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Effect of Aviation Spray Adjuvants on Defoliant Droplet Deposition and Cotton Defoliation Efficacy Sprayed by Unmanned Aerial Vehicles

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Abstract: Defoliant spraying is an important aspect of mechanized cotton harvesting. Fully and uniformly spraying defoliant could improve the quality of defoliation and reduce the impurity content in cotton. Improving the coverage of defoliant droplets in the middle and lower layers of cotton and ensuring the full and even dispersion of droplets in the cotton canopy are essentially in increasing the defoliation effect. In this study, we assessed the effect of aviation spray adjuvants on droplet deposition, defoliation, boll opening and defoliant retention in cotton leaves sprayed by an unmanned aerial vehicle (UAV). The results showed that adding aviation spray adjuvants could significantly improve the defoliant droplet deposition. Fifteen days after spraying, the defoliation rate was 80.31% and the boll opening was 90.61%. The defoliation rate increased by 3.12–34.62% and the boll opening rate increased by 6.67–29.56% after the addition of aviation spray adjuvants. Using a vegetable oil adjuvant could significantly increase the droplet coverage rate and the retention of defoliants in cotton leaves.

Keywords: aviation spray adjuvants; droplet deposition; cotton defoliants; unmanned aerial vehicles

1. Introduction

Cotton (*Gossypium hirsutum* L.) production is related to national security, sustainable development of foreign trade leading industries, strategic adjustment of China's agricultural structure and food security. Cotton production reflects the strategic demand of the development of a particular country and certain areas within this country, such as China and Xinjiang [1]. Xinjiang is one of the most important cotton-producing areas in the world. In 2018, the area used for cotton planting reached 2.49 million ha, accounting for 74.32% of the cotton planting area in China. Furthermore, the total cotton output in Xinjiang was 5.11 million tons, accounting for 83.84% of the national cotton output [2]. To solve the problem of the high cost of manual harvesting in cotton production, machine-picked cotton has been vigorously promoted in Xinjiang. In 2018, the planting area of machine-picked cotton in Xinjiang accounted for more than 30% and that of machine-picked cotton in the main cotton areas of Northern Xinjiang accounted for more than 80%. The total planting area of machine-picked cotton reached 870,000 ha in 2018 [2]. The promotion of machine-picked cotton has improved the efficiency of cotton harvesting and reduced the cost of cotton production, which have accelerated the adoption of mechanized cotton production in Xinjiang [3].

Spraying defoliants is an important aspect of mechanized cotton harvesting. Full and uniform spraying of defoliant could improve the quality of defoliation and reduce the impurities in cotton, which would significantly improve cotton quality. The low density-early planting pattern has potential and prospects in oasis agriculture in Xinjiang. However, the leaves overlap considerably. The main reason for the low defoliation rate and high impurity content in cotton is that the lower layer leaves of cotton do not fall off in time. Improving the coverage of defoliant droplets in the middle and lower layers of cotton and ensuring the full and even dispersion of droplets in the cotton canopy are essential in increasing the defoliation effect. Mechanization has been achieved in the sowing, pest control, chemical regulation and control and harvesting of cotton in Xinjiang. Boom sprayers are widely used for large farm crops due to their high working efficiency and effective spraying. However, using boom sprayers with ground machinery leads to problems, such as rolling cotton plants, hitting cotton bolls and pulling cotton branches, which reduce the yield and quality of cotton [4]. This has become a bottleneck and technical problem restricting the improvement of the quality and efficiency of the cotton industry in Xinjiang.

To adapt to this unique operating environment and improve the shortage of the crop protection equipment supply, unmanned aerial vehicles (UAVs) have been rapidly developed in Xinjiang, China for pesticide application [5,6]. UAVs could not only improve the efficiency of pesticide spraying, but also reduce cotton production costs. Precise variable rate pesticide spraying could be realized according to the crop type in order to reduce pesticide dosage and pesticide residues [7–12]. Introducing and popularizing pesticide spraying technology with plant protection UAVs in cotton fields could improve the mechanization level of cotton planting in China and promote the mechanization, intellectualization and light simplification of cotton production. According to the statistics provided by the Ministry of Agriculture and Rural Affairs of the People's Republic of China, nearly 30,000 crop protection UAVs are used in the country. The spraying area approached 17.8 million hectares in 2018.

Nowadays, there needs to be a balance between high efficacious/efficient spray applications and reduced spray drift risk, which can be achieved by adopting the appropriate direct measures to prevent drift at sources by giving preference to the most efficient application techniques [13,14]. Even if the nozzle type [15,16] and nozzle size [17] have the most important effect on droplet size and velocity as they substantially reduce the spray drift [18–21], the composition of sprayed liquid is very important in relation to the application and use of pesticides as it influences the behavior of droplets and their persistence at the site of action [22]. A large number of materials (surfactants, oils, polymers and other macromolecules, etc.) have been recommended as "additives" to pesticide sprays in order to improve their performance in a variety of ways [23]. In particular, the use of spray adjuvants is one of the main approaches used to improve the spray application process. Wang et al. found that the type of adjuvants has a significant effect on droplet drift, which could significantly decrease the risk of drift in agricultural spraying by reducing the percentage of fine droplets and widening the droplet spectra [24]. Meng et al. reported that an adjuvant improved the efficiency of UAV spraying as this adjuvant reduced the required dosage of imidacloprid by 20% [25]. To evaluate the effects of different spray adjuvants on droplet drift during aerial application, Gao et al. reported that spray drift during low volume aerial spraying is affected by the addition of the adjuvants Beidatong, 806 and Y-20079 [26]. Wang et al. [27], He et al. [28] and Zhang et al. [29] found that reasonable adjuvant addition helps to increase the droplet density and deposit rate spray during the aerial spraying. Plant species and pesticide types have a greater impact on the behavior of fog droplets [30].

