection operations in mango orchards, and to facilitate the construction of smart mango orchards, this study compared the pesticide droplet deposition performance of ground-based mist blowers and six-rotor plant protection UAVs (Unmanned Aerial Vehicles) in mango canopies. The mango canopy was stratified into upper, middle, and lower layers, with tartrazine employed as a tracer. High-resolution photographic paper and filter paper were utilized to collect pesticide droplets, and image processing techniques were applied to analyze the uniformity of droplet deposition distribution. The experimental results demonstrated that the plant protection UAV achieved significantly higher droplet coverage rates on leaf surfaces in the upper canopy of mango trees compared to the ground-based mist blower; for other canopy positions, no significant difference in leaf surface coverage was observed between the two application equipment types. The average coverage rates on both adaxial and abaxial leaf surfaces in the UAV treatment group were 1.5 to 2 times those of the ground-based mist blower, indicating superior control efficacy on abaxial leaf surfaces. The ground-based mist blower treatment group exhibited significantly higher droplet density on adaxial leaf surfaces than the UAV group, with no significant difference observed on abaxial surfaces; however, neither adaxial nor abaxial surfaces in the UAV treatment group satisfied the pest and disease control requirement of 20 droplets/cm^2 for low-volume spray applications. Pesticide deposition from the ground-based mist blower was concentrated in the middle and lower canopy regions (61.1%), whereas UAV deposition was concentrated in the upper canopy (43.0%). The proportion of deposition within the canopy interior was greater for the ground-based mist blower (48.6%) than for the UAV (25.5%), although the ground-based mist blower displayed insufficient deposition capacity in the upper canopy, with a deposition proportion of merely 17%. The study concludes that, compared to plant protection UAVs, ground-based mist blowers are more suitable for pest and disease control in the middle and lower layers and interior regions of mango canopies, while the higher droplet coverage density of this equipment also confers significant advantages when applying fungicides. Plant protection UAVs are appropriate for controlling pests and diseases targeting the upper canopy, such as thrips and anthracnose, which commonly infest external flowers and inflorescences.

Full Text

Comparison of Droplet Deposition Performance Between Ground Mist Sprayer and Six-Rotor Plant Protection UAV in Mango Canopy

LI Yangfan[1],[2], HE Xiongkui[1],[2]*, HAN Leng[1],[2], HUANG Zhan[1],[2], HE Miao[1],[2]

[1]College of Science, China Agricultural University, Beijing 100193, China
[2]College of Agricultural Unmanned System, China Agricultural University, Beijing 101206, China

Abstract: To address the issues of excessive pesticide use, uneven application, and low operational efficiency in conventional mango orchard protection, and to advance the development of smart mango orchards, this study compared the droplet deposition characteristics of two orchard spraying equipment types—ground mist sprayers and six-rotor plant protection unmanned aerial vehicles (UAVs)—within mango canopies. The mango canopy was stratified into upper, middle, and lower layers, with tartrazine employed as a tracer. High-resolution photographic paper and filter paper were used to collect spray droplets, and image processing techniques were applied to analyze deposition distribution uniformity. Experimental results demonstrated that the UAV achieved significantly higher droplet coverage on upper canopy leaf surfaces compared to the ground mist sprayer, while no significant differences were observed in other canopy positions. The average coverage rates on both leaf surfaces in the UAV treatment were 1.5–2 times those of the ground mist sprayer, indicating superior control of abaxial leaf surfaces. The ground mist sprayer treatment exhibited significantly higher droplet density on adaxial leaf surfaces than the UAV treatment, with no significant difference on abaxial surfaces; however, neither leaf surface in the UAV treatment met the low-volume spray requirement of 20 droplets/cm^2 for pest control. The ground mist sprayer concentrated deposition in the middle and lower canopy (61.1% of total deposition), whereas the UAV concentrated deposition in the upper canopy (43.0%). The internal canopy deposition proportion was higher for the ground mist sprayer (48.6%) than for the UAV (25.5%), though the ground mist sprayer' s deposition capacity in the upper canopy was insufficient, accounting for only 17% of total deposition. These findings indicate that, compared to UAVs, ground mist sprayers are more suitable for pest control in the middle-lower and internal canopy regions, and their high droplet coverage density (60 droplets/cm^2) offers clear advantages when applying contact insecticides or protective fungicides such as Bordeaux mixture. UAVs are better suited for controlling pests and diseases in the upper canopy that affect external floral tissues, such as thrips and anthracnose.

