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Design and Spray Performance Evaluation of an Air–Ground Cooperation Stereoscopic Plant Protection System for Mango Orchards

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Abstract: With the aim of solving the problems of high labor intensity, low operational efficiency, and poor deposition distribution uniformity in the mango canopy associated with traditional plant protection devices, an air-ground co-operation stereoscopic plant protection system consisting of an orchard caterpillar mist sprayer and a six-rotor plant protection UAV was designed to jointly undertake plant protection operations in mango orchards. We tested the spraying performance of the system on mango trees, compared with the single-machine operation, the air–ground co-operation system could significantly increase the droplet coverage on the upperside of mango leaves in each part of the canopy (a 14.7% increase for the mist sprayer and 12.9% for the UAV). This increased the active component deposition distribution uniformity in the mango canopy but could not significantly improve the deposition and coverage of droplets on the underside of leaves compared with the mist sprayer and plant protection UAV. Due to the characteristics of the mango canopy such as large leaf length and thickness and complex leaf inclination distribution, this led to poor deposition distribution uniformity of the two spray units, and the overall CV was over 150%. The pesticide active ingredients were almost uniformly distributed in the vertical direction when the application ratios (ground implements/plant protection drones) were 8/2 and 7/3, offering a promising protocol for reduced pesticide application in mango orchards. This study presents promising data that support the innovative integration of drones into crop protection programs for large canopy crops (e.g., mango) and provides guidance for the ACSPPS system in reduction and precision application research.

Keywords: smart mango orchard; co-operative plant protection; UAV; pest control

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Citation: Li, Y.; Han, L.; Liu, L.; Huang, Z.; Wang, C.; He, X. Design and Spray Performance Evaluation of an Air–Ground Cooperation Stereoscopic Plant Protection System for Mango Orchards. *Agronomy* **2023**, *13*, 2007. https://doi.org/10.3390/agronomy13082007

Academic Editor: Xiangjun Zou

Received: 21 June 2023
Revised: 19 July 2023
Accepted: 25 July 2023
Published: 28 July 2023

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1. Introduction

Asian mango production accounts for 72.9% of worldwide production, especially in some Southeast Asian countries, and their products occupy an important position in the export of agricultural products [1]. Mango plantations are widely distributed in tropical areas [2], with a high frequency of pest and disease outbreaks. The occurrence characteristics and laws of pest and disease differ between regions, producing difficulties in plant protection operations for mango trees. [3] In mango orchards, the common diseases included anthracnose, bacterial keratosis, and powdery mildew, and the common insect pests included thrips and weevils [4–6].

In Southeast Asian countries, manual knapsack sprayers and high-pressure line guns are still used as the main application equipment for chemical control [7], which means a low spray (i.e., pesticides) application efficiency for crops and poor deposition distribution uniformity [8]. The wind-assisted target orchard sprayer, with its higher spray volume and spray pressure, achieves an ideal pesticide deposition in the canopy of fruit trees to

effectively control pests and diseases [9]. Therefore, this type of equipment is widely used in the plant protection operations in orchards. However, when spraying large-volume canopy fruit trees with orchard sprayers, pesticide deposition shows a gradual increase from the upper to the lower parts of the canopy [10]. In order to obtain sufficient pesticide deposition in the top canopy, it is necessary to increase the pesticide spray volume [11]. As a result, excessive pesticide deposition occurs in the middle and lower parts, greatly reducing the effective utilization rate of pesticides. To address these issues, smart orchard sprayer integrating sensory detection, intelligent decision making, and variable spraying were developed [12–14]. The orchard automatic variable-rate sprayer, based on LiDAR scanning detection technology, can adjust spray parameters in real-time based on canopy characteristics, effectively improving pesticide utilization and operational efficiency, and potentially saving up to 45.7% of the usage of pesticides [14]. In addition, using binocular cameras to detect real-time grape leaf canopy depth and combining it with the sprayer's forward speed, the orchard sprayer can be guided to perform variable-rate spraying on the grape canopy. However, these technologies involve high development costs and are difficult to implement in complex orchard environments for pesticide application [13].

Furthermore, the development of plant protection unmanned aerial vehicle (UAV) technology has provided another solution to the challenges of pesticide application in orchards. In East and Southeast Asia, plant protection UAVs are replacing the conventional plant protection equipment [7,15]. Plant protection UAV can be deployed quickly with high spraying efficiency and outstanding terrain adaptability [16,17]. By choosing the right operating parameters, UAV can effectively control the pest population to a level that does not cause serious crop yield reduction in orchards and forestry [18,19]. However, there are serious problems such as poor droplet deposition uniformity, a lack of droplet deposition on the backs of leaves [20], and spray drift for UAV [21,22]. Especially when dealing with large volume canopies such as apricot trees [23], citrus [24], etc., the UAV spraying operations show low droplet penetration in the lower and middle canopy, and poor distribution uniformity. The high concentration of pesticides often leads to damage in the targeted crops. Furthermore, there are certain limitations when facing different control objects [25].

Therefore, a co-operative spraying strategy applied using plant protection drones and orchard sprayers may achieve an all-round coverage of the fruit tree canopy. In particular, this strategy intends to combine the advantages of plant protection UAVs with strong terrain adaptability and more deposition of the liquid in the upper canopy by using an orchard sprayer with strong penetration ability and uniform liquid distribution in the lower canopy. In the agricultural field, current applications using aerial and ground devices to coordinate operations have been conducted to establish remote sensing information collection platforms and crop protection operations. Zhang et al. [26] have invented a method and control system for air–ground co-operation plant protection operation. This system can plan collaborative operation paths based on the characteristics of orchards and fruit trees, and control the coordinated operation of unmanned aerial vehicles and ground spraying vehicles to carry out spraying according to the planned paths. Jiang et al. [27] tested the spray performance of a stereoscopic plant protection system consisting of a small swing-arm sprayer and a T16 plant-protection UAV, and determined the optimum spray parameters using CFD simulation. The results show that the uniformity was 38.3% higher than conventional approaches. Current research mainly focuses on the control and improvement of equipment parameters of the co-operation plant protection system. When pesticides are sprayed using two different types of equipment, it is necessary to ensure the behavior of droplet deposition and the spraying ratio (such as the spraying volume of the two devices and the type of pesticide used) in order to achieve the uniform distribution of pesticides in the canopy of fruit trees. The rational distribution ratio of pesticide solution on two types of spraying equipment will help us reduce pesticide usage while achieving a uniform deposition of pesticides.

Our study established an air–ground co-operation stereoscopic plant protection system (ACSPPS) which consisted of an orchard mist sprayer and a six-rotor UASS. The synergistic mode of ACSPPS was selected for spraying mango trees. We conducted a study to evaluate the deposition performance of the system in the mango tree canopy using a tracer method. Additionally, we tested the droplet deposition distribution of the two spray units when applied separately to analyze the composition of droplet deposition for the ACSPPS. This analysis was performed to establish a deposition distribution index for the system. Finally, the optimal spraying ratio (the proportion of fixed doses of pesticide spray using two devices) of two spraying units was expected to be determined across the result of the droplet deposition index distribution. We expect to provide data support and practical guidance for green, precision, and intelligent plant protection in orchards.