The rapid and efficient operation of UAVs makes them suitable for spraying cotton defoliants. However, few studies on the application of cotton defoliants by UAVs have been reported. Qin et al.

optimized and tested the spraying parameters of a cotton defoliant sprayer [31]. Xin et al. studied the effects of defoliant dosage and spraying volume on efficacy cotton defoliant sprayed by a UAV [32]. Ma et al. studied the effect of four types of UAVs that sprayed cotton defoliant [33]. Hu et al. analyzed the effects of UAV spraying and an artificial spraying cotton defoliant [34]. Wang et al. studied the effect of a UAV spraying different types of defoliants on cotton defoliation [35]. However, few reports have examined the effects of aviation spray adjuvants on droplet deposition and defoliation by UAV-spraying of a cotton defoliant. Herein, we report our results concerning the effect of aviation spray adjuvants on droplet deposition, defoliation, boll opening and defoliant retention in cotton leaves sprayed by a UAV. The purpose of this study was to provide scientific support for reducing defoliants and increase efficiency, with the ultimate aim to reduce the impurities in seed cotton and improve the quality of cotton fiber in Xinjiang.

2. Materials and Methods

2.1. Materials

2.1.1. Defoliant and Reagents

We obtained 360 g/L Thidiazuron and 180 g/L diuron suspension concentrate (Dropp ultra) and 280 g/L alkyl ethyl sulfonate soluble concentrate (BIOPOWER) from Bayer Crop Science Co., Ltd., Leverkusen, Germany. We used 40% Ethephon aqueous solution produced by Jiangsu Anpon Electrochemical Co., Ltd., Huaian, China. The thidiazuron standard (98.3%) and diuron standard (98.8%) from J&K Scientific Ltd., Beijing, China were used. Methanol (High Performance Liquid Chromatography, HPLC) was obtained from Sigma-Aldrich, St. Louis, MO, USA. Primary secondary amine (PSA) sorbent was produced by Welch Technology (Shanghai) Limited Co., Ltd., Shanghai, China. Water-sensitive paper (WSP, 26 × 76 mm) was obtained from Syngenta Crop Protection Co., Ltd., Basel, Switzerland. Aviation spray adjuvants are listed in Table 1.

Table 1. Details of aviation spray adjuvants.

Adjuvant	Chemical Structure Type	Manufacturer
Y-20079	Organosilicone	Momentive (Shanghai) Trading Co., Ltd., Shanghai, China
Maifei	Vegetable oil	Grand AgroChem Co., Ltd., Beijing, China
Beidatong	Vegetable oil	Hebei Mingshun Agricultural Technology Co., Ltd., Shijiazhuang, China
Nongjianfei	High molecular polymer	Guilin Jiqi Group Co., Ltd., Guilin, China
Star Guar X	High molecular polymer	Solvay Chemical Shanghai Co., Ltd., Shanghai, China

2.1.2. Instruments and Equipment

The aviation platform used was the P30 UAV (XAG Co., Ltd., Guangzhou, China; Figure 1). The UAV used Global Navigation Satellite System and Real-Time Kinematic (GNSS RTK) navigation technology, with the accuracy of the flying height and flying velocity both controlled to remain within the centimeter level. The UAV was powered by a 12,800 mAh Li-Po battery (XAG Co., Ltd., Guangzhou, China). The flying time was 15 min with a full tank. The nozzles (iRASS intelligent centrifugal spraying technology, with a nozzle flow range of 0–5.6 L/min, droplet size 90–300 μm) were placed at intervals of 1.18 m and the installation angle was vertically downward. The chemicals were transferred from the tank to the nozzles by a high frequency pulse peristaltic pump (XAG Co., Ltd., Guangzhou, China). The accuracy of the flight height and flight velocity were controlled by the well-trained operator. The flight height was 2.0 m and the effective spraying width was 3.5 m. The spray volume of one nozzle output was around 15 L/ha.

Figure 1. Unmanned aerial vehicle (UAV) sprayer (P30 UAV).

The electronic balance, BSA224S-CW, was produced by Sartorius, Göttingen, Germany. Swirl meter, MS3 D S25, IKA, was produced by Staufen im Breisgau, Staufen, Germany. The handheld Weather Station (NK5500L) was produced by Nielsen-Kellerman Company, Boothwyn, PA, USA.

2.1.3. Field Plots

The effect of defoliant dosage on defoliation, boll opening, absorption and decontamination in cotton leaves was determined in an experiment in the town of Beiquan, Xinjiang Production and Construction Crops, Shihezi, (85°58′48″ E, 44°23′21″ N), Xinjiang Uygur Autonomous Region, China, during September 2018. The experimental field had middle level fertilizer and had planted cotton for many years. Cotton (Hexin 47) was sown on 28 April 2018, using a mechanical cotton-picking planting model with a wide film that planted 6 lines (10 cm + 66 cm) at 192,000 cotton plants/ha. Furthermore, there was drip irrigation under a plastic film.

2.2. Experimental Treatment

Defoliation treatments were initiated at 40% boll opening time. The defoliant was sprayed using a P30 UAV. The operation height was 2 m, the flying speed was 5 m/s, the effective spraying width was 3.5 m and the spray volume was 15 L/ha. The meteorological data during the deposition measurement were collected with a kestrel 5500 digital meteorograph (Loftopia, LLC, USA). The first defoliant spraying was conducted 1:00–7:00 p.m. on 15 September 2018 (UTC+8). At this time, the average wind speed was 2.20 m/s, the average relative humidity was 25.32% and the average temperature was 23.20 °C. The second defoliant spraying was conducted at 12:00–5:00 p.m. on 22 September 2018 (UTC+8). At this time, the average wind speed was 1.08 m/s, the average relative humidity was 32.57% and the average temperature was 26.23 °C. There was no precipitation during the defoliation spraying. The weather during the experimental period is described in Table S1.