Keywords: smart mango orchard; mist sprayer; plant protection UAV; droplet deposition distribution uniformity; pest control

1 Introduction

China ranks as the world's second-largest mango producer, with national cultivation area reaching 349,400 hectares (5.241 million mu) and total output of 3.306 million tons by 2020 [1]. As a tropical fruit, mango is widely cultivated in rainforest climates where high pest and disease outbreak frequencies, coupled with inconsistent occurrence patterns across production regions, pose significant challenges for orchard protection [2]. Common mango diseases include anthracnose, bacterial angular leaf spot, and powdery mildew, while major pests comprise thrips and weevils [3,4].

Conventional chemical control relies primarily on manual application using backpack sprayers and high-pressure hose guns [5], which suffers from arbitrary operation, poor uniformity, and low pesticide utilization efficiency [6]. In recent years, with technological maturation, plant protection UAVs have been extensively deployed for orchard pest management. Current research on UAVs in orchard operations has focused primarily on evaluating overall average deposition levels within crop canopies by modifying technical parameters to assess spraying efficacy [7-11]. Compared to ground-based operations, UAVs demonstrate superior terrain adaptability and operational efficiency. However, UAV spraying suffers from serious issues including poor deposition uniformity, insufficient coverage on abaxial leaf surfaces, and significant spray drift [12,13], with high-concentration applications often causing phytotoxicity and foliar burn. When facing different control targets, these limitations become particularly problematic.

In contrast, most European and American orchards feature standardized layouts and high mechanization levels, with ground-based air-assisted sprayers being the primary application method [14,15]. Compared to UAVs, ground orchard sprayers reduce drift and improve deposition uniformity within canopies [16]. Currently, targeted directional spraying technology has become a research hotspot internationally [17-19], with intelligent orchard spraying systems integrating sensing, intelligent decision-making, and variable-rate control being developed [19-24]. Nevertheless, orchard protection in complex environments still faces challenges including difficulty for large machinery to enter orchards, poor adaptability, and inability of small equipment to effectively penetrate tree canopies [25].

Based on these challenges, this study compared and analyzed the deposition performance of these two spraying equipment types in mango canopies to provide technical parameters and references for reducing labor costs, improving operational efficiency, and decreasing pesticide usage.

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2 Materials and Methods

2.1 Equipment

A plant protection UAV (DJI T30 model, Figure 1: see original paper, hereinafter referred to as UAV) and a ground remote-controlled crawler mist sprayer (Shanxi Nonggu Feinong Technology Co., Ltd., 3WDZ-200D model, Figure 1: see original paper, hereinafter referred to as ground mist sprayer) were selected for comparison. Main parameters for both machines are presented in . The UAV operated in autonomous tree-row mode via remote controller waypoint setting, enabling constant altitude and speed operation. The ground mist sprayer was manually controlled by operators via remote control.

2.2 Test Site

The experiment was conducted on February 28, 2022, at Dabala Village, Yazhou District, Sanya City, Hainan Province (109°18 8728 E, 18°43 2527 N). During the test period, average temperature was 32.3°C, average humidity 41%, and average wind speed 0.5 m/s. The mango variety was Guifei, with trees aged 7–8 years. Tree characteristics: average height 2.70–2.90 m, crown diameter 3.2 m, spacing 4.5 m within rows and 5 m between rows. Trees exhibited healthy growth with fully developed leaves distributed in an umbrella-shaped canopy, with minimal foliage at the trunk center. The orchard was located on flat terrain with open space and no obstacles.

2.3 Experimental Design

A 30 m × 20 m plot was selected as the experimental area ([Figure 2: see original paper]). Three non-adjacent, uniformly growing mango trees were chosen for sampling within the plot. Two treatment groups were established: ground mist sprayer application and UAV application, with operational parameters detailed in . The UAV' s initial flight direction followed the north-south tree row orientation with above-row flight pattern, while the ground mist sprayer employed inter-row spraying mode. Tartrazine was used as the tracer in an aqueous solution.

Sampler placement is illustrated in [Figure 3: see original paper]. The mango canopy was divided into upper, middle, and lower layers. Lower layer outer samples were marked O1, inner samples I1; middle layer outer samples O2, inner samples I2. Due to mango canopy growth characteristics (long, rigid leaves), no inner samples were established for the middle-lower and upper canopy centers.

Upper canopy samples were marked O3. Filter papers were placed adjacent to photographic papers within 5 cm without mutual shading to detect deposition, with samplers placed on both adaxial and abaxial leaf surfaces. Four filter papers were placed at the ground projection of the four O1 lower-layer samples to collect ground runoff. Each treatment had two replicates.

2.4 Data Analysis Methods

Five minutes after operation, all photographic papers were collected into business card holders, placed in size-12 ziplock bags with desiccant to prevent moisture affecting results, and scanned within 5 days using a scanner (EPSON DS-1610) at 600 dpi. DepositScan software was used to analyze droplet deposition. Filter papers were placed in size-6 ziplock bags, stored in black bags protected from light, and analyzed within 5 days. Twenty milliliters of deionized water (5 mL for ground mist sprayer group) was added for elution, followed by analysis using a microplate reader (450 nm wavelength, iMark, USA) to calculate deposition.

Deposition distribution uniformity was expressed as coefficient of variation (CV, %), where lower CV values indicate better uniformity. Unit deposition was expressed as β (L/cm^2) using formula (1):

$$\beta = \frac{C \times V}{a \times A}$$

where β is deposition (L/cm^2), C is tracer concentration (g/mL), V is elution volume (mL), a is filter paper area (cm^2), and A is mother solution concentration (g/L).

Horizontal penetration coefficient KH was calculated using formula (2):

$$K_H = \frac{\beta_I}{\beta_O} \times 100\%$$

where βI is unit deposition in inner canopy (L/cm^2) and βO is unit deposition in outer canopy (L/cm^2).

Similarly, vertical penetration coefficient KV was calculated using formula (3):

$$K_V = \frac{\beta_a}{\beta_{b\&c}} \times 100\%$$

where for ground mist sprayer treatment, βa is upper canopy unit deposition and βb&c is average unit deposition of middle-lower canopy; for UAV treatment, βa is lower canopy unit deposition and βb&c is average unit deposition of middle-upper canopy.

Vertical unit area deposition distribution percentage (RV, %) characterized the vertical distribution proportion of active ingredients, with values closer across canopy positions indicating more uniform vertical deposition, calculated using formula (4):

$$R_V = \frac{\beta_{dep}}{\beta_U + \beta_M + \beta_L + \beta_G} \times 100\%$$

where βdep is unit deposition at a specific vertical position, and βU, βM, βL, βG are unit depositions in upper, middle, lower, and ground loss positions, respectively.

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3 Results

3.1 Droplet Coverage and Density Analysis

[Figure 5: see original paper] presents droplet coverage rates (Figure 5: see original paper and Figure 5: see original paper) and droplet densities (Figure 5: see original paper and Figure 5: see original paper) on adaxial and abaxial leaf surfaces for both equipment types, along with significance analysis results for deposition distribution across canopy positions.

The ground mist sprayer treatment concentrated deposition primarily on adaxial surfaces of outer leaves in the middle-lower canopy, with coverage rates below 5% in other positions, showing a decreasing trend from bottom to top and from outer to inner canopy. However, 得益于该机具较高的作业压力，产生的细雾滴 (DV50 of 170 m after spreading on collection cards) achieved droplet densities exceeding 30 droplets/cm^2 on adaxial surfaces across all canopy positions, meeting control requirements [26]. Overall droplet density was 6-7 times higher than the UAV, reaching 170 droplets/cm^2 in some areas, demonstrating clear advantages when applying contact insecticides or protective fungicides like Bordeaux mixture.