2. Material and Methods

2.1. Design of ACSPPS

An ACSPPS consists of an agricultural aviation pesticide spraying device and a land-based plant protection vehicle. It is used on pesticide spraying of three-dimensional crops such as fruit trees, especially the canopy with large volume and high canopy density, for which it is difficult to obtain a good droplet deposition distribution. Generally, the aerial application is undertaken by a plant protection drone, and the land-based plant protection jobs are undertaken by a small and medium-sized orchard sprayer. The two devices spray the same plot, and a fixed dose of pesticide is distributed to the two spray units for spraying according to a certain ratio. Depending on the spray target and fruit tree growth information, ACSPPS supports the following operational modes:

(1) Single-machine operation: When the tree is in the early growth stage, the canopy with a small canopy volume and low leaf density and BBCH is 0–31 (pome fruit for example) [28], or the pests or diseases are in the early stages of outbreak, one spray unit can meet the current plant protection needs of fruit trees; the application operation can be carried out using a mist sprayer or UAV alone. This mode is suitable for standard orchards such as standard apples orchard or vineyards.

(2) Co-operative operation using two machines: The crop phenological stage is at full development at BBCH 32–91 [28]. It is difficult to achieve uniform deposition of pesticides in the canopy via one-machine operation, when the occurrence of pests and diseases is at its peak, or when pesticides need high coverage such as a protective fungicide (e.g., Bordeaux solution, which is shared by two machines, and both apply to trees) (Figure 1). The movement track cannot spray two trees at the same time. This mode is suitable for a fruit tree canopy with large volume and high canopy density and standardized planting mode, such as olive, mango, grapefruit, and apricot, etc. At the same time, this mode has the potential to reduce the usage of pesticides on the basis of achieving spatially uniform distribution of pesticide.

(3) Dual-machine hybrid operation: In the complex terrain orchard application operation, ground sprayers and UAVs operate in accordance with the preset route, and the ground implements cannot pass the specified place to wait for the end of the collaborative operation in the UAV to make up the application. At the same time, this mode can avoid the antagonistic effect of pesticide mixing, which can separate the configuration of pesticides to avoid chemical reactions between pesticides, such as insecticide spraying via drone and fungicide spraying using a mist sprayer. Different pesticide dosage forms can also be separated for spraying.

The ACSPPS of this study consisted of a six-rotor electric UASS AGRAS T30 (manufactured by SZ DJI Technology Co., Ltd., Shenzhen, China (Figure 2a)) and an orchard caterpillar mist sprayer (3WDZ-200D, Shanxi Nonggu Feinong Plant Protection Technology Co., Ltd., Datong, China (Figure 2b)). The UAV sprayer was equipped with a 30 L PPP container, with a total weight (excluding battery) of 36.5 kg and maximum take-off weight of 78 kg (at sea level). Sixteen extended-range flat-fan nozzles (SX11002VS, Spraying Systems Co., Wheaton, IL, USA), divided into eight couples, were equipped below the cor-

responding rotors of the UAV. The mist sprayer was equipped with a 200 L container. One XR95/02S (Yushengpenwu, China) nozzle was installed between two XR45/01S nozzles (spacing 40 cm, one side) and the spray angle of the mist sprayer in the orchard spraying mode was −22.5° to 90° from the horizontal plane. It is operated using a remote control. Both equipment parameters are shown in Table 1.

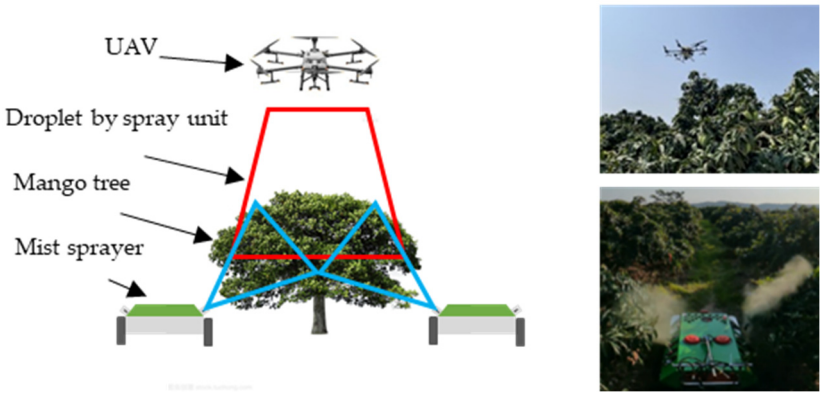


Figure 1. Air–ground co-operation stereoscopic plant protection system operation diagram.

Table 1. Two spray unit parameters.

Sprayer	Overall Size/mm × mm × mm	Maximum Payload/L	Nozzle Type × Number of Nozzles	Device Maximum Flow/(L/min)	Maximum Operating Speed/(m/s)	Spray Swath Width /m
UAV	2858 × 2685 × 790	30	TEEJET 11002VS × 16	9.0	7.0	9.0
Mist sprayer	1935 × 1140 × 690	200	XR45/01S × 4 XR95/02S × 2	16.0	1.25	8.0

UAV treatment is plant protection unmanned aerial vehicle spray treatment.



(**a**) Agras T30 UASS (**b**) 3WDZ-200D orchard caterpillar mist sprayer

Figure 2. Air–ground co-operation stereoscopic plant protection system component units.

2.2. Spray Test Site

This experiment was conducted from December 2021 to March 2022, with an average temperature of 30.4 °C, an average humidity of 41%, and an average wind speed of 0.6 m/s during the experiment. The test site was located in Dabuba Village (longitude: 109°18′9578″ E, latitude: 18°42′2322″ N), Sanya City, Hainan Province, China. The mango orchard was a traditional orchard, with high-pressure line guns and plant protection UAV that are used for daily pest control. The trees are 7–8-years-old, with an average plant height of 2.70–2.90 m, a crown diameter of 3.2 m, a plant spacing of 4.5 m, and a row spacing of 5 m. The mango trees were in good growth condition, with fully developed leaves, an umbrella-like distribution of canopy leaves, and almost no leaves inside the canopy, while the BBCH was at 74 [29]. Mango varieties included Mangifera indica Linn, and the mango trees were in the mango swelling stage during this experiment. The density of weeds in the test field was low and the height of weeds were below 0.3 m, which could be considered as having no effect on the spraying effect. The orchard was located on flat land with an open site free of obstacles (Figure 3).



Figure 3. Experimental orchard and test site.

2.3. Experimental Design

A plot measuring 30 m × 20 m was chosen as the experimental area within the orchard under investigation (Figure 4). Within this plot, three mango trees displaying uniform growth were selected for droplet sampling.

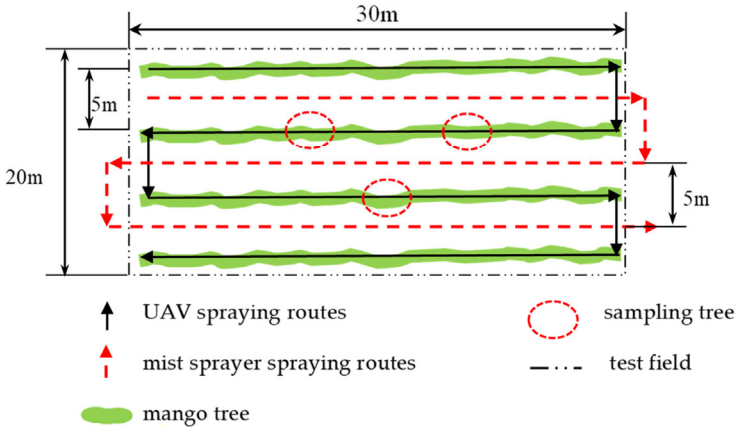


Figure 4. Test fields for spray test and work lines of UAV and caterpillar mist sprayer.

This study aims to test the droplet deposition distribution of the co-operative application mode of ACSPPS and determine a suitable spraying ratio, which refers to the pesticide distribution ratio between the two spray units. Initially, the droplet deposition distribution of the two spray units applied separately was tested to analyze the composition of the droplet deposition for the ACSPPS treatment. Subsequently, the deposition distributions of the two implements were combined, and the results were compared with the uniformity of the droplet deposition distribution achieved using the ACSPPS treatment. This comparison helped identify the optimal spray ratio for the two devices to work in synergy. To obtain the best spray ratio for the two machines to work together, three treatment groups were set up in this section: application using plant protection UAV, application using ground equipment, and ACSPPS. The parameter settings of the sprayer in each treatment are shown in Table 2. Three valid replicates were performed in each treatment group.

So as to avoid the mutual interference of flow fields during the operation of the two implements, the co-operation sprays using UAV firstly. The flight mode of the UAV is to mark the operational boundaries by using a remote control with an RTK module and then set the drone operation line distance and flight height for an autonomous operation. It can be ensured that the drone spraying path passed through the top of each mango tree. After the UAV operation was complete, the operator started the mist sprayer and controlled

the advance of the implements using a remote control to start the operation until all fruit trees were treated. Tartrazine was selected as the tracer, and the spraying solution was the tartrazine solution.

Table 2. The mango tree spray test design and sprayers' parameters.

Treatment	Application Volume/(L/ha)	Tartrazine Concentration/(g/L)	Velocity/(m/s)	UAV Flight Height/(m)	Spray Route/Track
UAV	120	4.20	2.5	3	Top of the tree row
Mist sprayer	510	0.40	1.25	/	Spraying between tree rows
ACSPPS	UAV: 120 Mist sprayer: 510	UAV: 4.20 Mist sprayer: 0.40	UAV: 2.5 Mist sprayer: 1.25	3	/

UAV treatment is plant protection unmanned aerial vehicle spray treatment and ACSPPS is air–ground co-operation stereoscopic plant protection system treatment.

The meteorological parameters of each treatment during the experiment are shown in Table 3 (measured using a mobile weather station, YG-BX Weather Station, Yigu technology company, Shenzhen, China). All of the meteorological parameters provided a suitable meteorological condition for spraying.

Table 3. Weather conditions for each application.

Treatment	Wind Speed/(m/s)	Wind Direction/°	Temperature/(°C)	Humidity/(%)
UAV	0.6	156.8	31.6	46.5
Mist sprayer	0.8	203.7	28.4	50.8
ACSPPS	0.5	180.2	30.1	60.2

UAV treatment is plant protection unmanned aerial vehicle spray treatment and ACSPPS is air–ground co-operation stereoscopic plant protection system treatment.

In this study, droplet coverage and tartrazine deposition were used as the indexes for investigation, and tartrazine was regarded as the active ingredient of the pesticide solution. Droplets were collected using HD photographic paper (38 × 26 mm, Chenguang, China) and 7 cm filter paper (AL-1, Aokexingainian, Liaoyang, China). The diagram of the photo paper layout was shown in Figure 5, and the mango trees were divided into upper, middle, and lower layers: the outer layer of the lower was marked as O1, the inner was marked as I1, the outer layer of the middle was marked as O2, and the inner layer of the middle was marked as I2. Due to the characteristics of the mango tree canopy, the upper layer was not set up in the inner canopy sample, marked as O3. A length of 7 cm of filter paper arranged within 5 cm around the phase paper, both unobstructed from each other to detect the amount of deposition, while the front and back of the leaf were covered with phase paper and filter paper. Four filter papers were placed under O1 at the ground projection to collect ground loss. Three sets of replicates were set up for each treatment.

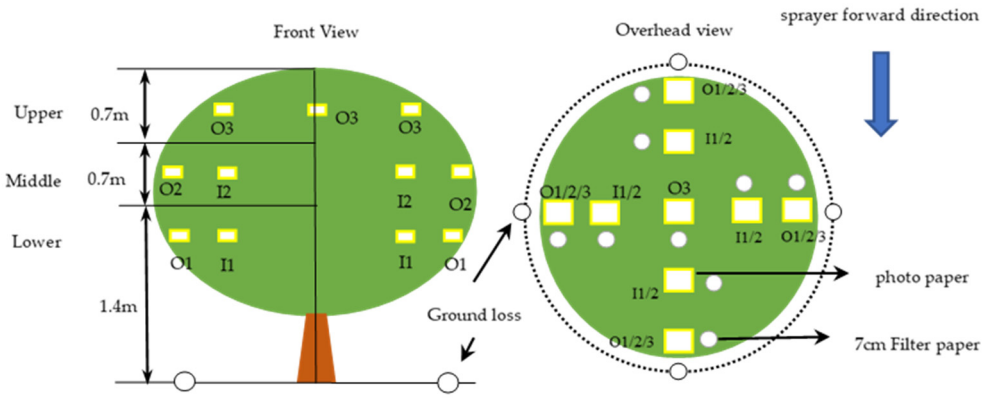


Figure 5. Sampler locations for assessing mango tree canopy spray deposition.

2.4. Droplet Site Measurement

Measurements of the droplet-size spectrum were carried out using a laser diffraction system (DP-02, Zhuhai Omeike, Zhuhai, China) in the Centre for Chemicals Application Technology, China Agricultural University according to ISO standard 25358 [30]. The tested nozzle of UAV, flat-fan nozzle SX11002VS, was mounted at a height of 50 cm above the laser analyzer vertically between the laser beam transmitter and the receiver lens. An electric diaphragm pump Shurflo 8000 series (Pentair, Golden Valley, MN, USA) and a 63 mm diameter pressure gauge (Lechler GmbH, Metzingen, Germany) were applied to maintain the pressure (3.0 bar) in accordance with the field trials. The tested nozzle of the mist sprayer, flat-fan nozzle XR45/01S, and XR95/02S were also mounted at a height of 50 cm above the laser analyzer; the nozzle is still connected to the spray system of the mist sprayer to maintain the pressure within the spray pressure in the field test state, by means of an extended pressure duct. In each test, the background measurement was performed for 5 s to eliminate the interference of other particles in the air, and the droplet-size spectrum measurements lasted for 10 s. The 10th percentile diameter (Dv10), volume median diameter (VMD, Dv50), 90th percentile diameter (Dv90), relative span (RS), and spray volume fractions generated using droplets finer than 75, 100, and 200 μm (V75, V100, and V200) were recorded for further analysis.