2.2.1. Effect of Aviation Spray Adjuvants on Defoliation Effect

The experiment utilized a spray mixture consisting of pesticides without an adjuvant as the blank control (Table 2). The aviation adjuvants were mixed with 360 g/L thidiazuron and 180g/L diuron suspension concentrate at 121.5 g a.i./ha (active ingredient/ ha) (Dropp ultra), 280 g/L alkyl ethyl sulfonate soluble concentrate at 252 g a.i./ha (BIOPOWER) and 40% ethephon in each treatment at 480 g a.i./ha (22 September 2018 was 600 g a.i./ha. Each treatment was repeated on two different dates (15 and 22 September 2018).

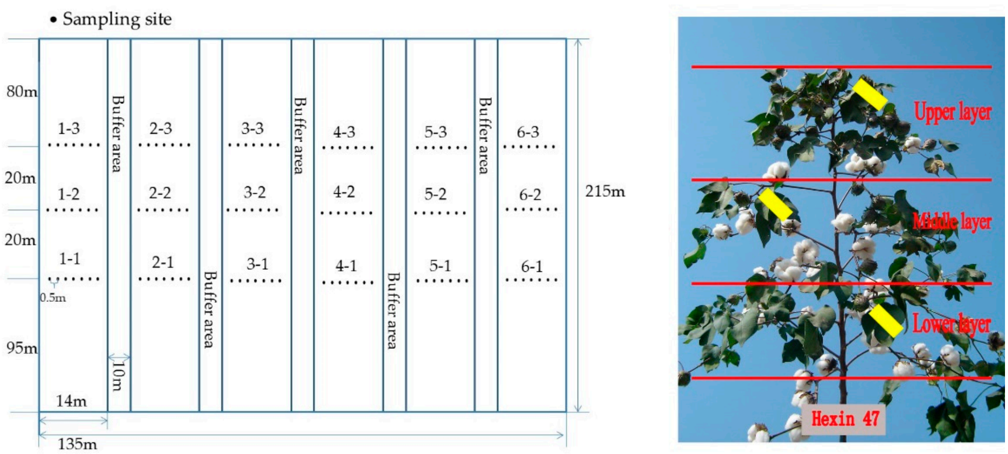
Table 2. Experimental design for screening aviation spray adjuvants.

Treatment	Aviation Spray Adjuvants [a]	Aviation Spray Adjuvants Dosage(mL/ha [b])
1	Beidatong	300
2	Nongjianfei	150
3	Star Guar X	75
4	Maifei	150
5	Y-20079	150

[a] The aviation adjuvants were mixed in the same dosage for both dates. [b] The dosage of all aviation spray adjuvants was the recommended dosage.

2.2.2. Effects of Aviation Spray Adjuvants on Droplet Distribution in Cotton Canopy

The experiment consisted of six treatments: five types of aviation spray adjuvant treatments and a blank control. The spray deposition, defoliation rate and boll opening rate were tested. The spray deposition and the control efficacy were measured in an area of 135 m × 215 m (Figure 2A). The sample layout was repeated three times, with adjacent repetition occurring 20 m apart. Each plot had dimensions of 14 m × 215 m. Ten-meter buffer zones were set between plots to avoid drift pollution (Figure 2A). Sample collectors at each sample site consisted of one water-sensitive paper (WSP; 25 mm × 75 mm; Figure 2B). The WSP was used to evaluate the following deposition characteristics: (i) coverage, (ii) number of spray impacts/stains and (iii) dimensions of impact/stains [36,37]. The WSPs were fixed to cotton leaves using paper clips. Nearly 30 s after spraying, all WSPs were removed and placed in ziplock bags along with a label describing the treatment, replication and WSP site information. Samples were placed into light-proof sealed boxes immediately after collection and transported to the laboratory for analysis.



(**a**) (**b**)

Figure 2. (**A**) Experimental layout of each treatment and (**B**) placement of water-sensitive paper at each sampling position within the cotton canopy.

In the laboratory, the WSPs were scanned at a resolution of 600 dpi with a scanner. ImageJ software (ImageJ 1.3 8, National Institutes of Health, Bethesda, MD, USA) was used to extract droplet deposits in the digital image for the analysis of the droplet size, number of spray deposits and the area of coverage [7]. Coverage was determined as the percent cover of the card from the blue dye of the deposited image. To characterize the uniformity of droplet deposition between spray width, the uniformity of droplet deposition was measured by the coefficient of variance (*CV*) of droplet deposition densities at different locations of the cotton plants within the UAV effective spray width. The *CV* of droplet deposition density was calculated by Equations (1) and (2) [9,30]:

$$CV = \frac{S}{\overline{X}} \times 100\% \tag{1}$$

$$S = \sqrt{\sum_{i=1}^{n} \left(X_i - \overline{X}\right)^2 / (n-1)} \tag{2}$$

where S is the sample standard deviation, X_i is the number of droplets per unit area at each collection point, *X(−)* is the mean number of collection points per layer and n is the total number of sampling cards in each cotton layer.

2.2.3. Defoliation and Boll Opening

To analyze the field efficacy of different aviation spray adjuvants with different spray deposition characteristics, we selected the cotton defoliation rate and the boll opening rate as the field test targets. Defoliation and boll opening were selected based on previous reports [31]. Prior to treatment application, 30 cotton plants were randomly tagged to count the number of leaves on each cotton plant. The number of leaves was counted again 4, 7, 12 and 15 days after spraying the same tagged plants. The defoliation rate was calculated using Equation (3):

$$\text{Defoliation rate (\%)} = ((N_a - N_b)/N_a) \times 100\% \tag{3}$$

where N_a is the number of leaves before treatment and N_b is the number of leaves after treatment.

Boll opening rate was determined on the same tagged 30 cotton plants. Bolls on each cotton plant were examined and recorded as either opened or closed. Boll opening rate was calculated by:

$$\text{Boll opening rate (\%)} = (N_c/N_d) \times 100\% \tag{4}$$

where N_c is the number of opened bolls and N_d is the total number of bolls.