UAV spraying (Figure 4: see original paper) showed no obvious vertical decreasing trend in coverage due to the umbrella-shaped canopy structure and downdraft diffusion effects at the treetop. Except at position I1, all adaxial leaf surface positions met the 2% coverage requirement. No significant differences in coverage were observed between the two machines at most positions except the canopy top (O3). The UAV treatment' s average adaxial coverage was 7.03%, 1.4 times that of the ground mist sprayer, while abaxial coverage was 2.7 times higher. However, due to poor atomization performance producing large droplets (DV50 of 631 m after spreading), droplet densities on both leaf surfaces failed to meet the low-volume spray requirement of 20 droplets/cm^2 for pest control [27], averaging only 9.2 droplets/cm^2 compared to 61.1 droplets/cm^2 for the ground mist sprayer. This disadvantage is particularly evident when applying protective fungicides and could be improved by installing lower-flow nozzles or centrifugal atomizers.

Overall droplet deposition parameters are summarized in . The ground mist sprayer treatment' s average abaxial coverage was only 1%, lower than the UAV' s 2.72%, with average droplet density of 20.7 droplets/cm^2, failing to meet control requirements. The low abaxial coverage and density resulted from mango canopy characteristics: compared to pear or apple canopies, mango leaves are long, rigid, and less likely to flip or be disturbed by airflow, preventing droplet deposition on abaxial surfaces. High canopy closure and severe leaf inter-shading also prevented droplets from penetrating outer canopies to reach inner regions, resulting in poor uniformity. The pressure-assisted spray delivery rarely caused leaf flipping, though high-pressure airflow could lift some leaves at certain angles, creating high-coverage samples as evidenced by multiple outliers in Figure 5: see original paper. This spray delivery method is unsuitable for abaxial leaf pest control in mango canopies and could be improved by adding air-assistance devices to enhance penetration and distribution uniformity.

The UAV treatment showed better abaxial leaf control, with abaxial coverage representing 38.7% of adaxial coverage compared to 20% for the ground mist sprayer. Abaxial coverage at O3 reached 5% but showed poor repeatability. Both treatments exhibited wide-ranging coverage values, with UAV treatment CV of 148.5% and ground mist sprayer CV of 165.9%, indicating poor overall uniformity. Contributing factors included: (1) high canopy closure with extensive leaf shading preventing penetration to inner canopies, (2) complex leaf angle distribution due to arc-shaped, long leaves causing large deposition variations within single leaves, making traditional sampling methods insufficiently precise for mango, and (3) lack of auxiliary droplet diffusion devices in ground mist sprayers causing localized over-deposition, while UAVs lacked more effective atomization methods.

Scanning results in [Figure 6: see original paper] revealed that large UAV droplets easily slid off leaves due to complex leaf angle distributions, causing pesticide loss. Although ground mist sprayer application rates were 5-6 times higher than UAVs, the lack of diffusion assistance led to volatilization and drift during droplet transport, reducing leaf surface coverage.

3.2 Deposition and Penetration Analysis

Unit deposition results are shown in Figure 5: see original paper and Figure 5: see original paper. Except at O3, ground mist sprayer adaxial deposition was significantly higher than UAV deposition. Due to higher application volumes, inner canopy abaxial deposition was also significantly greater. Vertical distribution percentages calculated using formula (4) are presented in . Ground mist sprayer deposition concentrated in middle-lower outer canopy (61% of total), with upper canopy unit deposition of only 0.38 L/cm^2 (47.0% of average deposition). UAV treatment concentrated deposition in the upper canopy (43.0% of total).

Internal canopy deposition proportion was 37.1% for ground mist sprayer versus 18.0% for UAV. Horizontal penetration coefficient was higher for ground mist sprayer (48.6%) than UAV (25.5%), indicating that under current UAV operational parameters, droplets could not penetrate outer canopies effectively, requiring parameter optimization. The ground mist sprayer' s fine droplets facilitated internal canopy delivery. Both machines showed approximately 21% ground loss, though UAVs are more susceptible to climate-induced drift. During high pest pressure periods, UAVs often operate with high pesticide concentrations, increasing phytotoxicity risk.