2.5. Data Analyses

Five minutes after spraying, all photo papers were collected in the corresponding position in the card holder and brought back to the laboratory within five days to be scanned using an (EPSON DS-1610, Tokyo, Japan) at 600 dpi and analyzed using DepositScan software (Version 1.38x) for droplet coverage and density. The filter paper was placed in a No. 5 self-sealing bag, eluted with 20 mL of deionized water (5 mL for the ground implement group) in the laboratory, and then analyzed using an enzyme standard (450 nm wavelength, iMark Analytical Instruments, Inc., Orange, LA, USA) to calculate the amount of deposition. A total of 20 mL of an initial solution for each sprayer was collected after each application and diluted 100 times. The uniformity in the deposit distribution of the spray coverage parameters on the tree canopy was expressed in the coefficient of variation (CV, %). A lower CV means a better homogeneity in the spray coverage distribution of the UAV spraying. The unit deposition was expressed as β, μg/cm^2, and calculated as follows:

$$\beta_{dep} = (C_t \times V_e)/(a \times A) \quad (1)$$

where β is the deposition volume, μg/cm^2; C_t is the tracer concentration, μg/mL; V_e is the eluent volume, mL; a is the filter paper area, cm^2; and A is the concentration of initial solution, g/L.

The homogeneity of the spray distribution over the upperside and the underside of the leaves was calculated for the spray coverage (*HSC*) as expressed in Equation (2):

$$HSC = \frac{SC_{und}}{SC_{upp}} \times 100\% \quad (2)$$

where SC_{upp} and SC_{und} are the mean values of the spray coverage obtained from the upper side and the underside of leaves, %, respectively.

The penetration coefficient in the vertical direction (K_V) of the mango tree, %, was calculated using the following equation:

$$K_V = \frac{\beta_a}{\beta_{b\&c}} \times 100\% \quad (3)$$

where β_a is the upper canopy deposition per area in the mist sprayer treatment and the lower canopy in the UAV treatment, μg/cm^2, and $\beta_{b\&c}$ is the middle and lower canopy

deposition per area in the mist sprayer treatment and the upper and middle canopy in the UAV treatment, μg/cm^2.

The proportion of inner canopy deposition (R_I, %) could be calculated as:

$$R_I = \frac{\overline{\beta_I}}{\overline{\beta_I} + \overline{\beta_O}} \times 100\% \quad (4)$$

where $\overline{\beta_I}$ is the inner canopy droplet deposition per area, μg/cm^2, and $\overline{\beta_O}$ is the outer canopy droplet deposition per area, μg/cm^2.

The summation deposition per area (β_{add}, μg/cm^2) was used to calculate the deposition number of different concentrations of chemical solution in each canopy part using the synergistic operation and to construct the droplet deposition distribution index, which was calculated as

$$\beta_{add} = C_1V_1 + C_2V_2 \quad (5)$$

where C_1 and C_2 are the tartrazine concentrations of the mist sprayer and UAV treatment, g/L and V_1, V_2 is the deposition per area of the mist sprayer and UAV treatment, μL/cm^2.

The percentage distribution of the deposition unit area in the vertical direction (R_V, %) is the distribution ratio of the tartrazine in the vertical direction; when the value is closer to each part of the canopy, the more uniform the deposition of the solution in the vertical direction. This can be calculated as

$$R_V = \frac{\beta_{dep}}{\overline{\beta_U} + \overline{\beta_M} + \overline{\beta_L} + \overline{\beta_G}} \times 100\% \quad (6)$$

where $\overline{\beta_U}$, $\overline{\beta_M}$, $\overline{\beta_L}$, and $\overline{\beta_G}$ are the summation deposition of upper, middle, lower, and ground loss respectively, μg/cm^2.

All data were subjected to Anderson–Darling, Kolmogorov–Smirnov, and Lilliefors normality tests, and Levene and Bartlett tests for the equality of residual variances. Data from abnormal distributions were subjected to nonparametric Kruskal–Wallis tests at the 5% probability level. The result of the three application methods on droplet coverage and deposit density were compared using a three-way analysis of variance (ANOVA) at a significance level of 0.05 and Duncan's post hoc test at a significance level of 0.05 for the mean of each droplet deposit parameter. All statistical analyses were performed using SPSS Statistics Version 20 for Windows (IBM Corporation, Armonk, NY, USA).

3. Result

3.1. Droplet-Size Spectrum

The mean values of parameters Dv10, Dv50, Dv90, RS, V75, V100, and V200 and the spray quality classification for droplet-size spectrum characteristics are presented in Table 4. At the higher spraying pressure of the mist sprayer, both nozzles XR45/01S and XR95/02S produced droplets with VDM of no more than 65 μm, which was much smaller than UAV at 3-bar spray pressure (139 μm). Most of the droplet produced by the mister were below 100 μm, while the 75% droplet size of UAV is larger than 100 μm. The average RS value (0.7) of the mist sprayer for both nozzles of the implement was only 42.6% of that of the plant protection drone, indicating that this device has better fogging ability compared to UAV, which may increase the droplet deposition in the inner canopy.

Table 4. Droplet-size spectrum of the nozzles used in orchard tests.

Nozzle	Device	DV10 (μm)	DV50 (μm)	DV90 (μm)	RS	V75 (%)	V100 (%)	V150 (%)
SX11002VS	UAV	63.01	139.02	289.74	1.63	10.94	25.98	60.17
XR45/01S	Mist Sprayer	36.34	61.23	80.66	0.72	63.75	97.37	100.00
XR95/02S	Mist Sprayer	38.66	64.00	81.82	0.67	59.14	96.51	100.00

3.2. Characteristics of Deposition Distribution in The Mango Canopy

3.2.1. Spray Coverage and Deposit Density

Table 5 shows the distribution of droplet coverage and deposit density in the mango canopy using three application methods and the results of the significance analysis. The results showed that there was no significant difference ($p < 0.05$) in droplet coverage and deposit density in each layer of the canopy in ACSPPS treatment, and co-operation spray could improve the uniformity of droplet deposition distribution compared with the UAV and mist sprayer; however, there was poor deposition distribution uniformity on the underside of mango leaves in three application, and there was no statistical difference in the deposition on the underside of leaf ($p > 0.05$).

Table 5. Droplet deposition distribution characteristics of three applications.

Treatment	Sample Position	Coverage/%		Deposit Density/cm^2		HSC/%
		Upperside	Underside	Upperside	Underside	
Mist sprayer	O1	10.9 ± 2.0 a	2.8 ± 1 a	186.9 ± 23.2 a	36.6 ± 15.5 a	25.7
	O2	7.5 ± 2.3 a	5.2 ± 4.4 a	124.9 ± 30.1 b	26.9 ± 10.3 a	69.3
	O3	2.4 ± 0.9 b	0.5 ± 0.4 a	60.0 ± 16.3 c	15.5 ± 9.3 a	20.8
	I1	2.0 ± 1.0 b	0.6 ± 0.3 a	48.7 ± 17.6 c	19.8 ± 10.8 a	30.0
	I2	2.4 ± 1.7 b	0.1 ± 0.1 a	38.1 ± 17.7 c	4.8 ± 2.5 a	4.2
UAV	O1	14.6 ± 4.0 a	1.4 ± 1.1 a	22.1 ± 4.0 a	4.0 ± 2.2 ab	9.6
	O2	6.6 ± 2.7 b	5.2 ± 3.8 a	12.9 ± 4.7 ab	9.4 ± 4.2 ab	78.8
	O3	7.9 ± 2.0 ab	5.8 ± 2.7 a	16.1 ± 3.7 ab	11.9 ± 3.7 a	73.4
	I1	1.0 ± 0.4 b	0.2 ± 0.1 a	6.6 ± 2.3 bc	2.3 ± 0.6 b	20.0
	I2	4.1 ± 2.0 b	0.3 ± 0.3 a	1.8 ± 0.8 c	1.8 ± 0.8 b	7.3
ACSPPS	O1	27.8 ± 6.7 a	3.2 ± 1.6 a	120.5 ± 22.3 a	49.7 ± 19.3 a	11.5
	O2	25.8 ± 7.9 a	4.4 ± 2.6 a	116.7 ± 29.8 a	26.6 ± 10.9 b	17.0
	O3	21.1 ± 7.3 a	0.6 ± 0.3 a	89.1 ± 28.3 a	5.0 ± 1.3 b	2.8
	I1	24.0 ± 7.3 a	0.5 ± 0.2 a	124.1 ± 37.0 a	11.4 ± 3.4 b	2.0
	I2	8.9 ± 2.6 a	1.2 ± 1.0 a	79.9 ± 21.9 a	9.2 ± 6.2 b	13.5

