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Comparison of Droplet Distribution and Control Effect of Wheat Aphids under Different Operation Parameters of the Crop Protection UAV in the Wheat Flowering Stage

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Abstract: Aphid is one of the main insect pests of wheat in the flowering stage, so timely and effective control of wheat aphids plays an important role in ensuring wheat yield. The crop protection Unmanned Aerial Vehicle (UAV) is widely used in the control of wheat pests and diseases nowadays. In order to screen out the suitable operation parameters of the crop protection UAV to control the wheat aphids, this study conducted wheat aphid distribution investigation tests and droplet distribution tests. With the P20 electric four-rotor crop protection UAV (Guangzhou Jifei Technology Co., Ltd., Guangzhou, China) as the test equipment, four levels of flight speed (FS: 3, 4, 5, 6 m/s) and three levels of flight height (FH: 1.5, 2, 2.5 m) were combined as operation parameters, tests were carried out to compare the density and uniformity of droplet coverage, and the wheat aphid control tests were carried out by using the optimized operation parameters. The results of the wheat aphid distribution investigation test showed that aphids mainly distributed in the lower layer of the wheat plant canopy, accounting for more than 90.61%. The results of the droplet distribution test showed that with the increase in FS and FH, the coverage density and the droplet distribution uniformity in the upper and lower layers of wheat showed a downward trend under the condition of considering the boundary overlap of spraying width (SW) in multi-routes. Through the comparison of operation efficiency and droplet distribution quality, two combinations of parameters A1 (FS: 3 m/s, FH: 1.5 m) and B1 (FS: 4 m/s, FH: 1.5 m) were selected for the aphid control effect test. The results of the control test showed that the average control effect of A1 (92.05%) on aphids was 10.3% higher than that of B1 (81.75%) 7 days after pesticide application, which indicated that improving the droplet distribution uniformity in the lower layer of wheat could significantly improve the control effect of aphids. This study result could provide reference for the same type of crop protection UAV to control the same type of wheat diseases and insect pests in the same growing stage.

Keywords: crop protection UAV; parameter optimization; wheat; flowering stage; droplet distribution; aphids; control effect

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Citation: Sun, T.; Zhang, S.; Xue, X.; Jiao, Y. Comparison of Droplet Distribution and Control Effect of Wheat Aphids under Different Operation Parameters of the Crop Protection UAV in the Wheat Flowering Stage. *Agronomy* **2022**, *12*, 3175. https://doi.org/10.3390/agronomy12123175

Academic Editor: Francisco Manzano Agugliaro

Received: 18 November 2022
Accepted: 14 December 2022
Published: 15 December 2022

1. Introduction

Aphid is one of the main insect pests of wheat. It has two reproduction modes, parthenogenetic reproduction and sexual reproduction. It spreads explosively in wheat fields, and it would cause great yield loss if the control is not timely [1–3]. In the area of this study, before the wheat seedling stage, due to the low temperature, it is not suitable for the growth and reproduction of wheat aphids, the quantity of aphids is small and the damage is relatively light. When the wheat grows into the turning-green stage, the quantity of aphids gradually increases with the increase in temperature and the continuous improvement of the nutritional conditions of wheat plants. From the heading stage to the flowering stage, the quantity of aphids increases sharply with the further increase in temperature. Therefore, controlling aphids in the flowering stage of wheat plays a very important role in ensuring the healthy development and yield of wheat [4–6]. However, in the flowering stage, as the wheat row gap is closed, the boom-sprayer will crush and destroy the wheat plants during pesticide application, which will affect wheat yield. At the same time, due to the planting methods and other factors, some fields with small area and complex shape are not suitable for the entry of the boom sprayer. The use of the knapsack sprayer also faces some problems, such as trampling on wheat plants, low operation efficiency, and low spraying quality [7,8]. The crop protection UAV has been widely used in wheat plant protection in recent years because of its high efficiency, low labor intensity, and good flexibility [9–12].

With the gradual popularization of crop protection UAVs, the suitable operation parameters for the pesticide application are becoming more and more important. The plant characteristics and the diseases and insect pests of wheat show great differences in different growth stages [13,14]. In the process of pesticide application, if the operator ignores this feature and uses excessively high flight speed (FS) to improve the operation efficiency, not only would it be difficult to achieve a good control effect, but it would also lead to pesticide drift pollution [15–18], which would have a very negative impact on the development of the crop protection UAV industry. In order to screen out the suitable operation parameters and improve the operation quality of the crop protection UAV, many researchers have conducted a lot of tests and studies. In the research of the relationship between operation parameters and droplet distribution, Zhang et al. [19] measured the actual spraying width (SW) of the crop protection UAV under different operation parameters according to the crop protection UAV industry standard, and the results showed that the FS and flight height (FH) had a significant impact on the SW and the droplet distribution uniformity. Xiao et al. [20] found that under the same operation parameters, the coverage density and droplet distribution uniformity gradually decreased along the plant from top to bottom through the spraying test of the crop protection UAV. Gu et al. [21] studied the droplet distribution at different FSs and rotating speeds of centrifugal nozzles, the results showed that the average coverage and droplet density were negatively correlated with FS, and the average droplet density was also negatively correlated with droplet size. Qiu et al. [22] arranged a test by two factors and three levels to find out the factors and degree of influence affecting the UAV spraying deposition. The results showed that the FH, FS, and the interaction between the two factors all affected the deposition and uniformity. Chen et al. [23] studied the influence of different spray operation parameters of the HY-B-10L UAV on the deposition and distribution of droplets in the rice canopy, and proved that the FS and FH had a significant impact on the deposition of droplets. In the research of operation parameters and the pest control effect, Zhao et al. [24] used a four-rotor crop protection UAV to conduct a control test on the corn leafhopper and studied the penetration of droplets under different operating parameters. The results showed that reducing the FH can effectively improve the deposition of droplets in the lower layer of corn and the control effect of pests. Meng et al. [25] studied the droplet distribution of the oil-powered single-rotor crop protection UAV in a wheat canopy under different FSs, FHs, and nozzle flow rates, and conducted aphid control tests. The results showed that reducing FS and FH, and increasing the nozzle flow rate could increase the droplet deposition in the upper, middle, and lower layers of wheat, and improve the aphid control effect. Zhang et al. [26] studied the droplet distribution of single-rotor and multi-rotor crop protection UAVs in the rice canopy under different operation parameters, and the results showed that improving the deposition and uniformity of the droplet distribution on crops could improve the control effect of diseases and insect pests. Wang et al. [27] studied and proved that improving the spray uniformity of crop protection UAVs by optimizing the spray system and UAV path planning had great significance in improving the spray quality and ensuring the control effect.

Determining suitable operating parameters to ensure operational quality has become one of the focal points in the research field of the crop protection UAV. At present, most of the research results focus on optimizing the operation parameters of the crop protection UAV to improve spray quality, such as droplet distribution uniformity and coverage density.

In the research of the disease and pest control, most of them were carried out by spraying directly and counting the control effect, where there is a lack of research on the matching of the occurrence characteristics of crop diseases and insect pests, the control requirements, and the operation parameters. Little research has been carried out on the integration of crop protection machinery and agronomy. With reference to previous research achievements, this paper investigated the plant characteristics and aphids distribution characteristics in the flowering stage, and carried out the operation parameters optimization with the P20 UAV as test equipment, which would provide a reference for the same type of crop protection UAV to control wheat diseases and insect pests in the same growing stage.

2. Materials and Methods

2.1. Test Site

The field tests were conducted at Sihong Agricultural Demonstration Area (33.3636° N, 118.2599° E), Suqian district, Jiangsu, China. There were more than 6000 ha in agricultural acreage in the Sihong Agricultural Demonstration Area, and the farmland situation was suitable for carrying out the pesticide application test of the crop protection UAV. The wheat variety, Qianmai 33, was planted in late October 2019. The sowing mode was machine drilling, the row spacing was 15 cm, and the planting density was about 300 plants/m^2. There were several wheat planting plots in the demonstration area, and each spot was 50 m long and 18 m wide, which could be used for the spray test and control test of the crop protection UAV. The main characteristics of wheat and the weather conditions are shown in Table 1.

Table 1. The wheat characteristics and weather conditions.

Test Time	Growth Period	Plant Mean Height (cm)	Mean Wind Speed (m/s)	Mean Temperature (°C)	Mean Relative Humidity (%)
20–22 April 2020	Flowering Stage	65.6	1.6	17.3	63.6

Note: The values of wind speed, temperature, and relative humidity were the mean values from April 20 to 22.

2.2. Test Equipment and Materials

The P20 electric four-rotor crop protection UAV (Guangzhou Jifei Technology Co., Ltd., Guangzhou, China) was used as the test equipment, the main parameters of which are shown in Table 2. The P20 UAV with the RTK global position system can perform spray operation accurately following the route set by the remote controller. The LAI-2200C hand-held leaf area index instrument (the LI-COR Co., Lincoln, NE, USA) was used to measure the wheat canopy leaf area index (LAI). The Kestrel 4500 hand-held meteorological instrument (the Nielsen Kellerman Co., Boothwyn, PA USA) was used to record the wind speed, the temperature, and the relative humidity. Droplets were collected by water-sensitive paper (Syngenta Co., Ltd., Beijing, China). The 9000F-Mark II scanner (Canon Co., Ltd., Beijing, China) was used to scan the water-sensitive paper (WSP) to obtain the digital image. The data of droplet distribution were analyzed and processed by ImageJ (ImageJ 1.3 8, National Institutes of Health, Bethesda, MD, USA) software.

Table 2. Main parameters of P20 UAV.

Items	Parameter
Size of UAV/mm	1262 × 1250 × 490
Type of nozzle	Centrifugal nozzle
Numbers of nozzles	4
Rated capacity/L	10
FS/(m/s)	3–6
FH/m	1.5–2.5

The pesticides used to control wheat aphids were 20% *cyanophoxim* (Henan Jinwang Biochemical Co., Ltd., Zhoukou, China), 41% *methiazol* (Jiangsu Longdeng Chemical Co., Ltd., Kunshan, China), 60% *oxystrobin* (Hainan Boshiwei Agricultural Chemical Co., Ltd., Haikou, China), and the special auxiliary agent for the crop protection UAV (Jiangsu Kesheng Group Co., Ltd., Yancheng, China).

2.3. Methods

2.3.1. Investigation on Field Distribution of Wheat Aphids and Plant Characteristics

According to the standard NY/T612-2002 Rules for the investigation and forecast of wheat aphides [28], the diagonal five-point sampling method was used in the field test. The main wheat aphids species in the test site in the flowering stage were *Sitobion avenae* and *Schizaphis graminum*. The quantity of aphids on 50 wheat plants was recorded at each sampling point regardless of the specific species of aphids, and then converted into the quantity of 100 wheat plants. In order to obtain the distribution characteristics of the aphids on wheat plants, the wheat plants were divided into upper, middle, and lower layers according to their physiological characteristics [29]. The upper layer was the part between the spike and flag leaf, the middle layer contained the part between the flag leaf and the third leaf, and the lower layer was the part from the third leaf to the root of wheat (Figure 1). The quantity of aphids was counted every two hours from 7 a.m. to 5 p.m., and the field temperature was recorded at the same time. The canopy height and leaf area index (LAI: one-sided green leaf area per unit ground area) of wheat were measured at each sampling point, and the arithmetic average was used as the LAI and canopy height of the wheat field population.

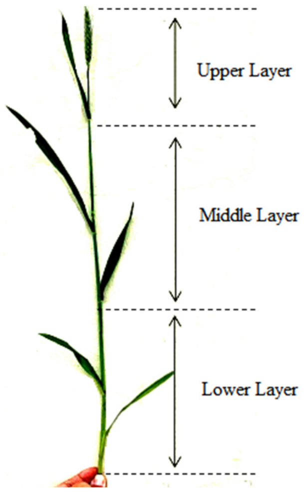

Figure 1. Schematic diagram of wheat stratification.

2.3.2. Droplet Distribution Test of P20 UAV

Operation Parameter Design

According to the operation parameters commonly used in the practical application of the P20 UAV, the FSs were set at four levels: 3, 4, 5, and 6 m/s, and the FHs were set at three levels: 1.5, 2.0, and 2.5 m [19]. According to the standard NY/T3213-2018 Technical specification of quality evaluation for crop protection UAS [30], the SW of the P20 UAV under different operation parameters was measured [19], the specific values of which are shown in Table 3. On this basis, the droplet distribution of the P20 UAV in the SW in the flowering stage was measured. In this test, the dosage per unit area was set as 12 L/ha.

Table 3. Test parameters of P20 UAV.

No.	FS/(m/s)	FH/m	SW Measured/m	SW Set/m	Dosage/(L/ha)
A1	3	1.5	2.96	3	
A2	3	2	2.81	2.8	
A3	3	2.5	2.7	2.7	
B1	4	1.5	2.43	2.5	
B2	4	2	2.31	2.3	
B3	4	2.5	2.2	2.2	
C1	5	1.5	2.13	2.1	12
C2	5	2	2.09	2.1	
C3	5	2.5	1.98	2.0	
D1	6	1.5	2.01	2.0	
D2	6	2	1.88	1.9	
D3	6	2.5	1.79	1.8	

Sampling Point Arrangement

The arrangement of sampling points is shown in Figure 2. Considering that the SW boundary was affected by two adjacent routes at the same time, a total of three routes (R1–R3) were set-up. The sampling points were arranged on the central route (R2), and the central sampling points were coincided with R2. The distance between the adjacent sampling points on both sides was 25% of the SW set. A sampling rod was inserted at each sampling point, and the WSP was clamped on the sampling rod through a universal clamp. In order to ensure that the UAV could spray stably when passing the sampling area, 15 m acceleration and deceleration buffer zones were set at both ends of the route, and three rows of sampling points were set at 10 m intervals in the middle (S1–S3). The arrangement of WSP was divided into upper and lower layers, 15 cm away from the wheat plant canopy and ground, respectively (Figure 3). The WSP was labeled according to the location of the sampling points. After each test, the WSP was collected into sealed bags by the orders of the sampling points when the droplets on them were fully dried, and it was taken back to the laboratory for data reading and processing.

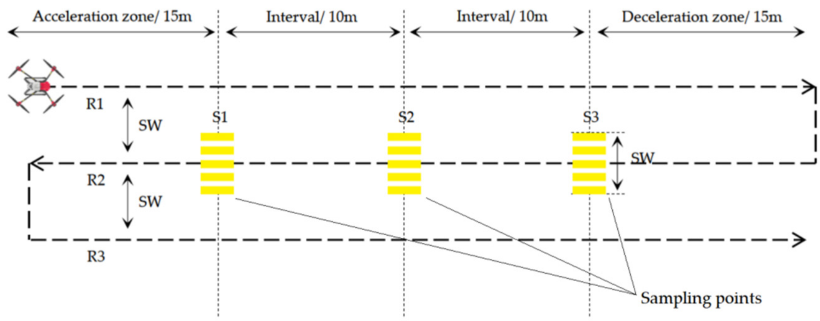

Figure 2. Arrangement of sampling points.

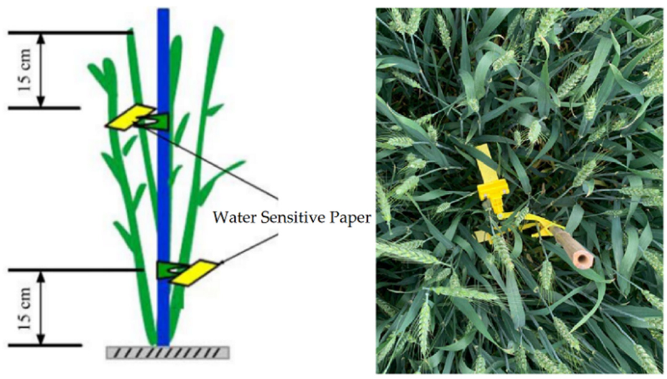

Figure 3. Arrangement of Water-Sensitive Paper [19].

Droplet Distribution Analysis

In the laboratory, the WSP was scanned with the scanner at a resolution of 600 dpi. ImageJ software was used to extract droplet deposits in the digital image for analysis of the droplet coverage density, and the droplet distribution uniformity was further analyzed. The droplet distribution uniformity was evaluated by the coefficient of variation (CV) of the droplet coverage density. The CV of the droplet coverage density was calculated by Equations (1) and (2):

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

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

where S is the sample standard deviation of X_i, X_i is the droplet coverage density at each sampling point, n is the number of sampling points, and $\overline{X}$ is the average of X_i.

2.3.3. