agronomy

MDPI

Article

Effects of Spray Adjuvants on Droplet Deposition Characteristics in Litchi Trees under UAV Spraying Operations

Xiaonan Wang [1], Yanping Liu [1], Shilin Wang [2,*] and Siwei Wang [1,*]

[1] Plant Protection Research Institute, Guangdong Academy of Agricultural Sciences, Key Laboratory of Green Prevention and Control on Fruits and Vegetables in South China, Ministry of Agriculture and Rural Affairs, Guangdong Provincial Key Laboratory of High Technology for Plant Protection, No. 7 Jinying Road Tianhe District, Guangzhou 510640, China; wangxiaonan@gdaas.cn (X.W.); liuyanping@gdppri.cn (Y.L.)

[2] Institute of Agricultural Facilities and Equipment, Jiangsu Academy of Agricultural Sciences, Nanjing 210014, China

* Correspondence: shilin@jaas.ac.cn (S.W.); wangsiwei@gdaas.cn (S.W.)

Abstract: In the last decade, unmanned aerial vehicles (UAVs) for plant protection have rapidly developed worldwide as a new method for pesticide application, especially in China and other Asian countries. To improve the deposition quality in UAV applications, adding appropriate types of spray adjuvants into pesticide solutions is one of the most effective ways to facilitate droplet deposition and control efficacy. At present, research on spray adjuvants for UAVs are mainly based on droplet drift and laboratory tests. Few studies have been conducted on the physicochemical properties of spray adjuvants and the effects of droplet deposition characteristics. To explore the properties of four different kinds of spray adjuvants (Mai Fei, Bei Datong, G-2801, and Agrospred 910) and the deposition characteristics of spray adjuvants on litchi leaves, an automatic surface tension meter, a contact angle measuring device, an ultraviolet visible spectrophotometer, and a DJI AGRAS T30 plant protection UAV was used to measure the surface tension, contact angle, and droplet deposition characteristics on litchi under UAV spraying operations. The results showed that the addition of spray adjuvants could significantly reduce the surface tension of the solution. The surface tension value of the solution after adding the spray additives was reduced by 53.1–68.9% compared with the control solution. Among them, the Agrospred 910 spray adjuvant had the best effect on reducing the surface tension of the solution. The contact angle of the control solution on the litchi leaves varied from 80.15° to 72.76°. With the increase in time, the contact angle of the spray adjuvant solution gradually decreased, the Agrospred 910 spray adjuvant had the best effect, and the contact angle decreased from 40.44° to 20.23° after the droplets fell on the litchi leaves for 60 s. The adjuvant solutions increased the droplet size, but the uniformity of the droplet size decreased. The Dv0.5 of different spray solutions ranged from 97.3 to 117.8 μm, which belonged to the fine or very fine droplets, and the Dv0.5 of adjuvants solutions were significantly greater than that of the control solution. The RSs of adjuvant solutions were very similar and ranged from 0.92 to 0.96, all of which were significantly greater than the result of the control solution (0.57). Compared with the deposition of the control solution, the Mai Fei, Bei Datong, and G-2801 solutions clearly increased spray deposition, with total depositions of 0.776, 0.705, and 0.721 μL/cm^2, which are all greater than the total deposition of the control solution of 0.645 μL/cm^2. The addition of tank-mixed adjuvants could effectively increase the uniformity of the spray deposition, and all the average CVs of adjuvant solutions were lower than 96.86%. On the whole, Mai Fei performed best in increasing the spray deposition and promoting penetration, followed by Bei Datong and G-2801. Meanwhile, the test can also provide a reference for improving the utilization rate of UAV pesticide applications.

Keywords: UAV; spray adjuvants; droplet density; coverage; deposition; surface tension; contact angle

check for updates

Citation: Wang, X.; Liu, Y.; Wang, S.; Wang, S. Effects of Spray Adjuvants on Droplet Deposition Characteristics in Litchi Trees under UAV Spraying Operations. *Agronomy* **2024**, *14*, 2125. https://doi.org/10.3390/agronomy14092125

Academic Editor: Dimitrios Kateris

Received: 6 August 2024
Revised: 16 September 2024
Accepted: 17 September 2024
Published: 18 September 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Pesticide applications are one of the most important methods of pest and disease control, playing a crucial role in ensuring agricultural production and food security in China. The application rate of pesticide per unit area is about 2.5 times the world average in China, which ranks among the top in the world [1,2]. Since 2015, China has implemented the "zero growth" strategy for pesticides; the utilization rate of pesticides had reached 41.8% until 2022, indicating that nearly 60% of pesticides were wasted. The efficient, scientific, and rational use of pesticide spraying still has a long way to go.

With the development of agricultural aviation technology, the plant protection UAV has been widely used as a new type of efficient crop protection machinery in recent years, especially in some agricultural industries with limited operating conditions, such as paddy fields, hilly and mountainous areas, and disorderly orchards, due to its advantage of high efficiency [3,4]. Plant protection UAV has strong adaptability to pesticide application scenarios for field crops and fruit trees, and have significantly improved pesticide utilization efficiency compared to manual operations. Therefore, these advances aim to facilitate the application of UAVs in mountainous orchards with complex terrains [5]. However, the canopy of fruit trees is larger and denser compared to field crops. When UAVs are used for pesticide application in orchards, the droplets released from the nozzles penetrate the tree canopy from top to bottom. In the meantime, parts of the droplets were intercepted by the canopy, resulting in the uneven distribution of droplets and significantly lower deposition on the back side of the leaves compared to the front side [6]. Due to the fine droplets and high concentration of pesticide applied by UAVs, it might also cause serious risks of spray drift in non-target areas. It does not only fail to guarantee the effectiveness of pest control, but also exacerbates issues such as pesticide residues and environmental pollution [7].

To strike a balance between efficient spray applications and reducing the spray drift risk of UAVs on fruit trees such as apple [8], citrus [9,10], peach [11], pear [12], vineyards [13], and more, researchers have currently explored the appropriate measures to prevent drift by giving preference to the most efficient application techniques. These studies mainly concentrated on nozzle type and droplet size, which can both directly affect spray drift [14,15] and application parameters such as flight height and velocity. As it influences the behavior of droplets and the position in contact with the target [16], the composition of the spray liquid is very important in relation to the application rate as it enhances the physicochemical attributes of the pesticide solution and the effectiveness of pest and disease control [17,18]. In particular, adding appropriate types and concentrations of spray adjuvants is one of the most direct ways to improve the deposition quality in UAV applications [19]. The addition of appropriate adjuvants in pesticide formulations can improve the wetting and deposition properties on target surfaces, which will result in the infiltration and transmission of active ingredients to prevent plants from harmful organisms. Spray adjuvants are normally marketed for their enhancement benefits according to the function they are designed to perform. Some adjuvants are designed to enhance the performance of the pesticide by reducing the surface tension of the solution and increasing the retention of droplets, whereas others are designed to enhance the qualities of the spray by modifying the physical properties of the spray solution. Xiao et al. found that using a vegetable oil adjuvant could significantly increase the droplet coverage rate and improve the cotton defoliation efficacy sprayed by the UAV [20]. To explore the effects of different spray additives using an XAG XP 2020 plant protection UAV, Lan et al. measured the surface tension, contact angle, droplet deposition characteristics, and other parameters of six kinds of aviation spray additives, among which the effect of Be Datong spray additives was the best [21]. However, the improper addition of adjuvants may cause potential risks instead. For example, Sun et al. demonstrated that the addition of Silwet 408 and XL-70 may reduce DV50 and increase DV < 100 μm, which has a negative effect on the deposition of pesticides on peanut plants [22]. Various types of commercial adjuvants and plant species have a great impact on the behavior of droplets, but the function and mechanism of adjuvants are not yet fully understood [23].

Litchi chinensis Sonn. is a subtropical evergreen fruit tree, and China accounted for approximately 80% of the world's total litchi cultivation. Guangdong province is the main production area for litchi. However, this vital fruit crop faces a persistent threat from a great variety of plant diseases and insect pests. Due to the high temperature and high humidity in South China, chemical control remains the most effective means for prevention and treatment. Leaves are critical organs for plant photosynthesis and organic nutrient production. The adhesion of droplets to leaf surfaces significantly affects pesticide efficacy [24,25]. Currently, few studies have been carried out on the leaf surface wettability of litchi. Wang et al. conducted investigations concerning the microstructure of litchi leaf surfaces and the critical surface tension (CST) as well as the surface free energy (SFE) of litchi leaves [26]. Song et al. investigated the surface structure of litchi leaves infested with Aceria litchii, measured different levels of contact angles (CAs), and calculated its polar and dispersive components. The results showed that the infestation behavior of Aceria litchi changed the surface structure and chemistry of litchi leaves, which changed the surface wettability of litchi leaves from hydrophobic to superhydrophobic [27]. However, the research rarely focused on the effect of adding spray adjuvants on the wettability of litchi leaves. Moreover, there are few systematic studies that combine indoor field experiments with UAV-based plant protection for litchi.

Based on the above considerations, this study aims to explore the effects of four different spray adjuvants on the surface tension of the solution, the time-dependent contact angle of the solutions on litchi leaves, and the droplet deposition characteristics under UAV spraying operations in litchi orchards. This research aims to contribute to the advancement and application of UAV-based, high-efficiency pesticide spraying technologies for plant protection.

2. Materials and Methods

2.1. Unmanned Aerial Vehicle Sprayer

A motor six-rotor unmanned aerial vehicle sprayer (AGRAS T30, SZ DJI Technology Co., Ltd., Shenzhen, China) was used in field tests (Figure 1). The specific parameters of the plant protection UAV are shown in Table 1. The UAV was assembled with a maximum diagonal wheelbase of 2145 mm, an unfolded size of length 2858 mm, a width of 2685 mm, a height of 790 mm, and a propeller diameter of 38 inch. The UAV sprayer was equipped with a 30 L detachable container, with a total weight (excluding battery) of 26.4 kg and a maximum spray take-off weight of 66.5 kg (at sea level). Sixteen extended-range flat-fan nozzles (SX11001VS, Spraying Systems Co, Wheaton, IL, USA), were equipped below the corresponding rotors of the UAV, producing a total flow rate of 0–7.2 L/min and a working swath width of 4–9 m. During operations, the sprayer can fly at a maximum speed of 7.0 m/s with a hovering accuracy of ±10 cm when the Datalink Pro Real-Time Kinematic (D-RTK) was enabled.

Table 1. Main parameters of the DJI AGRAS T30 plant protection UAV.

Main Parameter	Values or Type
Dimensions/mm × mm × mm	2858 × 2685 × 790
Max loading capacity/L	30
Maximum flight speed/(m·s^{-1})	7
Maximum flow rate/L/min	7.2
Spraying width/m	4–9
Nozzle type	SX11001VS
Nozzle number	16

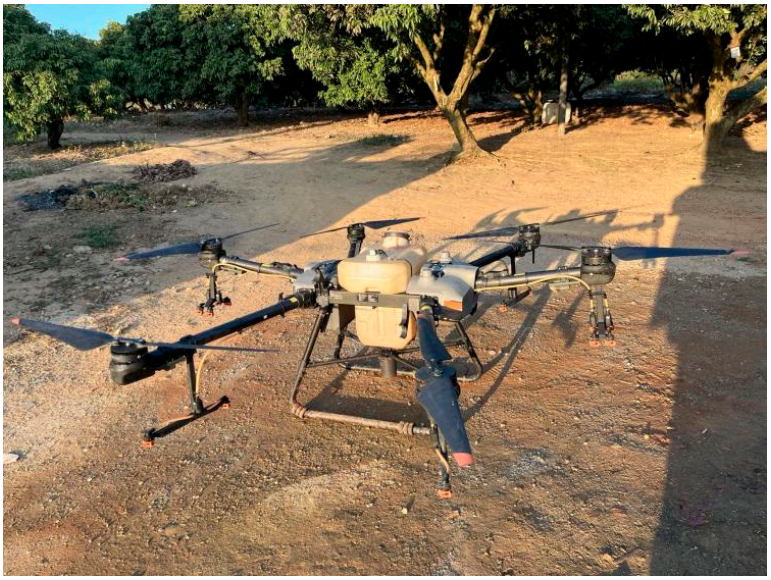


Figure 1. DJI AGRAS T30 six-rotor electric UAV sprayer used in litchi orchard tests.

2.2. Spray Adjuvants

The experiment selected a variety of tank-mixed adjuvants on the market for aerial application. The selected adjuvants were Mai Fei, Bei Datong, G-2801, and Agrospred 910. The main ingredients and key commercial information of these adjuvants are shown in Table 2.

Table 2. The main ingredients and key commercial information of spray adjuvants.

Spray Adjuvant	Main Ingredients	Characteristic	Manufacturer
Mai Fei	methylated vegetable oil	increase wetting and spreading	Guangyuan Yinong Co., Ltd., Beijing, China
Bei Datong	methylated vegetable oil	anti-evaporation and anti-drift	Mingshun Agriculture Co., Ltd., Hebei, China
G-2801	high polymer	anti-evaporation and anti-drift	Daqian Co., Ltd., Shantou, China
Agrospred 910	methylated vegetable oil nonionic surfactant	anti-evaporation and anti-drift	Momentive performance materials Co., Ltd., NY, USA

2.3. Experimental Design

2.3.1. Static Surface Tension

The static surface tension of water (CK) and the tank-mixed adjuvant dilutions were determined using an automatic surface tension meter JK99C (POWEREACH Co., Ltd., Shanghai, China) via the Wihelmy plate method. All the tested adjuvants were diluted with water with a volume fraction of 1%. For each sample, the average of three tests was calculated and used as the static surface tension value.

2.3.2. Contact Angle

The contact angle measurements were performed using a JC2000D1 contact angle measuring device (POWEREACH Co., Ltd., Shanghai, China) equipped with drop shape analysis software (Software Copyright Registration No. 2020SR0134364). During the experiment, the flat parts of fresh and clean Guiwei litchi leaves were placed horizontally on the stage of the contact angle measuring device. The droplet image was clearly displayed on the computer screen by adjusting the focal length of the camera and the brightness of the halogen lamp. In order to ensure a consistent droplet size, 2 μL of deionized water and adjuvant solution at each concentration was dripped on the adaxial surface of litchi leaves. The changing trend in the contact angle of droplets in 0–60 s was recorded by using the video function of the contact angle measuring device, and the test was run once every 10 s (click the start measurement button when the liquid drops onto the litchi leaves, and record the test time as 0). The test was repeated three times, and the results were averaged.

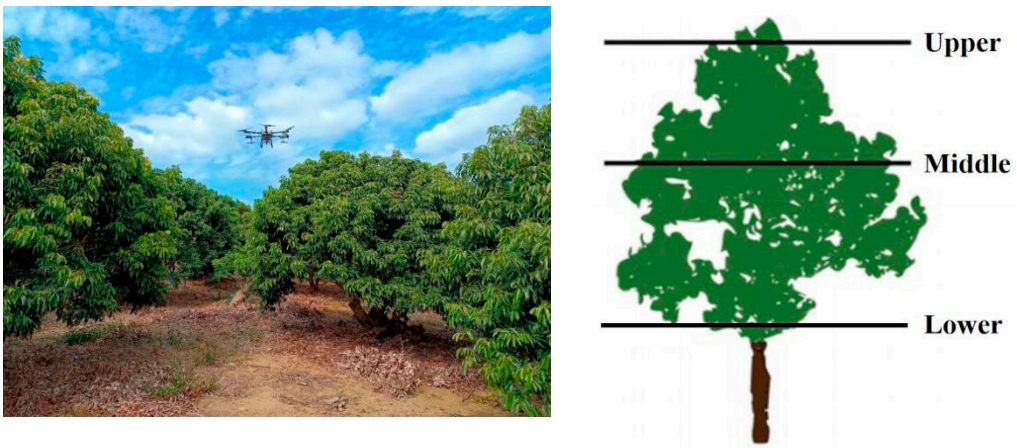
2.3.3. Field Trails

Field trials were conducted in January, 2022 during the flower bud morphological differentiation stage at Conghua, Guangdong, China (23°38′19″ N, 113°31′40″ E) in a 35-year-old (4 years after dwarfing) standardized Guiwei litchi orchard with a small and sparse canopy shape. The row spacing of the litchi orchard was 6.0 m, and the spacing in the row was 4.0 m. The litchi trees in the plain orchard had an average height of 4.0 m and a maximum canopy diameter of 5.0 m. During the test, the T30 plant protection UAV sprayer was operated 2.0 m above the tree canopy, with a forward speed of 1.8 m/s and a spray width of 4.0 m. The application volume was 8.0 L/hm^2. A portable meteorological station (WatchDog, Spectrum Technologies, Aurora, IL, USA) was used to measure the weather conditions during the field experiments, and the station was located upwind of the litchi orchard at a height of 3 m. The station was used to sample temperature, relative humidity, and wind speed. The meteorological parameters of treatments are shown in Table 3.

Table 3. Meteorological parameter of each treatment adding spray adjuvants.

Adjuvants Treatment	Temperature/°C	Relative Humidity/%	Wind Speed/(m·s^{-1})
Pure water	25.0	47.9	0.5
Mai Fei	22.5	52.6	0.8
Bei Datong	23.8	45.8	0.6
G-2801	18.2	62.3	1.0
Agrospred 910	25.8	55.1	1.5

The spray deposition of water and the four spray adjuvant solutions were measured in the litchi orchard (Figure 2a). All the spray adjuvant solutions used in the field spray test were shown in Table 2 with a volume concentration of 1%. To evaluate the droplet distribution and deposition of each treatment, 5 typical litchi trees were selected from the application row as sample trees for repetitions. Considering the external features of the litchi canopy, each canopy was divided into top, middle, and lower layers (Figure 2b). In each layer of the canopy, 5 points were selected randomly for sampling. Coated papers (40 × 60 mm) were fixed on the sample points to characterize the spraying performance. In this case, there were 15 coated papers in total fixed on a sample tree.



(**a**) spray test of the UAV (**b**) Height division of the litchi canopy

Figure 2. Spray deposition measurement of T30 plant protection UAV sprayer in litchi orchard.

2.4. Sample Processing and Calculation

2.4.1. Droplet Spectrum of Spray Liquids

The droplet spectra of the spray liquids were measured using a laser diffraction system (SprayTec, Malvern Panalytical Ltd., Malvern, UK) according to ISO standard 25358 [28]. The flat-fan nozzle SX11001VS was mounted 50 cm above the laser analyzer vertically

between the laser beam transmitter and the receiver lens. In each test, the droplet spectrum measurements lasted for 10 s. An electric diaphragm pump was applied to maintain the pressure at 0.3 MPa in accordance with the field trials. Five replicates were conducted for each solution at the measured pressures in a treatment. The volumetric droplet size spectrum parameters selected for data interpretation were the 10th percentile diameter $D_{V0.1}$, volume median diameter $D_{V0.5}$, 90th percentile diameter $D_{V0.9}$, and relative span (RS).The RS represents the uniformity of the atomized droplets, and the smaller the RS is, the more uniform the atomization is. The RS was calculated with Equation (1).

$$RS = \frac{D_{V0.9} - D_{V0.1}}{D_{V0.5}} \quad (1)$$

2.4.2. Deposition on the Samples

Before the application of each treatment, its original spray liquid was taken as the mother liquor, and the absorbance of its diluent was measured to quantify the deposition. To quantify the deposition of the spray liquid on different layers of the litchi canopy, 20 mL of deionized water was added into the coated paper bags in the laboratory and oscillated for 2 min, and the absorbance of the eluate was measured at a wavelength of 501 nm by a UV-1800 ultraviolet–visible spectrophotometer (Meipuda Instrument Co., Ltd., Shanghai, China). The deposition volume (Vs) of the spraying liquid on the coated papers was calculated according to Equation (2), and the deposition volume (d) of the spray liquid was acquired according to the area of the coated papers (Equation (3)).

$$V_s = \frac{V_w \times FL_S}{N_d \times FL_a} \times 10^3 \quad (2)$$

$$\mathrm{d} = \frac{V_s}{S} \quad (3)$$

where V_s is the deposition on the sample, μL; Vw is the volume of the eluent, mL; FLs is the absorbance value of the eluent; Fla is the absorbance value of the diluted liquid; N_d is the dilution times of the spray liquid; d is the deposition on the unit area, $\mu L/cm^2$; and S is the area of the filter paper, cm^2.

In order to evaluate the homogeneity of the droplet deposition distribution in the litchi canopy, the coefficient of variation (CV) was calculated as the ratio between the standard deviation of spray deposition values at the different sampling points (in the same layer) to the mean spray deposition value in that layer. The lower the CV, the more uniform the droplet distribution in one layer. The calculation method is shown in Equation (4).

$$CV = \frac{\sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})}{n-1}}}{\overline{X}} \times 100\% \quad (4)$$

where X_i is the spray deposition value of the i-th sampling point, $\overline{X}$ is the mean spray deposition over all sampling points, and n is the total number of sampling points.

3. Results and Discussion

3.1. Effect of Spray Adjuvants on Surface Tension

The volume concentration of the four tested adjuvants in this research was only 1%. In this case, the viscosities of the adjuvant solutions were quite close with that of the control solution. Therefore, this paper mainly focused on the surface tension of the adjuvant solutions, while the viscosity of the solutions was not measured. The surface tension of the solutions can be reduced by adding spray adjuvants (Table 4). Compared with pure water, the surface tension of each kind of adjuvant solution was significantly reduced, and the reduction in surface tension was in the range from 53.1% to 68.9%. The Agrospred 910 solution had the lowest surface tension of 22.9 $mN \cdot m^{-1}$, followed by the

Bei Datong solution with 25.6 mN·m ^{1}, and the surface tension of Mai Fei and G-2801 were 29.9 mN·m^{-1} and 34.5 mN·m^{-1}, respectively. It was worth mentioning that there were significant differences in surface tension between the four adjuvant solutions.

Table 4. Added concentration and surface tension of different adjuvant solutions.

Adjuvant Solutions	Concentration/%	Surface Tension/(mN·m^{-1})
CK	/	73.6 ± 0.18 a
Mai Fei	1.0	29.9 ± 0.18 c
Bei Datong	1.0	25.6 ± 0.24 d
G-2801	1.0	34.5 ± 0.28 b
Agrospred 910	1.0	22.9 ± 0.16 e

Note: The numbers in the table is the mean ± standard error, and different lowercase letters represent significant differences for the surface tension of the adjuvant solution.

The spreading characteristics of droplets on the target surface are mainly determined by the surface tension of the spray solutions [29]. The lower the surface tension of the spray solution, the larger the spreading area of the deposited droplets. For UAV aerial applications with low or ultra-low volumes, reducing the surface tension of the spray solution plays an important role in improving the spreading performance and enhancing the application effect.

3.2. Contact Angle of Spray Adjuvant on Litchi Leaves

The contact angle of droplets on the surface is determined by the surface tension of the solid–liquid two phase. The control efficacy of the spray solutions is mainly influenced by their wetting properties and mechanism of action [30]. Wetting can only occur when the surface tension of the liquid is lower than the leaf surface [31]. The time-dependent contact angle is measured to evaluate the wettability of the spray adjuvant on litchi leaves, as well as to better understand the process of the interaction between droplets and litchi leaf surfaces. Figure 3 showed the time-dependent contact angle of water and adjuvant solutions on litchi leaves. For all the tested solutions, the contact angles of droplets on litchi leaves decreased gradually with the increase in time, but the decreasing trend was more apparent in the first 10 s. In addition, the difference in the contact angle values for the different time measurements of the adjuvant solutions was more obvious compared with the CK solution.

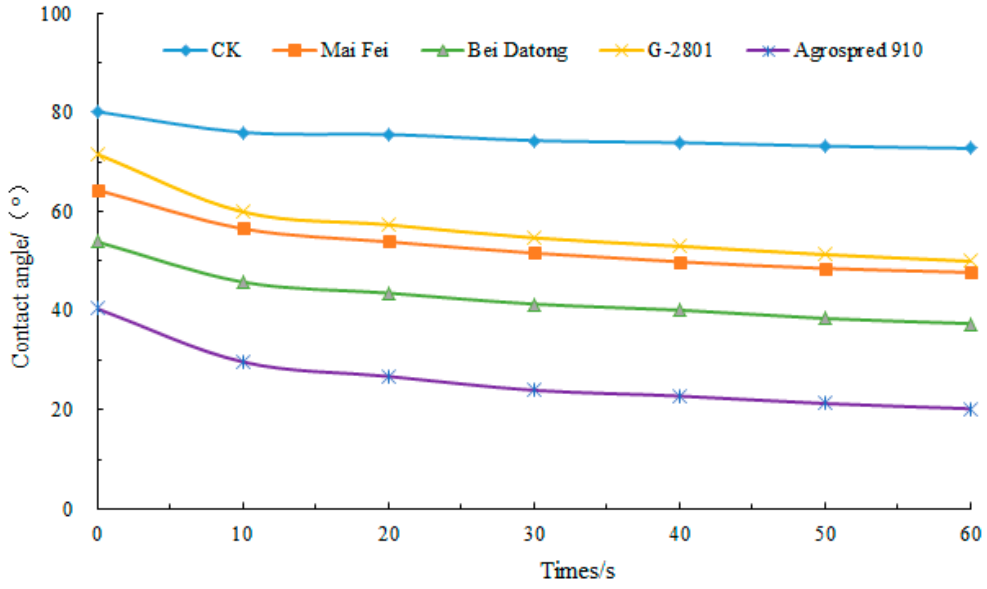


Figure 3. Time-dependent contact angle of water and different adjuvant solutions on litchi leaves.

The smaller the surface tension of the liquid, the lower the contact angle on the leaf. Because the surface tension of water was the largest, its contact angle on the litchi leaf was the maximum. The initial (at 0 s) contact angle of CK was 80.15°, and the final (at 60 s) contact angle of CK was 72.26°. By contrast, the addition of adjuvants reduced the contact angles of droplets on the litchi leaves dramatically, and the final contact angles of the adjuvant solutions ranged from 20.23° to 49.98°. Among all the tested solutions, the contact angle of Agrospred 910 was the minimum, with initial and final contact angles of 40.44° and 20.23° respectively, which showed preferable wettability on litchi leaves.

3.3. Effect of Spray Adjuvants on Droplet Spectra

The mean values of parameters $D_{V0.1}$, $D_{V0.5}$, $D_{V0.9}$, and relative span (RS) are presented in Table 5. For the control spraying solution, the $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ were 66.1 μm, 97.3 μm, and 129.5 μm, respectively, and the droplet relative span was 0.59. When Mai Fei was added to the spray solution, the $D_{V0.5}$ and $D_{V0.9}$ of the droplets were 117.8 μm and 175.8 μm, respectively, which were significantly greater than that of the control solution; however, the $D_{V0.1}$ was 63.3 μm, which showed no significant difference with the control solution ($p < 0.05$). For the Bei Datong, G-2801, and Agrospred 910 solutions, their corresponding $D_{V0.5}$ and $D_{V0.9}$ were all significantly greater than the results of the control solution. In addition, the $D_{V0.5}$ and $D_{V0.9}$ of the Mai Fei solutions was significantly greater than the results of the Bei Datong, G-2801, and Agrospred 910 solutions. For all the tested solutions, the $D_{V0.1}$ of spray droplets ranged from 54.7 μm to 66.1 μm, and there was no significant difference between their $D_{V0.1}$ ($p < 0.05$).

Table 5. Droplet diameter and relative span of spray solutions.

Spray Solutions	$D_{V0.1}$/μm	$D_{V0.5}$/μm	$D_{V0.9}$/μm	RS
CK	66.1 ± 1.4 a	97.3 ± 2.7 c	129.5 ± 1.1 d	0.57 ± 0.02 b
Mai Fei	63.3 ± 0.8 a	117.8 ± 1.6 a	175.8 ± 2.4 a	0.95 ± 0.01 a
Bei Datong	55.5 ± 0.8 a	106.9 ± 2.7 b	155.7 ± 2.4 b	0.94 ± 0.01 a
G-2801	54.8 ± 0.7 a	102.0 ± 1.8 b	153.2 ± 1.7 b	0.96 ± 0.01 a
Agrospred 910	54.7 ± 0.3 a	102.2 ± 0.7 b	149.1 ± 0.6 c	0.92 ± 0.01 a

Notes: Different lowercase letters indicate significant difference among the same column data ($p < 0.05$).

The droplet size is an important indicator to evaluate the characteristics of atomization and to compare the atomization quality of the spray [32]. The $D_{v0.5}$ of the different spray solutions ranged from 97.3 to 117.8 μm, which belonged to the 'fine' (F) or 'very fine' (VF) categories according to the ASABE S572.3 Droplet Size Classification [33]. The ISO standard 25358 states that the smaller the droplet size is, the more beneficial it is for the droplets to be attached on the target [28]. Furthermore, the 'fine' (F) and 'very fine' (VF) droplets are also more conducive to improve the target coverage rate of the UAV aerial applications with low or ultra-low volume. The RS of the control solution was 0.57, indicating a homogeneous droplet size distribution. The RSs of the adjuvant solutions were very similar and ranged from 0.92 to 0.96, all of which were significantly greater than the result of the control solution. Therefore, the adjuvant solutions increased the droplet size, but the uniformity of the droplet size decreased.

3.4. Effect of Spray Adjuvants on Spray Deposition

Figure 4 shows the spray deposition of the spray liquids in the litchi canopy. Comparing the droplet deposition of the spraying solutions on different layers, the middle layer and the upper layer had similar amounts of deposition, all of which were significantly greater than that of the lower layer. This might be caused by the occlusion of the peripheral leaves of the canopy. It can be seen in Figure 2 that the canopy of litchi was spindle-shaped and the width of the middle layer was greater than that of the upper and lower layers. In this case, the upper layer had little effect on the middle layer, while the lower layer was completely shielded by the upper and middle layers.

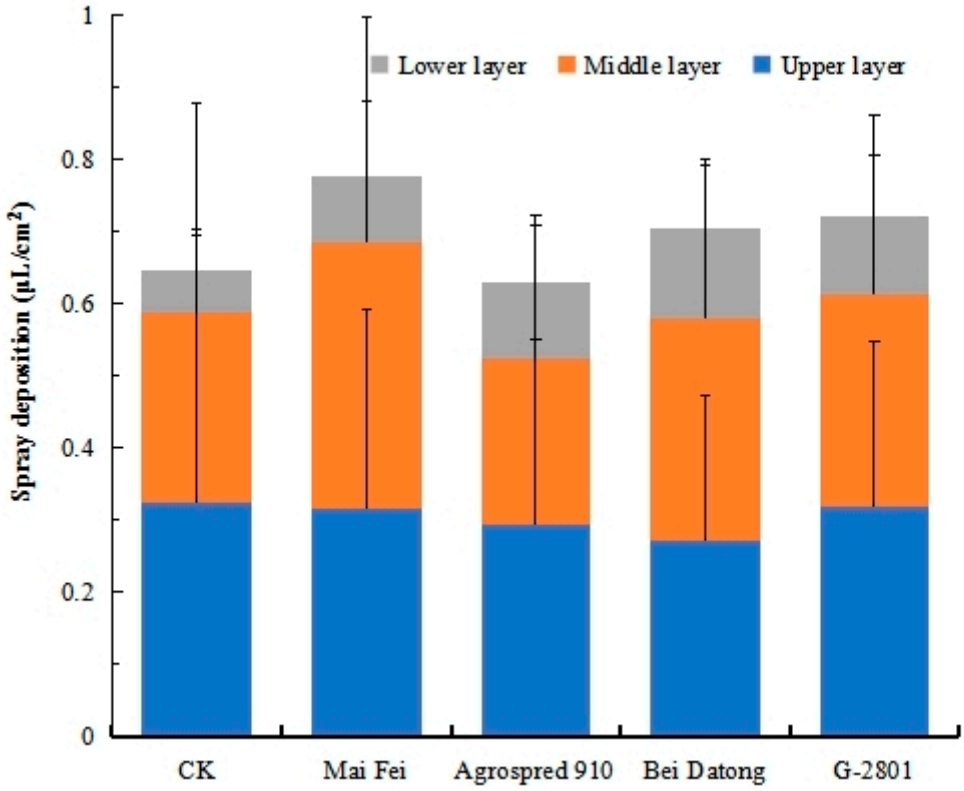


Figure 4. Spray droplet deposition distribution in the litchi canopy.

Pesticide applications aim at depositing the highest possible amount of the spray liquid on the target surface [34]. For the control spraying solution, the spray deposition on the upper, middle, and lower layers was 0.325, 0.263, and 0.057 μL/cm^2, respectively. Compared with the deposition result of the control solution, the Mai Fei, Bei Datong, and G-2801 solutions clearly increased the spray deposition, with total depositions of 0.776, 0.705, and 0.721 μL/cm^2, which are all greater than the total deposition of the control solution of 0.645 μL/cm^2. However, the Agrospred 910 solution held a similar total deposition with the control solution, indicating very limited effects on the spray deposition.

The deposition amount of the control solution in the litchi canopy was increased with increasing canopy height, and the depositions on the lower, middle, and upper layers were 0.057, 0.263 and 0.325 μL/cm^2, respectively. The spray deposition of the adjuvant solutions on the lower layer ranged from 0.089 to 0.123 μL/cm^2, which was obviously greater than that of the control solution, indicating that these adjuvants could enhance the penetration of the spray droplets. It should be mentioned that the depositions on the middle layer of the Mai Fei and Bei Datong solutions were greater than that of the upper layer, which also indicated their performance in facilitating penetration. On the whole, Mai Fei performed best in increasing the spray deposition and promoting penetration, followed by Bei Datong and G-2801.

3.5. Effect of Spray Adjuvants on Droplet Distributionin the Litchi Canopy

The droplet distribution uniformity of a canopy is commonly described by the coefficient of variation (CV) [35]. The smaller the CV is, the better the uniformity of the droplet distribution [36]. To comprehensively evaluate the droplet deposition distribution in the litchi canopy, the CV of the droplet deposition characteristics was calculated to characterize the droplet distribution uniformity after the addition of spray adjuvants. Table 6 shows the coefficient of variation of spraying solutions in the litchi canopy. The control solution had the highest CVs in the litchi canopy, and the CVs of the control solution in the upper, middle, and lower layers of the canopy were 113.88%, 110.60%, and 101.47, respectively. The addition of tank-mixed adjuvants could effectively increase the uniformity of the spray

deposition, and all the average CVs of the adjuvant solutions were lower than 96.86%. The Bei Datong solution had the best droplet distribution uniformity, and the average CV of the spray in the litchi canopy was 71.80%. The uniformity of the droplet distribution of the G-2801 solution was second with an average CV of 78.50%.

Table 6. Coefficient of variation (CV) of droplet distribution in the litchi canopy.

Adjuvant Solutions	CV (%)			
	Upper Layer	Middle Layer	Lower Layer	Average
CK	113.88	110.60	101.47	108.65
Mai Fei	86.89	84.57	119.12	96.86
Bei Datong	74.33	71.16	69.92	71.80
G-2801	72.13	84.31	79.06	78.50
Agrospred 910	86.93	86.66	76.35	83.31

4. Conclusions

The performances of four kinds of tank-mixed adjuvant solutions were compared by analyzing the surface tension, time-dependent contact angle, droplet spectra, and litchi canopy deposition for UAV aerial application. The results showed that the addition of adjuvants could significantly reduce the surface tension of the solution, and the surface tension value of the solution after adding the spray additives was reduced by 53.1–68.9% compared with the control solution. The contact angle of the control solution on the litchi leaves varied from 80.15°to 72.76°. With the increase in time, the contact angle of the spray adjuvant solution gradually decreased, the Agrospred 910 spray adjuvant had the best effect, and the contact angle decreased from 40.44° to 20.23° after the droplets fell on the litchi leaves for 60 s. The adjuvant solutions increased the droplet size, but the uniformity of the droplet size decreased. In the field application, the Mai Fei, Bei Datong and G-2801 solutions clearly increased the spray deposition, with total depositions of 0.776, 0.705, and 0.721 $\mu L/cm^2$, which are all greater than the total deposition of the control solution of 0.645 $\mu L/cm^2$. In addition, the addition of tank-mixed adjuvants could effectively increase the uniformity of the spray deposition, and all the average CVs of the adjuvant solutions were lower than 96.86%. On the whole, Mai Fei performed best in increasing the spray deposition and promoting penetration, followed by Bei Datong and G-2801.

Author Contributions: X.W. and Y.L. conceived the research idea and designed the experiments; X.W. performed the field experiments; X.W. and S.W. (Shilin Wang) analyzed the data and wrote the paper; S.W. (Siwei Wang) conceived the research and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by Research Fund of Maoming Branch, Guangdong Laboratory for Lingnan Modern Agriculture (2022KF002), Guangzhou Science and Technology Program Project (202201010479), the earmarked fund for CARS-32 (CARS-32-12).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

Acknowledgments: The authors would like to give special thanks to Xueming Gao for providing the test orchard and the sprayer storage.

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

References

1. He, X.K. Rapid development of unmanned aerial vehicles (UAV) for plant protection and application technology in China. *Outlooks Pest Manag.* **2018**, *29*, 162–167. [CrossRef]
2. Wei, J.J.; Tang, Y.T.; Wang, M.M.; Hua, G.P.; Zhang, Y.Q.; Peng, R. Wettability on plant leaf surfaces and its effect on pesticide efficiency. *Int. J. Precis. Agric. Aviat.* **2020**, *3*, 30–37. [CrossRef]

3. Wang, G.B.; Lan, Y.B.; Qi, H.X.; Chen, P.C.; Hewitt, A.J.; Han, Y.X. Field evaluation of an unmanned aerial vehicle (UAV) sprayer: Effect of spray volume on deposition and the control of pests and disease in wheat. *Pest Manag. Sci.* **2019**, *75*, 1546–1555. [CrossRef] [PubMed]
4. Li, S.; Li, J.; Yu, S.; Wang, P.; Liu, H.; Yang, X. Anti-Drift Technology Progress of Plant Protection Applied to Orchards: A Review. *Agronomy* **2023**, *13*, 2679. [CrossRef]
5. Guo, S.; Chen, C.L.; Du, G.D.; Yu, F.H.; Yao, W.X.; Lan, Y.B. Evaluating the use of unmanned aerial vehicles for spray applications in mountain Nanguo pear orchards. *Pest Manag. Sci.* **2024**, *80*, 3590–3602. [CrossRef]
6. Zhu, H.; Jiang, Y.; Li, H.Z.; Li, J.X.; Zhang, H.H. Effects of application parameters on spray characteristics of multi-rotor UAV. *Int. J. Precis. Agric. Aviat.* **2019**, *2*, 18–25. [CrossRef]
7. Wang, J.; Lan, Y.B.; Zhang, H.H.; Zhang, Y.L.; Wen, S.; Yao, W.X.; Deng, J.J. Drift and deposition of pesticide applied by UAV on pineapple plants under different meteorological conditions. *Int. J. Agric. Biol. Eng.* **2018**, *11*, 5–12. [CrossRef]
8. Liu, Y.; Li, L.L.; Liu, Y.J.; He, X.K.; Song, J.L.; Zeng, A.J.; Wang, Z.C. Assessment of spray deposition and losses in an apple orchard with an unmanned agricultural aircraft system in China. *Trans. ASABE* **2020**, *63*, 619–627. [CrossRef]
9. Yu, T.; Hou, C.J.; Luo, S.M.; Lin, J.T.; Zhengang, Y.; Huang, W.F. Effects of operation height and tree shape on droplet deposition in citrus trees using an unmanned aerial vehicle. *Comput. Electron. Agric.* **2018**, *148*, 1–7.
10. Martinez-Guanter, J.; Agüera, P.; Agüera, J.; Pérez-Ruiz, M. Spray and economics assessment of a UAV-based ultra-low-volume application in olive and citrus orchards. *Precis. Agric.* **2020**, *21*, 226–243. [CrossRef]
11. Meng, Y.H.; Su, J.Y.; Song, J.L.; Chen, W.H.; Lan, Y.B. Experimental evaluation of UAV spraying for peach trees of different shapes: Effects of operational parameters on droplet distribution. *Comput. Electron. Agric.* **2020**, *170*, 105282. [CrossRef]
12. Jiang, Y.L.; He, X.K.; Song, J.L.; Liu, Y.J.; Wang, C.L.; Li, T.; Qi, P.; Yu, C.W.; Chen, F. Comprehensive assessment of intelligent unmanned vehicle techniques in pesticide application: A case study in pear orchard. *Front. Plant Sci.* **2022**, *13*, 959429. [CrossRef] [PubMed]
13. Miranda-Fuentes, A.; Marucco, P.; Gonzalez-Sanchez, E.J.; Gil, E.; Grella, M.; Balsari, P. Developing strategies to reduce spray drift in pneumatic spraying vineyards: Assessment of the parameters affecting droplet size in pneumatic spraying. *Sci. Total Environ.* **2018**, *616–617*, 805–815. [CrossRef] [PubMed]
14. Balsari, P.; Grella, M.; Marucco, P.; Matta, F.; Miranda-Fuentes, A. Assessing the influence of air speed and liquid flow rate on the droplet size and homogeneity in pneumatic spraying. *Pest Manag. Sci.* **2019**, *75*, 366–379. [CrossRef]
15. Nuyttens, D.; Baetens, K.; De Schampheleire, M.; Sonck, B. Effect of nozzle type, size and pressure on spray droplet characteristics. *Biosyst. Eng.* **2007**, *97*, 333–345. [CrossRef]
16. Wang, C.L.; Liu, Y.; Zhang, Z.H.; Han, L.; Li, Y.F.; Zhang, H.; Wongsuk, S.; Li, Y.Y.; Wu, X.M.; He, X.K. Spray performance evaluation of a six-rotor unmanned aerial vehicle sprayer for pesticide application using an orchard operation mode in apple orchards. *Pest Manag. Sci.* **2022**, *78*, 2449–2466. [CrossRef]
17. Zhao, R.; Yu, M.; Sun, Z.; Li, L.J.; Shang, H.Y.; Xi, W.J.; Li, B.; Li, Y.Y.; Xu, Y.; Wu, X.M. Using tank-mix adjuvant improves the physicochemical properties and dosage delivery to reduce the use of pesticides in unmanned aerial vehicles for plant protection in wheat. *Pest Manag. Sci.* **2022**, *78*, 2512–2522. [CrossRef]
18. Klein, R.N.; Golus, J.A.; Nelms, K.L. The Effect of Adjuvants, Pesticide Formulation and Spray Nozzle Tips on Spray Droplet Size. *J. ASTM Int.* **2009**, *6*, 1–7.
19. Wang, X.N.; He, X.K.; Song, J.L.; Wang, Z.C.; Wang, C.L.; Wang, S.L.; Wu, R.C.; Meng, Y.H. Drift potential of UAV with adjuvants in aerial applications. *Int. J. Agric. Biol. Eng.* **2018**, *11*, 54–58. [CrossRef]
20. Xiao, Q.G.; Xin, F.; Lou, Z.X.; Zhou, T.T.; Wang, G.B.; Han, X.Q.; Lan, Y.B.; Fu, W. Effect of aviation spray adjuvants on defoliant droplet deposition and cotton defoliation efficacy sprayed by Unmanned Aerial Vehicles. *Agronomy* **2019**, *9*, 217. [CrossRef]
21. Lan, Y.B.; Shan, C.F.; Wang, Q.Y.; Liu, Q.; Yang, C.L.; Xie, Y.J.; Wang, H.B. Effects of different spray additives on droplet deposition characteristics during plant protection UAV spraying operations. *Trans. Chin. Soc. Agric. Eng.* **2021**, *37*, 31–38.
22. Sun, Z.; Zhao, R.; Yu, M.; Liu, Y.B.; Ma, Y.J.; Guo, X.Y.; Gu, Y.C.; Formstone, C.; Xu, Y.; Wu, X.M. Enhanced dosage delivery of pesticide under unmanned aerial vehicle condition for peanut plant protection: Tank-mix adjuvants and formulation improvement. *Pest Manag. Sci.* **2024**, *80*, 1632–1644. [CrossRef] [PubMed]
23. Massinon, M.; De Cock, N.; Forster, W.A.; Nairn, J.J.; McCue, S.W.; Zabkiewicz, J.A.; Lebeau, F. Spray droplet impaction outcomes for different plant species and spray formulations. *Crop Prot.* **2017**, *99*, 65–75. [CrossRef]
24. Koch, K.; Bhushan, B.; Barthlott, W. Diversity of structure, morphology and wetting of plant surfaces. *Soft Matter* **2008**, *4*, 1943–1963. [CrossRef]
25. Li, J.; Cui, H.J.; Ma, Y.K.; Xun, L.; Li, Z.Q.; Yang, Z.; Lu, H.Z. Orchard spray study: A prediction model of droplet deposition states on leaf surfaces. *Agronomy* **2020**, *10*, 747. [CrossRef]
26. Wang, X.N.; Liu, Y.P.; Wang, S.W.; Sun, H.B. Effects on wettability of 10% difenoconazole water dispersible granule with adjuvants on litchi leaves. *Chin. J. Pestic. Sci.* **2018**, *20*, 803–808.
27. Song, Q.K.; Zheng, J.Y.; Chen, S.D.; Lan, Y.B.; Li, H.F.; Zeng, L.L.; Yue, X.J. The effect of Aceria litchii (Keifer) infestation on the surface properties of litchi leaf hosts. *Pest Manag. Sci.* **2024**, *80*, 2647–2657. [CrossRef]
28. *ISO 25358*; Crop Protection Equipment Droplet Size Spectra from Atomizers-Measurement and Classification. ISO International Standard: Geneva, Switzerland, 2018.

29. Wang, S.L.; Li, X.; Zeng, A.J.; Song, J.L.; Xu, T.; Lv, X.L.; He, X.K. Effects of Adjuvants on Spraying Characteristics and Control Efficacy in Unmanned Aerial Application. *Agriculture* **2022**, *12*, 138. [CrossRef]
30. Hilz, E.; Vermeer, A. Spray drift review: The extent to which a formulation can contribute to spray drift reduction. *Crop Prot.* **2013**, *44*, 75–83. [CrossRef]
31. Zheng, L.; Cao, C.; Chen, Z.; Cao, L.D.; Huang, Q.L.; Song, B.A. Efficient pesticide formulation and regulation mechanism for improving the deposition of droplets on the leaves of rice (*Oryza sativa* L.). *Pest Manag. Sci.* **2021**, *77*, 3198–3207. [CrossRef]
32. Cunha, J.P.A.R.; Assuno, H.; Landim, T.N. Evaluation of droplet spectra of the spray tip AD 11002 using different techniques. *ENG AGR-JABOTICABAL.* **2019**, *39*, 476–481. [CrossRef]
33. *ANSI/ASAE S572.3*; Spray Nozzle Classification by Droplet Spectra, ASABE Standard. ASABE: St. Joseph, MI, USA, 2020.
34. Matthews, G.; Bateman, R.; Miller, P. *Pesticide Application Methods*, 4th ed.; Wiley & Blackwell: Hoboken, NJ, USA, 2014.
35. Qin, W.C.; Qiu, B.J.; Xue, X.Y.; Chen, C.; Xu, Z.F.; Zhou, Q.Q. Droplet deposition and control effect of insecticides sprayed with an unmanned aerial vehicle against plant hoppers. *Crop Prot.* **2016**, *85*, 79–88. [CrossRef]
36. Smith, D.B. Uniformity and Recovery of Broadcast Sprays Using Fan Nozzles. *Trans. ASAE* **1992**, *35*, 39–44. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.