Note: Data of coverage and deposit density were expressed as mean ± standard error. Different letters after the numbers indicate significant differences in different canopy positions in the same group of treatments at the $p < 0.05$ level using Duncan's test values.

Droplet coverage on the underside of the leaves is shown in Figure 6a. Co-operation spraying can significantly improve ($p < 0.05$) the underside droplet coverage of the mango canopy except for the innerside of the lower layer (I2) compared with mist sprayer and UAV treatment. There was no significant difference ($p > 0.05$) between the mist sprayer and UAV in terms of upperside coverage in all parts of the canopy. The deposition from bottom to top showed a more obvious decreasing trend in the mist sprayer treatment. Because of the umbrella shape of the mango canopy, the downwash airflow when the UAV passed the top of the mango tree would have a diffusion effect so that the droplet coverage did not show a significant decreasing trend in UAV treatment; the related penetration analysis was conducted in Section 3.2.2.

The underside coverage distribution is shown in Figure 6b, except for the upper layer (O3) where the UAV was significantly higher than the remaining two groups, and there was no significant difference between the treatment in others parts; according to Table 5, the mean value of the HSC in mist sprayer treatment was 9.36%, which were 30.0% and 37.82% in the mist sprayer and UAV treatment. Co-operative operation using two machines cannot significantly improve droplet coverage on the underside of mango leaves and only increases the droplet deposition rate on upperside of the leaves. According to Table 5, the mean value of underside coverage of the inner layer canopy (I1 and I2) did not exceed 1.2%, which meant that the two-sprays unit lacked the ability to deliver droplets to the underside of mango leaves.

Figure 6c,d shows the droplet density distribution on the upper and underside of mango leaves. The mist sprayer involved in spray treatment, for which the density on the

upperside of all layers was significantly higher than that of the UAV treatment alone, which was due to the atomization performance of the mist sprayer under higher spray pressure. The droplet density on the upperside of the outer canopy of leaves could reach 92/cm^2 in the mist sprayer group, while the UAV only had 12/cm^2, for which most areas failed to meet the pest control requirement density of 20 deposit/cm^2. Through collaborative work, the value could be increased to 109/cm^2, and the distribution uniformity of droplet density in the canopy was improved. There was no significant difference in droplet density on upperside of leaves in each part of the canopy in this treatment. Except for O3, droplet density on the underside of other parts of the ACSPPS treatment group was improved compared with UAV, but without significant difference except for O1.

3.2.2. Spray Deposition and Penetration

The distribution of droplet deposition on the upper and the underside of mango leaves was shown in Figure 6e,f. In this test, using this application method, the mean deposition value for the mist sprayer was 0.26 μg/cm^2, while the UAV resulted in a deposition value of 0.68 μg/cm^2. Normalizing these values (deposition/spray volume), we obtain 0.12 (constant dimensionless) for the mist sprayer and 0.13 (constant dimensionless) for the UAV. There were no significant differences between the two methods in terms of the overall effective utilization of pesticides. The main difference was the distribution uniformity in the mango canopy. Except for O3, there was no significant difference in deposition per area on the upperside of leaves in the remaining parts. The tartrazine deposition on the underside of in ACSPPS treatment mainly came from UAV, and the deposition of UAV treatment at O1 was 2.6 times that of the mist sprayer, but there was no significant difference, because of the poor deposit distribution uniformity (CV value of 178.9%) of UAV on the underside of the blade, and deposition in some areas was slightly higher than that of the ACSPPS treatment.