4 Conclusions and Outlook

This study experimentally compared droplet deposition distribution characteristics of six-rotor UAVs and ground mist sprayers in mango canopies, yielding the following conclusions:

(1) UAV spraying achieved significantly higher droplet coverage on upper canopy leaf surfaces compared to ground mist sprayers, with no significant differences at other canopy positions. UAV average coverage on both leaf surfaces was 1.5–2 times higher than ground mist sprayers, demonstrating superior abaxial leaf control. Ground mist sprayer adaxial droplet density was significantly higher than UAVs, with no significant difference on abaxial surfaces; however, UAV treatments failed to meet the low-volume spray requirement of 20 droplets/cm^2 on either surface. Ground mist sprayer deposition concentrated in middle-lower canopy (61.1%), while UAV deposition concentrated in upper canopy (43.0%). Internal canopy deposition proportion was higher for ground mist sprayers (48.6%) than UAVs (25.5%).

(2) Due to mango canopy characteristics—high closure, long and thick leaves, and complex leaf angle distribution—both equipment types exhibited poor deposition uniformity, with overall CV values exceeding 100%.

(3) Both machines demonstrated distinct advantages and limitations. Ground mist sprayers are more suitable for middle-lower and internal canopy pest control, with high droplet density (60 droplets/cm^2) advantageous for contact insecticides and protective fungicides like Bordeaux mixture. However, insufficient upper canopy deposition and poor overall uniformity could be improved by adding air-assistance devices. UAVs exhibit good leaf surface deposition and terrain adaptability, making them suitable for upper canopy pests affecting external floral tissues, such as thrips and anthracnose. However, their limited internal canopy penetration could be addressed through improved atomization methods or optimized operational parameters to enhance uniformity.

Future work will develop a collaborative aerial-ground stereoscopic plant protection system where both machines operate sequentially on the same plot without interference, distributing pesticides according to optimized ratios. This approach would leverage the ground mist sprayer' s excellent middle-lower and internal canopy performance while using UAVs to supplement insufficient upper canopy deposition and conduct secondary applications in inaccessible terrain, achieving uniform canopy coverage and significantly improving deposition uniformity and pesticide use efficiency. Subsequent research on reduced-rate application and integration of intelligent orchard protection systems (including sensing, decision-making, and execution mechanisms) will enable unmanned, intelligent mango orchard protection operations.

References

[1] KE Youpeng. Brief analysis of challenges and solutions for Hainan mango industry development under RCEP[J]. Hainan Today, 2022(3): 50-51.

[2] CEN Yanxi. Preliminary study on occurrence and control of main diseases and insect pests in mango[J]. South China Agriculture, 2019, 13(9): 11-12.

[3] YE Xiaoxiao. Occurrence and control of mango fruit main diseases and pests[J]. Journal of Agricultural Catastrophology, 2015, 5(9): 7-10.

[4] XING Chuming, HAN Dongyin, LI Lei, et al. Spatio-temporal dynamics of thrips in mango orchard[J]. Chinese Journal of Environmental Entomology, 2017, 39(6): 1258-1265.

[5] YIN Pingfa. Technology of mango disease and insect pest control in Hainan[J]. Special Economic Animals and Plants, 2021, 24(7): 47-48.

[6] HE Xiongkui. Plant protection UAV spray systems and application technology in China[J]. Agricultural Engineering Technology, 2018, 38(9): 33-38.

[7] ZHU Xiaofeng, WANG Ming, XU Bingqiang, et al. Optimization of unmanned aerial vehicle (UAV) operation parameters in walnut orchards[J]. Plant Protection, 2020, 46(4): 25-32.

[8] WANG C, LIU Y, ZHANG Z, et al. Spray performance evaluation of a six-rotor unmanned aerial vehicle sprayer for pesticide application using an orchard operation mode in apple orchards[J]. Pest Management Science, 2022, 78(6): 2449-2466.

[9] MENG Y, SU J, SONG J, et al. Experimental evaluation of UAV spraying for peach trees of different shapes: Effects of operational parameters on droplet distribution[J]. Computers and Electronics in Agriculture, 2020, 170: ID 105282.

[10] WANG C, HERBST A, ZENG A, et al. Assessment of spray deposition, drift and mass balance from unmanned aerial vehicle sprayer using an artificial vineyard[J]. Science of The Total Environment, 2021, 777: ID 146181.

[11] CHEN Shengde, LAN Yubin, ZHOU Zhiyan, et al. Effects of spraying parameters of small plant protection UAV on droplets deposition distribution in citrus canopy[J]. Journal of South China Agricultural University, 2017, 38(5): 97-102.

[12] LIU Dejiang, GONG Yan, WANG Guo, et al. Comparison of pesticide deposition distribution in orchard aerial spraying[J]. Jiangsu Agricultural Sciences, 2018, 46(6): 207-211.

[13] WANG Changling, HE Xiongkui, ZENG Aijun, et al. Measuring method and experiment on spray drift of chemicals applied by UAV sprayer based on an artificial orchard test bench[J]. Transactions of the CSAE, 2020, 36(13): 56-66.

[14] HE Xiongkui. Research progress and developmental recommendations on precision spraying technology and equipment in China[J]. Smart Agriculture, 2020, 2(1): 133-146.

[15] HE Xiongkui. Improving severe draggling actuality of plant protection machinery and its application techniques[J]. Transactions of the CSAE, 2004(1): 13-15.

[16] ZHOU Liangfu, XUE Xinyu, ZHOU Lixin, et al. Research situation and progress analysis on orchard variable rate spraying technology[J]. Transactions of the CSAE, 2017, 33(23): 80-92.

[17] ZHANG Jiachen, DENG Wei, ZHANG Yan. Status quo on research of constant pressure and variable-rate spraying technology[J]. Journal of Agricultural Mechanization Research, 2015, 37(2): 257-260.

[18] PETERSON D L, HOGMIRE H W. Tunnel sprayer for dwarf fruit-trees[J]. Transactions of the ASAE, 1994, 37(3): 709-715.

[19] LI Longlong, HE Xiongkui, SONG Jianli, et al. Design and experiment of automatic profiling orchard sprayer based on variable air volume and flow rate[J]. Transactions of the CSAE, 2017, 33(1): 70-76.

[20] ESCOLÀ A, ROSELL-POLO J R, PLANAS S, et al. Variable rate sprayer. Part 1—Orchard prototype: Design, implementation and validation[J]. Computers and Electronics in Agriculture, 2013, 95: 122-135.

[21] YAN Chenggong, XU Liming, YUAN Quanchun, et al. Design and experiments of vineyard variable spraying control system based on binocular vision[J]. Transactions of the CSAE, 2021, 37(11): 13-22.

[22] SONG Shuran, CHEN Jianze, HONG Tiansheng, et al. Design and experiment of orchard flexible targeted spray device[J]. Transactions of the CSAE, 2015, 31(10): 57-63.

[23] FAN Daoquan, ZHANG Meina, PAN Jian, et al. Development and performance test of variable spray control system based on target leaf area density parameters[J]. Smart Agriculture, 2021, 3(3): 60-69.

[24] OSTERMAN A, GODEŠA T, HOČEVAR M, et al. Real-time positioning algorithm for variable-geometry air-assisted orchard sprayer[J]. Computers and Electronics in Agriculture, 2013, 98: 175-182.

[25] SUN Chengda, LIU Changding. Construction and application of droplet canopy penetration model for air-assisted spraying pattern[J]. Transactions of the CSAE, 2019, 35(15): 25-32.

[26] GB/T17997-2008. Field operation procedures and spray quality evaluation for pesticide sprayers (machines)[S]. Beijing: China Standards Press, 2008.

[27] MH/T 1002.1-2016. Technical indicators for agricultural aviation operation quality—Spraying operations[S]. Beijing: Civil Aviation Administration of China, 1995.