2.2.4. Attachment and Absorption

Cotton leaf extraction and purification, standard curves and added recovery were based on previous reports [31]. Thidiazuron and diuron were analyzed with an Agilent 1200 HPLC equipped with a reversed-phase column (Agilent XDB-C18, 4.6 mm × 150 mm, 5 µm, Agilent, Santa Clara, CA, USA) at 25 °C. The mobile phase was methanol/water (65/35, *v*/*v*) at a flow rate of 0.8 mL/min. The injection volume was 20 µL. The standard curve was obtained by drawing the area as an ordinate and drawing the concentration of the thidiazuron and diuron standard solution as abscissa. The standard curve equations of thidiazuron and diuron were $y = 35.76x + 26.18$ ($R^2 = 0.9779$) and $y = 128.86x - 18.83$ ($R^2 = 0.9956$), respectively. The peak area and concentration of thidiazuron and diuron exhibited a good linear relationship (2.0–10.0 mg/L).

Each additional level was repeated three times while setting the blank control (Table 3). The average recoveries of 0.05, 0.50 and 1.0 mg/kg thidiazuron from cotton leaves were 108.67%, 96.67% and 104.33%, respectively. The average recoveries of 0.05, 0.50 and 1.0 mg/kg diuron from cotton leaves were 97.33%, 104.40% and 101.33%, respectively. The relative standard deviation (RSD) was 2.0–9.3%. These values met the requirements for residue analysis.

Table 3. Recovery rate of thidiazuron and diuron in cotton leaves.

Compound	Added Concentration(mg/kg)	Recovery Rate (%) [a]			Average Recovery Rate (%)	RSD (%)
		1	2	3		
Thidiazuron	0.05	117.52	98.35	112.55	108.67	8.70
	0.50	90.45	97.51	105.60	96.67	7.27
	1.00	102.58	105.43	106.55	104.33	2.00
Diuron	0.05	103.13	92.85	98.91	97.33	5.17
	0.50	115.53	99.85	97.83	104.40	9.28
	1.00	96.41	112.65	98.58	101.33	7.47

[a] Three replicates; RSD, relative standard deviation.

2.2.5. Yield Characteristics and Fiber Quality

The cotton yield was measured after all the cotton bolls opened. For this measurement, 50 cotton bolls from the canopies (upper, middle and lower layers) were randomly tagged and collected in each experimental area to determine the cotton yield characteristic and fiber quality. Cotton yield and quality factors were determined by the Key Laboratory of Cotton Biology and Genetics and Breeding in the Northwest Inland Region of the Ministry of Agriculture (Shihezi, China).

2.3. Data Statistics and Processing

Certain variables, namely the percentage of the area covered on the WSP, defoliation rate and boll opening rate, were transformed to arcsin $\sqrt{X}/100$. The other variables were log $(x + 1)$ transformed prior to analysis in order to stabilize the wide variances and meet normal assumptions. After transformation, the data were analyzed for normality using the Kolmogorov–Smirnov test and for equal variance across the treatments and replicates using Levene's test. Data were compared across different application rates using analysis of variance (ANOVA) (Origin 9.1 originLab, Northampton, MA, USA). By comparing the mean one-way ANOVA, the least significant difference (LSD) was selected. The confidence interval was set to 95% and $p < 0.05$ was chosen to indicate a significant difference between the two groups.

3. Results and Discussion

3.1. Effect of Aviation Spray Adjuvants on Droplet Deposition

Many factors, including adjuvants, pesticide formulations and nozzle tips, affect spray droplet size [38]. Table 4 displays the effects of aviation spray adjuvants on defoliant cotton canopy spray quality parameters, namely dimension of droplet impacts, density and surface coverage. Beidatong and Maifei are vegetable oil adjuvants, which reduce droplet surface tension, evaporation and drift and promote droplet deposition. For the spray with added Beidatong and Maifei, the average number of impacts (72.03 and 34.46) of the defoliant in the upper layer of cotton canopy was significantly higher than that of the other adjuvants. Although there is no specific droplet size range that is liable to drift under all conditions, droplets with diameters less than 100 μm are considered to be highly driftable [39,40]. We found that the high molecular polymer adjuvants, Nongjianfei and Star Guar X, demonstrated characteristics of anti-drift and facilitated droplet drop and formed larger size droplets, which showed a certain anti-evaporation effect (Dv_{50} was 474.71 and 526.28 μm, respectively). However, the average number of impacts (27.83%, 19.03% and 17.16% for upper, middle and lower layers, respectively) was lower than those of vegetable oils and polymer adjuvants. This was caused by the formation of a strong acidic solution after adding ethephon, which affected the stability of Y-20079. The droplet density (18.70, 12.92 and 25.70 droplets/cm^2 for upper, middle and lower layers, respectively) of the defoliant without aviation spray adjuvants was significantly lower than the aviation spray with adjuvants. However, due to drifting and evaporation, the coverage rate (1.83% for the upper layer) without aviation spray adjuvants was significantly lower than that of with aviation sprays with adjuvants. After the second spray, the droplet coverage rate of the middle and lower layers increased because the upper layer leaves had defoliated. The mean dimension of the impacts after the second spray was larger than after the first spray because some leaves of the middle and lower layers had defoliated after the first spraying and the angle of the remaining leaves decreased. The defoliant droplets were greatly affected by the gravity and formed larger size droplets.

Table 4. Coverage rate, number and mean dimension of impacts in the cotton canopy (aviation spray adjuvants).