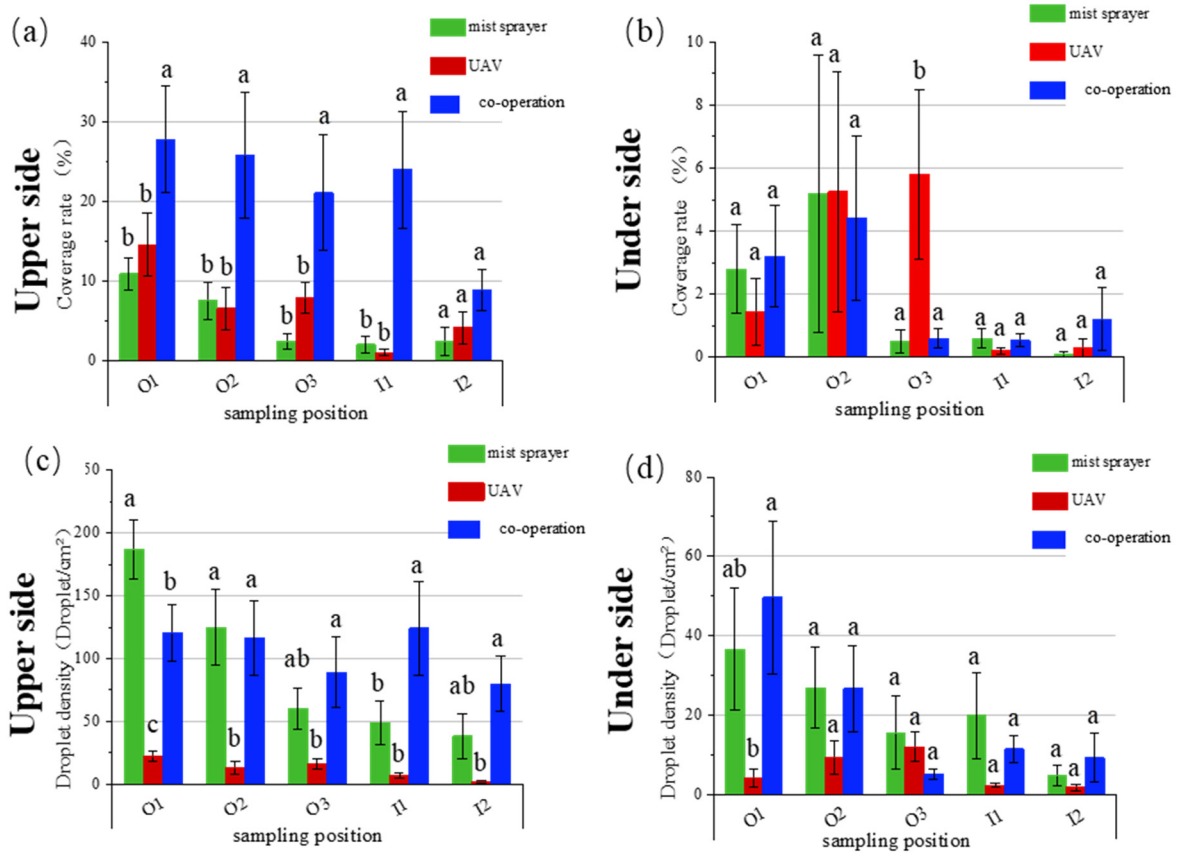


Figure 6. *Cont.*

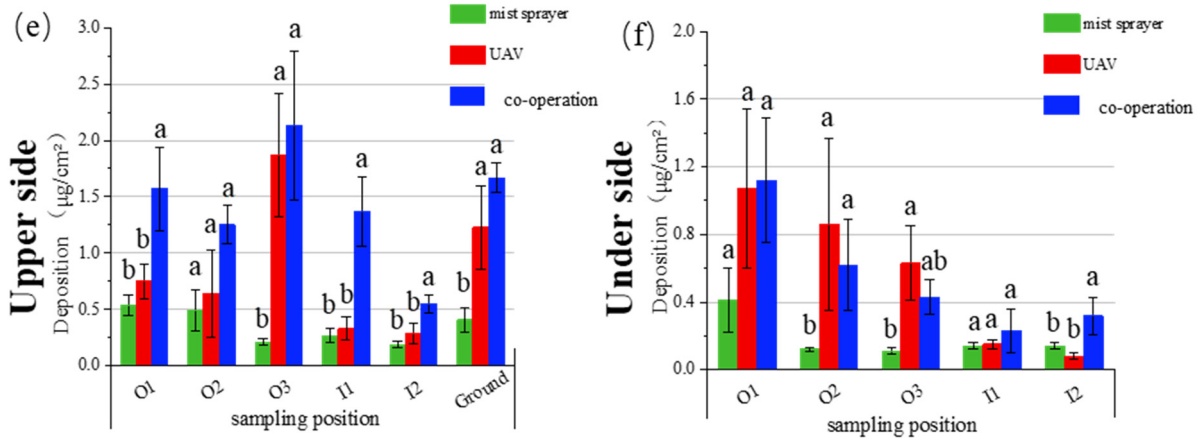


Figure 6. Droplet coverage (**a**,**b**), droplet density (**c**,**d**), and droplet deposition (**e**,**f**) on the upper- and underside of mango leaves in three application treatments. All data were expressed as mean ± standard error, and different letters on each bar indicate significantly different differences at the $p < 0.05$ level using Duncan's test values.

The mist sprayer treatment major deposition was concentrated in the outer part of the middle and lower canopy (a share of more than 50%). The deposition per area in the upper canopy was 0.16 μg/cm^2, which was only 47.0% of the average deposition, and the UAV treatment had the highest proportion of deposition in the upper layer (43.0%). According to Table 6, the proportion of the inner canopy deposition of the mist sprayer was 37.1%, while the UAV was only 18.0%. This was due to the large droplets (size after spreading, Dv50 = 631.4 μm) produced by the TEEJET 11002VS nozzle of UAV, which had limited penetration into the inner canopy and caused most of the droplets to deposit in the outside canopy, while the fine droplet produce by the mist sprayer was good at delivering the liquid into the interior, so that the proportion of the deposition to the inner canopy could be improved with the increase in the application ratio of the mist sprayer in ACSPPS plant protection work. The ground loss rate was about 21% for both of the spray units in the single-machine operation mode, which was basically the same as that of the co-operative operation (21.2%). Therefore, the ground loss ratio could not be reduced through co-operative operation.

3.3. Vertical Direction Droplet Deposition Distribution Index

The purpose of the air–ground co-operation stereoscopic plant protection system is to optimize the spatial distribution of the pesticide in the canopy and improve the effective utilization rate of the pesticide to achieve the purpose of reducing pesticide use. This section establishes a droplet deposition distribution index of pesticide deposition distribution in the mango canopy based on the depositional behavior of the mist sprayer and UAV and analyzes the droplet deposition distribution in mango trees with a different spray mass distribution ratio (which can be interpreted as the distribution of a certain amount of pesticide active ingredients using a two-spray unit sprayed evenly into a certain area of the orchard). The ratio was expressed as the ratio of application mass (g/ha) × tartrazine concentration (g/L) of two spray units; the approximate ratio of the mist sprayer to UAV application is 3.5:6.5 in this experiment. According to Equation (5), the added deposition of this experiment was calculated and compared with the actual deposition of the ACSPPS treatment (Figure 7).

The results of Figure 7 show that, except for the significant difference between the add deposition and the actual deposition at I1, the deviation between the theoretical add deposition and the actual value within 20%, with an average difference of 14.7%. The reason for the deviation may be that the travel routes of the mist sprayer cannot be fully overlapped, or the change in ambient wind speed has an impact on the spraying process of the UAV. Therefore, this error has little influence on the establishment of the add droplet

deposition distribution index, and the add deposition of the spray mass distribution ratio (mist sprayer/UAV = 1/9, 2/8, 4/6, 5/5, 6/4, 7/3, 8/2, and 9/1) could be calculated according to this index, assuming that the deposition of the pesticide in all parts of the canopy in each co-operation was consistent with this experiment, and the add deposition of each application ratio could be calculated under the conditions of this application volume. The results of the spray mass distribution ratio add deposition are shown in Figure 8.

Table 6. Droplet deposition parameter.

Parameter		Treatment		
		Mist Sprayer	**UAV**	**ACSPPS**
Upperside droplet size	D_{v50upp} (μm)	189.0 ± 7.5 b	792.7 ± 69.9 a	968.6 ± 127.7 a
Underside droplet size	D_{v50und} (μm)	152.1 ± 9.6 b	470.0 ± 56.3 a	345.3 ± 45.3 a
Mean droplet size	D_{V50} (μm)	170.6 ± 8.6 b	631.4 ± 63.1 a	656.9 ± 76.0 a
Upperside coverage	SC_{upp} (%)	5.0 ± 0.8 b	6.8 ± 1.2 b	19.7 ± 4.5 a
Underside coverage	SC_{und} (%)	1.8 ± 0.8 a	2.5 ± 1.1 a	2.0 ± 0.6 a
Mean coverage	SC (%)	3.4 ± 0.6 b	4.6 ± 1.0 b	10.85 ± 2.3 a
Coverage distribution uniformity	CV_{Cov} (%)	165.9	158.0	124.8
Upperside deposit density	N_{dupp} (deposit/cm^2)	91.7 ± 11.1 a	11.5 ± 1.7 b	106.1 ± 12.1 a
Underside deposit density	N_{dund} (deposit/cm^2)	20.7 ± 5.4 a	5.9 ± 0.8 a	21.1 ± 4.9 a
Mean deposit density	N_d (deposit/cm^2)	56.2 ± 8.3 a	8.7 ± 1.2 b	67.6 ± 10.2 a
Upperside deposition	β_{upp} (μg/cm^2)	0.34 ± 0.1	0.77 ± 0.3	1.4 ± 0.4
Underside deposition	β_{und} (μg/cm^2)	0.18 ± 0.1	0.59 ± 0.3	0.54 ± 0.3
Mean deposition	B (μg/cm^2)	0.26 ± 0.1	0.68 ± 0.3	0.97 ± 0.3
Vertical penetration coefficient	K_V (%)	27.8	33.4	/
Proportion of inner canopy deposition	R_I (%)	37.1	18.0	34.2
Ground loss rate	$R_{Groundloss}$ (%)	21.8	21.2	21.2

Note: Data of coverage, deposit density, and deposition were expressed as mean ± standard error. Different letters after the numbers indicate significant different differences at the $p < 0.05$ level for Duncan's test values.

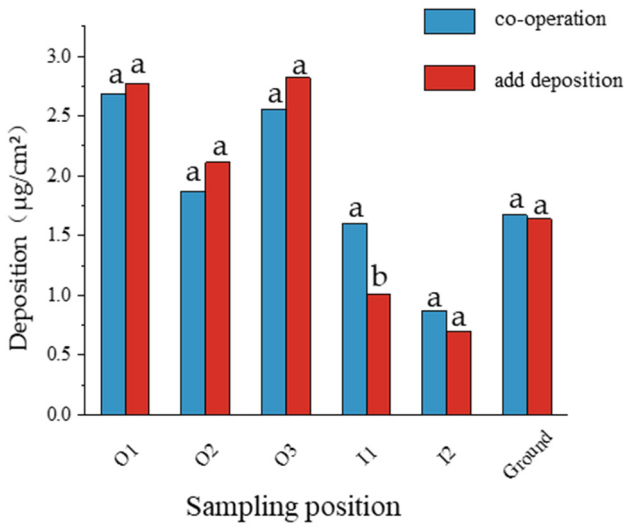


Figure 7. Add deposition versus actual deposition of ACSPPS, different letters on each bar indicate significantly different differences at the $p < 0.05$ level using Duncan's test values.

Based on Figure 8, it could be concluded that the percentage of ground loss basically remained between 21% and 22% when the co-operative operation was sprayed with different application ratios at the current spray volume. Changing the application ratios could not reduce the ground loss ratio. By increasing the application ratio of the mist sprayer, the proportion of deposition in the upper canopy layer decreased, while the deposition proportion in the middle and lower layers increased. Droplet deposition distribution uniformity (CV, %) in the vertical direction of the mango canopy via different application ratios are shown in Table 7. It can be conduct that, when the application ratios were 8/2 and

7/3 (0.92 g/L and 0.80 g/L for the tartrazine concentration of the mist sprayer and 1.29 g/L and 1.94 g/L for the UAV), the pesticide active ingredients were most evenly distributed in the vertical direction; the CV value of the percentage of vertical direction pesticide distribution in the canopy was the smallest among all application ratios at 13.64% and 14.34%. Therefore, the study of pesticide reduction could be carried out on the basis of these two applications ratios.

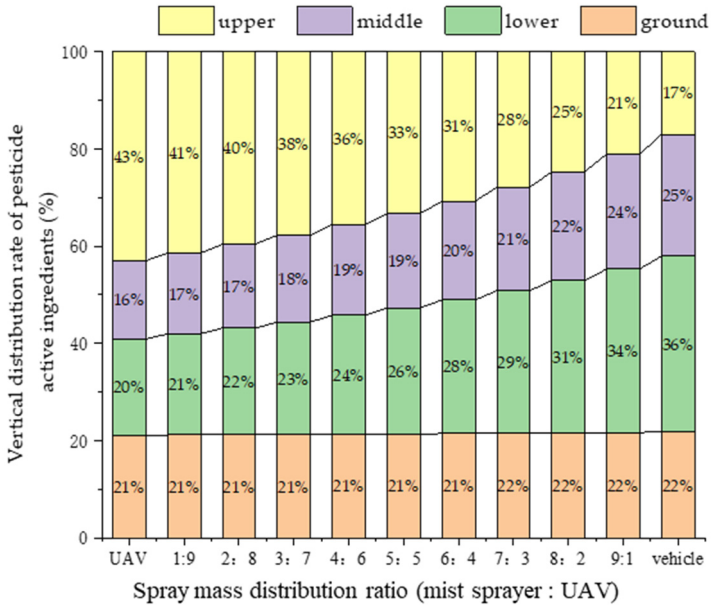


Figure 8. Vertical distribution rate of pesticide active ingredients of spray mass distribution ratio.

Table 7. Droplet deposition distribution uniformity in the vertical direction of the mango canopy via different application ratios.

Application Ratios	UAV	9:1	8:2	7:3	6:4	5:5	4:6	3:7	2:8	1:9	Vehicle
droplet deposition index/%	26.3 ± 11.9	26.3 ± 10.5	26.3 ± 9.9	26.2 ± 8.5	26.2 ± 7.1	26.2 ± 5.7	26.2 ± 4.6	26.1 ± 3.6	26.1 ± 3.7	26.1 ± 5.6	26.1 ± 7.8
CV/%	45.24	39.92	37.56	32.44	27.23	21.81	17.72	13.64	14.34	21.29	29.84

Note: Data of droplet deposition index was expressed as mean ± standard deviation.

4. Discussion

The deposition distribution uniformity test using two spray units shows that the application of the mist sprayer is faced with the problem of an insufficient deposition capacity in the upper layer canopy and underside of leaves. According to the result of the droplet-size spectrum, the mist sprayer has an outstanding atomization capacity which can deliver more pesticide to the inner canopy. While the droplets applied using the UAV were mainly deposited in the upper layer of the canopy, the droplets deposition density could not meet the pest control demand of 20 droplets/cm^2. The result aligns with what has been documented in recent literature. Specifically, the UAV encounters certain challenges, including inadequate droplet coverage density, a scarcity of droplets reaching the lower canopy, and inconsistent droplet distribution. These issues arise due to the lower spraying dosage of the plant protection UAV, exacerbated by the turbulent downwash airflow [20,23,24]. According to Table 6, the synergistic operation of two sprayers significantly improved the deposit coverage of the mango leaves and made up for the deficiency of an insufficient droplet deposition density of UAV application. Generally, only some large-scale air-assistant orchard sprayers can achieve more than 20% coverage on the surface of the canopy [11,31], but these sprayer are still difficult to adapt to spraying operations in complex orchard environments. Therefore, the small ground plant protection vehicle of ACSPPS in this study can be used to enhance the terrain adaptability of the system. However, due to the high canopy density of mango trees, and the high mutual

cover-up rate of leaves, it is unfavorable for the droplets to penetrate outside the canopy to reach the inner canopy, and most of the droplets are deposited on the outside canopy. According to Figure 9, the characteristics of the mango canopy, such as large leaf length and thickness and complex leaf inclination distribution, led to poor deposition distribution uniformity of the two spray units; the overall CV was over 150%. The CV was improved by 24% via synergistic operation but could not solve the problem of less droplet deposition on the underside of mango leaves.



Figure 9. Test field mango trees' canopy characteristics.

The three-treatment droplet deposition scans results show that, the large droplets produced using the UAV (the average Dv50 value of 631 μm after spreading of the droplets) and the fine droplets produced using the mist sprayer (the average Dv50 value of 171 μm) on the leaves surface deposit action are shown in Figure 10. According to the study by Ebert et al. [32,33], the control effect can be significantly improved by increasing the droplet density under the same pesticide dose conditions. In addition to the biological optimum size theory (BODS theory) proposed by Himel and UK [34], the biological optimum size of foliar crawling pest larvae was 30~150 μm. Therefore, the mist sprayer had a better potential pest control ability than UAV. In actual orchard plant protection operations, the UAV was prone to damage the initial period fruit epidermis due to the higher application concentration. In addition, the mango tree's pests and diseases are prone to occur in the inner canopy and on tender shoots, but the ground-based orchard sprayer lacks the ability to deliver a deposit to the upper canopy. Through the co-operation of a two-spray unit, a high-concentration liquid can form a dilution and certain doses of the pesticide can be dispersed through the two machines, which can avoid causing damage to the crop while increasing the pesticide deposition proportion in inside and upper layer canopy and improving the deposition distribution uniformity in the vertical direction of the canopy. Through the droplet deposition distribution index, it can be found that increasing the application ratios of ground-based devices can increase the deposition uniformity of the canopy in the vertical direction, but the proportion is not as large as it should be. If the ground base device takes up too much application ratio it will result in insufficient deposition of the system in the upper canopy of the fruit tree. Therefore, when the application ratios were 8/2 and 7/3, the ACSPPS had the best deposition distribution index. It can be surmised that this ratio has the best potential for reduced application.

Research on the synergistic application of UAV using orchard sprayers is not yet mature. Jiang et al. [34] tested the spray performance of a stereoscopic plant protection system and determined the optimum spray parameters using CFD simulation. The results show that the uniformity was 38.3% higher than conventional approaches. But, it did not optimize the application ratio of the two spray units. This experiment verified the importance of air–ground co-operative plant protection operations to improve the pesticide distribution characteristics in the mango canopy and optimized application ratios for both spray units in the ACSPPS. This system was designed for tropical crops such as mango trees which have frequent pest outbreak cycles and high insect density, and its high droplet coverage and uniform distribution has obvious advantages when applying some pesticides such as contact insecticides and protective fungicides.

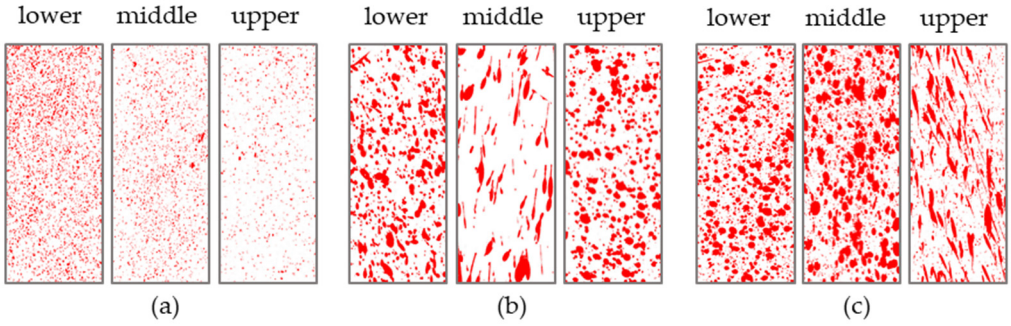


Figure 10. The scan results of mist sprayer (**a**), UAV (**b**), and ACSPPS (**c**) treatment droplet collecting cards.

However, there are still some shortcomings:

(1) In this study, only the droplet deposition analysis of the ACSPPS system was conducted under large spray volume conditions, which is not conducive to improving effective pesticide utilization.
(2) The field control efficiency of ACSPPS was not tested. The ACSPPS's strategies for reducing pesticide use have not been developed.

In a subsequent study, the focus will shift towards researching methods to reduce pesticide application while maintaining effective pest control. Building upon the findings of this experiment, further research can be conducted to explore strategies for reducing pesticide application. One aspect that will be investigated in later stages is the optimization of application ratios between the two spray units. This research will aim to reduce the water spray volume and pesticide dosage of the spray units while preserving the efficiency of the insecticide. For example, potential measures include halving the volume of spraying for both spray units and reducing pesticide usage by 30% by following a 8/2 or 7/3 (mist sprayer/UAV) application ratio for pest control. These adjustments will be based on the best application ratios derived from the results of this experiment, ensuring that the effectiveness of the insecticide is maintained while achieving a reduction in pesticide application.

With the maturity of artificial intelligence technology, intelligent agricultural equipment has become an inevitable trend for replacing traditional plant protection equipment. The two spray units in this study were retrofitted with autonomous navigation and variable spray technology. This system was applied to the management of smart orchards to develop a plant protection decision plan based on the detection information of the pest and disease sensing system, which was sent down to the variable spray system for accurate environmental pest management.

5. Conclusions

In this paper, an air–ground co-operation stereoscopic plant protection system combining a ground-based orchard mist sprayer with a plant protection UAV was established. The deposition distribution characteristics of three plant protection applications (spray using a mist sprayer, UAV, and ACSPPS application) in the mango canopy were evaluated, and a vertical droplet deposition index distribution of co-operative operation was constructed. The results show the following:

The air–ground co-operation stereoscopic plant protection system has shown significant improvements in droplet coverage on the upper side of mango leaves in all parts of the canopy (a 14.7% increase for the mist sprayer and a 12.9% increase for the UAV), as well as an increase in the uniform distribution of active components in the mango canopy. However, it cannot significantly improve the deposition and coverage of droplets on the underside of leaves compared with the mist sprayer and plant protection UAV.

Due to the characteristics of the mango canopy, such as large leaf length and thickness and complex leaf inclination distribution, this led to poor deposition distribution uniformity for the two spray units; the overall CV was over 150%.

Under the spraying volume in this experiment, it can be concluded from the vertical droplet deposition model that changing the spray mass distribution ratio of two devices cannot reduce the ground loss rate for the pesticide. Deposition in the upper canopy will be decreased and the ratio of deposition in the middle and lower layers will be increased with the increase in the application ratio of the mist sprayer. When the application ratios of a two-spray unit (mist sprayer/UAV) come to 8/2 and 7/3, the active ingredients in the pesticides are most evenly distributed in the vertical direction. A study of on pesticide reduction can be carried out on the basis of this these application ratios. This could be a new idea for mango orchard plant protection and provides a technical solution to improve spray uniformity in the canopy of fruit trees.

Author Contributions: Conceptualization, X.H.; methodology, Y.L., L.H. and L.L.; validation, X.H.; formal analysis, Y.L. and L.H.; investigation, Y.L., L.H. and Z.H.; resources, Z.H. and L.H.; data curation, Y.L., L.H. and L.L.; writing—original draft preparation, Y.L.; writing—review and editing, X.H. and C.W.; visualization, Y.L. and C.W.; supervision, X.H.; funding acquisition, X.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the Sanya Institute of China Agricultural University Guiding Fund Project, Grant (SYND-2021-06), the earmarked fund for China Agriculture Research System (CARS-28), and National Natural Science Foundation of China (No. 32202343).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to give special thanks to Penghui Agriculture Company for providing the UAV for this experiment.

Conflicts of Interest: The authors declare no conflict of interest.

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