Date of Spraying	Cotton Canopy	Aviation Spray Adjuvants	Coverage Rate (%)	Droplet Density(Number of Impacts /cm^2)	Mean Impacts Dimension (μm)
15 September 2018	Upper layer	Beidatong	1.31 c	72.03 a	555.43 b
		Nongjianfei	3.63 a	20.03 b	474.71 c
		Star Guar X	2.07 bc	29.30 b	526.29 bc
		Maifei	2.92 ab	34.46 b	529.29 b
		Y-20079	2.53 abc	27.83 b	803.43 a
		Defoliant only	1.83 bc	18.70 b	341.29 d
	Middle layer	Beidatong	1.91 a	69.01 a	639.29 ab
		Nongjianfei	1.40 a	29.15 b	540 b
		Star Guar X	0.96 a	12.53 b	692.57 a
		Maifei	1.62 a	46.26 ab	565.29 b
		Y-20079	1.63 a	19.03 b	663.71 ab
		Defoliant only	1.55 a	12.92 b	409.71 c
	Lower layer	Beidatong	0.52 a	44.50 a	500.57 b
		Nongjianfei	1.16 a	18.53 a	459.57 bc
		Star Guar X	1.31 a	32.51 a	597.29 a
		Maifei	0.94 a	22.30 a	495.29 b
		Y-20079	1.85 a	17.16 a	488.57 bc
		Defoliant only	1.34 a	25.70 a	365.57 c
22 September 2018	Middle layer	Beidatong	2.51 ab	31.34 a	695.71 ab
		Nongjianfei	2.63 a	25.87 a	678.14 b
		Star Guar X	2.84 a	44.79 a	746.57 a
		Maifei	2.62 a	38.68 a	720.57 a
		Y-20079	3.20 a	21.57 a	743.57 a
		Defoliant only	1.40 b	16.76 a	578.86 c
	Lower layer	Beidatong	1.65 a	83.13 a	614.29 c
		Nongjianfei	1.38 a	41.07 b	602.43 cd
		Star Guar X	1.61 a	79.14 a	875.14 a
		Maifei	1.99 a	82.39 a	658.57 bc
		Y-20079	1.47 a	57.83 ab	737.0 b
		Defoliant only	1.46 a	6.01 c	452.14 d

Note: The data in the table are the original data and were not converted. Means within a column followed by the same letter were not significantly different according to LSD at $p = 0.05$. The data were from WSP samples and thus, the data may differ from the actual values from the leaves.

As shown in Figure 3, after the first spraying, the defoliant droplet coverage rate increased significantly with the addition of adjuvants. However, the defoliant droplet coverage rate in the middle and lower layers of the cotton canopy was significantly lower than in the upper layer of the cotton canopy. The upper layer leaves of the cotton canopy are intricate and overlapping and the penetration of defoliant droplets was limited in the cotton canopy. The penetration performance of aviation spray adjuvants was not very good. Six days after the first spraying, the defoliation rate of the upper layer leaves of cotton canopy was more than 75% (Figure 4A). Because there was no leaf occlusion, the defoliant droplet coverage rate in the middle and lower layers of cotton canopy increased significantly (Figure 3). The defoliant droplet coverage rate for the aviation spray with adjuvants was significantly higher than that of the control (Figure 3F). Influenced by the wind field of the UAV rotor, the defoliant droplet coverage rate varies considerably in the range of spray width [41,42]. The spray center was simultaneously affected by the wind fields of the four UAV rotors and the defoliant droplet coverage rate was higher than that at the edge of the spray width [43].

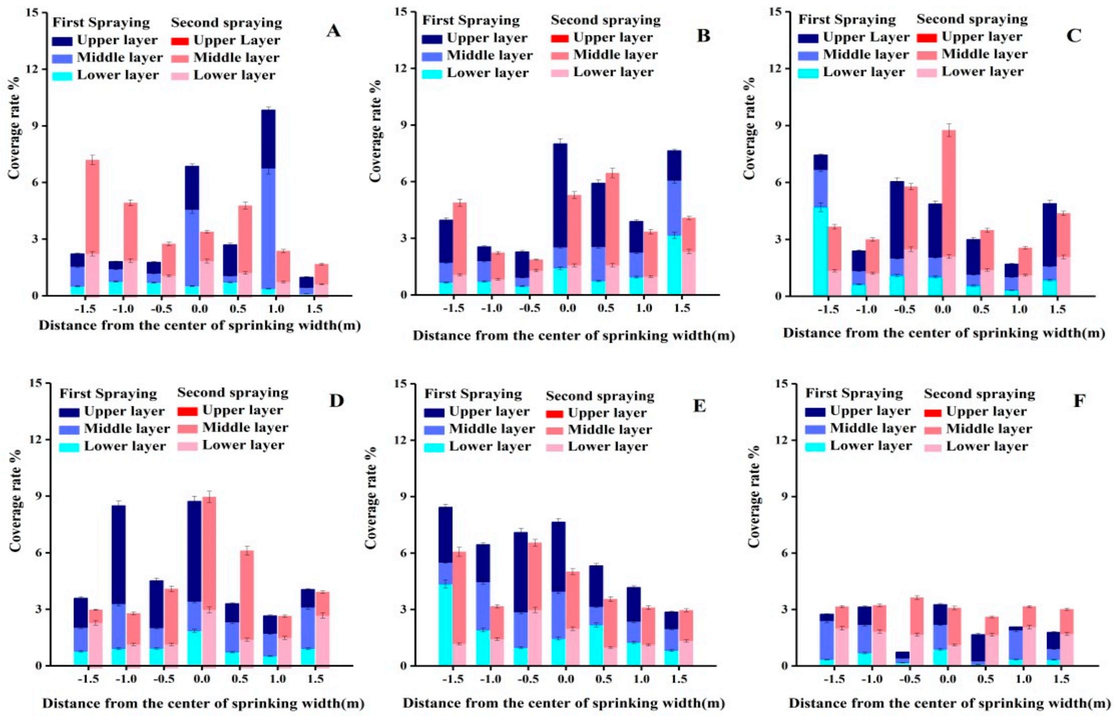


Figure 3. Effect of aviation spray adjuvants on coverage rate of droplets in cotton canopy sprayed by UAV. (**A**) 300 mL/ha Beidatong; (**B**) 150 mL/ha Nongjianfei; (**C**) 75 mL/ha Star Guar X; (**D**) 150 mL/ha Maifei; (**E**) 150 mL/ha Y-20079; and (**F**) control without aviation spray adjuvants.

To comprehensively evaluate the droplet deposition distribution in the cotton canopy, the coefficient of variation (*CV*) of the droplet deposition characteristics (droplet density and coverage rate) was calculated to characterize the droplet distribution uniformity after the addition of aviation spray adjuvants (Table 5). Field experiments were influenced by environmental conditions and the *CV* of droplet density and coverage rate was relatively large. The uniformity of droplet distribution in the first spraying was lower than that in the second spraying (Table 5). The maximum *CV* of the spray droplet coverage rate was 62.33%. Therefore, aviation spraying must be conducted under the best possible weather conditions [44].

Table 5. Variation coefficient (CV) of droplet distribution (aviation spray adjuvants).

Aviation Spray Adjuvants	CV (%)							
	First Spraying				Second Spraying			Average
	Upper Layer	Middle Layer	Lower Layer	Average	Middle Layer	Lower Layer	Average	
Beidatong	79.59	84.41	44.27	69.42	56.13	42.53	49.33	59.38
Nongjianfei	94.76	55.53	80.65	76.98	57.95	35.71	46.83	61.91
Star Guar X	64.47	49.93	115.67	76.69	62.68	33.25	47.97	62.33
Maifei	96.22	30.93	45.02	57.39	77.03	38.07	57.55	57.47
Y-20079	45.73	42.38	65.17	51.09	36.73	29.22	32.98	42.04
Control	62.67	68.23	70.14	67.01	29.30	18.82	24.06	45.54

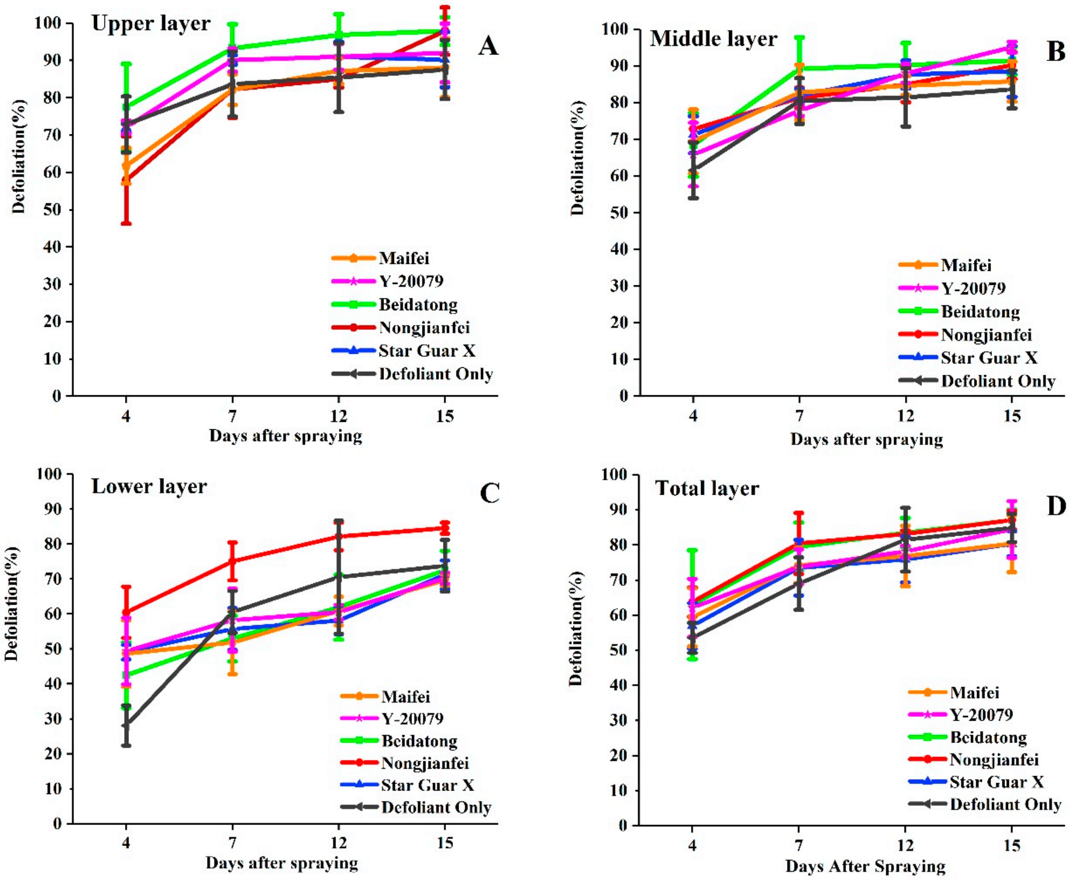


Figure 4. Effect of aviation spray adjuvants on the defoliation effect of cotton sprayed by UAV. (**A**) Cotton upper layer, (**B**) cotton middle layer, (**C**) cotton lower layer and (**D**) cotton total layer. CK: Defoliate only; Maifei: 150 mL/ha; Beidatong: 300 mL/ha; Nongjianfei: 150 mL/ha; Y-20079: 150 mL/ha; and Star Guar X: 75 mL/ha.

3.2. Effect of Aviation Spray Adjuvants on Defoliation and Boll Opening

The analysis of variance in defoliation efficacy and aviation spray adjuvants due to cotton parameters is presented in Figure 4. Leaf abscission began to form four days after the first spraying and the aviation spray adjuvants had a considerable effect on the defoliation effect. For the upper layer of the cotton canopy, the Beidatong treatment showed the best defoliation efficacy. The defoliation efficacy of other treatments were significantly lower than that of the control treatment (without aviation spray adjuvants, Figure 4A). For the middle layer of the cotton canopy, after 7, 12 and 15 days after spraying, the defoliation rate of the Beidatong was 89.19%, 90.24% and 91.39%, respectively, which was significantly better than other aviation spray adjuvants. Nongjianfei, Y-20079 and Star Guar X were significantly better than the control treatment (Figure 4B). Due to the poor penetrability of the canopy sprayed by UAV, the defoliation of the lower layer of cotton canopy was significantly lower than that of the upper and middle canopies while the defoliation effect of Nongjianfei was significantly higher than that of others (Figure 4C). For the cotton canopy, four days after the spraying, the defoliation rate was more than 40% when treated with the aviation spray adjuvants and 15 days after spraying (9 days after the second spraying), the defoliation rate was more than 80% (Figure 4D). In general, the upper and middle canopies demonstrated the highest defoliation rate when treated with Bidatong. The lower canopy achieved the best defoliation rate when treated with Nongjianfei. Bidatong produced the best defoliation effect at different times after spraying and showed a long-lasting effect.

The tested aviation spray adjuvants were classified into three types according to their chemical structure: silicone (Y-20079), vegetable oils (Beidatong and Maifei) and high molecular polymers

(Nongjianfei and Star Guar X). The effects of different types of aviation spray adjuvants on the defoliation effect are shown in Figure 5. The best defoliation effect was produced by vegetable oil adjuvants (Beidatong and Maifei), which is potentially because vegetable oil adjuvants are highly adaptable to environmental changes and not limited by pH. The defoliation effect of the control treatment was superior to the silicone adjuvant (Y-20079) and the high molecular polymer adjuvants (Nongjianfei and Star Guar X). Silicone adjuvants are sensitive to acid and mixed with a strongly acidic 40% ethephon, resulting in no wetting or spreading properties, which affects the defoliation effect. The high molecular polymer adjuvants have high humidity requirements and the maximum humidity on the day of spray was only 38.21%, which affects the synergistic effect of high molecular polymer adjuvants. These studies show that the addition of aviation spray adjuvants (especially vegetable oil adjuvants) during the spraying of cotton defoliants by UAV could improve the defoliation effect.

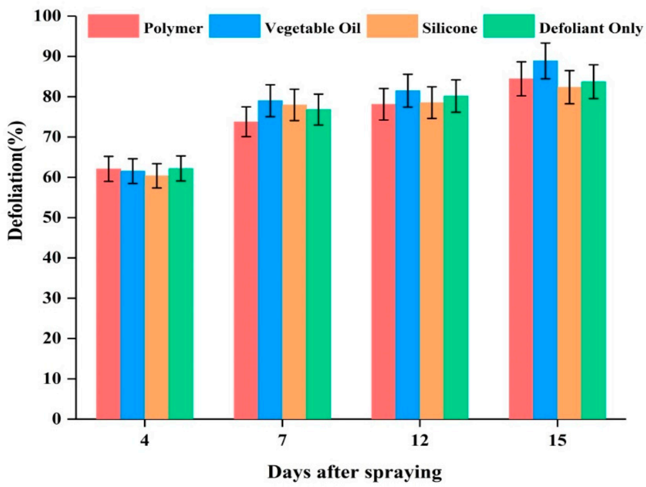


Figure 5. Effect of aviation spray adjuvants on defoliation of cotton sprayed by UAV.

As illustrated in Table 6, the cotton boll opening effect significantly increased after spraying with added adjuvants by UAVs. Four days after spraying, the boll opening rate of control was 44.36% while the boll opening rates of the Beidatong and Maifei treatments reached 70.0%. Seven days after the first spraying, the boll opening rate of high molecular polymer adjuvants (Nongjianfei and Star Guar X) increased by 58.11% and 38.13%, respectively, but the boll opening effect was reduced compared to that of vegetable oil adjuvants. Twelve days after spraying, the boll opening rate of all adjuvants reached more than 80%. The control boll opening rate was 75.94% and those of the adjuvants treatments all reached more than 90% fifteen days after spraying. Generally, vegetable oil adjuvants, namely Beidatong and Maifei, had synergistic effects on cotton boll opening. Organosilicon adjuvant Y-20079 is decomposed by ethylene and high molecular polymer adjuvants were affected by low ambient humidity, which showed no synergistic effect.

Table 6. Effect of aviation spray adjuvants on cotton boll opening sprayed by UAV.

Treatment	Days After First Spraying (%)				
	0	4	7	12	15
Beidatong	42.38 a	71.66 a	82.85 a	90.88 a	94.73 a
Nongjianfei	43.12 a	45.69 b	72.24 ab	85.46 ab	91.87 a
Star Guar X	42.11 a	61.89 ab	85.49 a	88.76 a	90.61 a
Maifei	41.16 ab	70.93 a	86.79 a	89.77 a	95.89 a
Y-20079	43.77 a	64.71 a	80.10 a	88.80 a	92.48 ab
CK	40.98 b	44.36 b	61.45 b	68.86 b	75.94 b

Note: Means within a column followed by the same letter were not significantly different according to LSD at $p = 0.05$.

3.3. Effect of Aviation Spray Adjuvants on Retention of Thidiazuron and Diuron

As shown in Figure 6, UAV spraying of cotton defoliant with added aviation spray adjuvants significantly affects the retention of thidiazuron and diuron in cotton leaves. The retention of thidiazuron and diuron in cotton leaves was closely related to the canopy structure of cotton. Maifei and Y-20079 significantly increased the retention of defoliant in cotton leaves, but their penetration was not very good and they had no synergistic effect on the retention of defoliant in middle and lower cotton leaves. Beidatong significantly improved the retention of thidiazuron throughout the whole cotton canopy and showed good droplet penetration effects, which was consistent with the droplet deposition and the effect on defoliation and boll opening. Nongjianfei and Star Guar X displayed no significant effects on the retention of thidiazuron and diuron in cotton leaves. The second spraying was conducted seven days after the first spraying. At that time, the retention of thidiazuron and diuron in different cotton canopy was the highest.

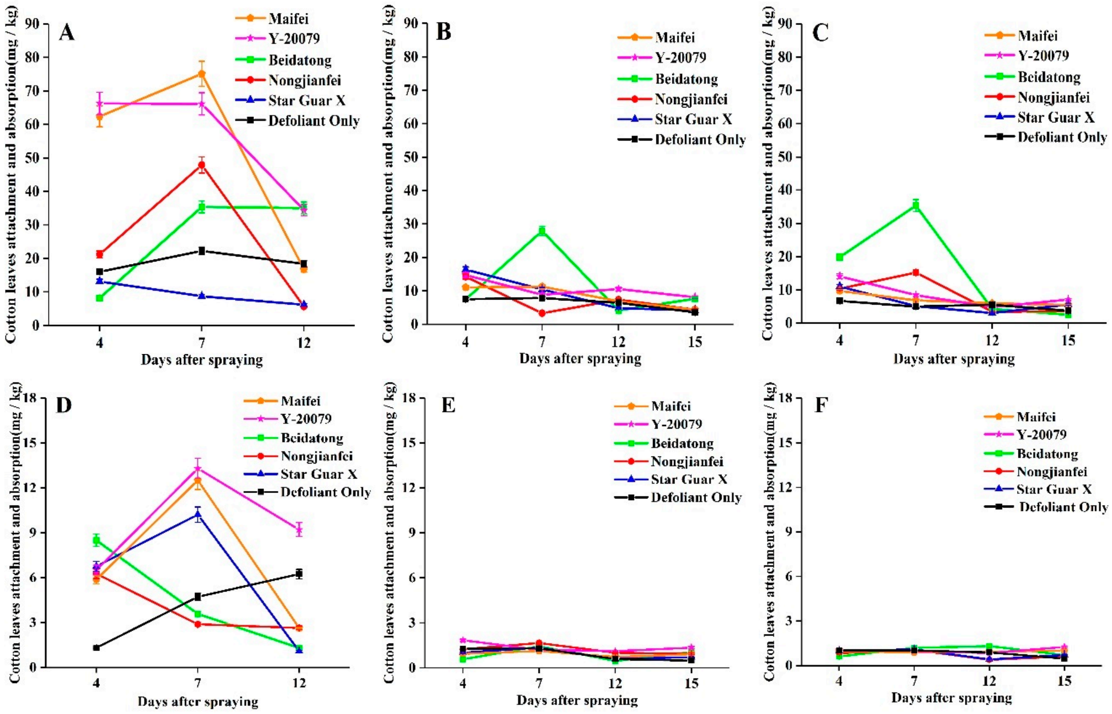


Figure 6. Effect of aviation spray adjuvants on attachment and absorption of thidiazuron and diuron on cotton leaf sprayed. Thidiazuron: (**A**) upper, (**B**) middle and (**C**) lower layers; Diuron: (**D**) upper, (**E**) middle and (**F**) lower layers. Fifteen days after spraying, the rate of defoliation of the upper canopy of cotton was over 85% although this sample was not collected.

3.4. Effect of Aviation Spray Adjuvants on Cotton Yield Characteristics and Fiber Quality

The effects of aviation spray adjuvants on cotton yield and quality factors are shown in Table 7. Compared with the control, the cotton boll weight (BW) reduced after the addition of aviation spray adjuvants, of which Beidatong, Nongjianfei and Y-20079 reached significant levels. All aviation spray adjuvants had no effect on elongation rate (Elg) and the short fiber index (SFI) of cotton fiber quality factors. Beidatong had no effect on cotton upper half mean length (UHML), uniformity index (UI), micronaire (Mic) or maturity rate (MR) but had a significant effect on breaking strength (Str). Star Guar X had a significant effect on UHML and Str; Maifei had a significant effect on UHML, UI and Str; Y-20079 had a significant effect on Mic; and Nongjianfei had little effect on fiber quality factors. To enable mechanical harvesting, defoliants are sprayed on the top of cotton bolls before they are fully developed. This would seriously affect the development of bolls and fibers, leading to a decline in cotton fiber quality [44]. No direct report on the impact of aviation spray adjuvants on cotton yield and fiber quality has been published.

Table 7. Effect of aviation spray adjuvants on cotton fiber quality and yield sprayed by UAV.

Treatment	BW (g)	UHML (mm)	UI (%)	Mic	Str ($cN \cdot tex^{-1}$)	Elg (%)	MR	SFI
Beidatong	5.12 c	28.32 a	84.40 a	5.17 bc	28.35 c	6.85 a	913.33 bc	0.85 a
Nongjianfei	5.13 c	29.13 a	83.00 b	5.23 b	28.47 bc	6.83 a	1347.67 a	0.85 a
Star Guar X	5.37 ab	26.63 c	83.87 ab	5.40 ab	27.80 c	6.77 a	1107.33 ab	0.85 a
Maifei	5.39 ab	26.39 c	81.43 c	5.51 a	26.33 c	6.63 a	1072.67 abc	0.85 a
Y-20079	5.1 c	27.84 b	82.85 bc	5.10 c	28.95 b	6.90 a	1001.33 bc	0.85 a
CK	5.63 a	28.25 ab	83.35 ab	4.89 c	29.60 a	6.75 a	785.33 c	0.85 a

Note: BW, Boll weight; UHML, Upper Half Mean Length; UI, Uniformity Index; Mic, Micronaire; Str, Breaking Strength; Elg, Elongation rate; MR, Maturity Rate; and SFI, Short Fiber Index. Means within a column followed by the same letter were not significantly different according to LSD at $p = 0.05$.

4. Conclusions

In this study, WSP was used to measure the deposition and spray quality parameters of UAV spraying cotton defoliants with different aviation spray adjuvants. The defoliation and boll opening effects were investigated after defoliant spraying. Extensive field experimental results showed that adding aviation spray adjuvants could significantly increase the defoliant droplet deposition. Vegetable oil adjuvants (Beidatong) could significantly increase the droplet coverage rate and the retention of defoliant in cotton leaves. However, since the data were based only on a limited range of aviation spray adjuvants, further studies should aim to evaluate the effects of additional aviation spray adjuvants to determine the applicability of the results. The effects of the addition of aviation spray adjuvants on defoliant reduction should be further studied.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/9/5/217/s1, Table S1: Weather conditions during the test period (Shihezi, China).

Author Contributions: X.H. and W.F. conceived and designed the experiments; Q.X., F.X., Z.L. and G.W. performed the field experiments; T.Z. performed the chemical analysis; F.X., X.H. and W.F. analyzed the data; X.H. and W.F. wrote the paper; Y.L. conceived the research and revised the manuscript.

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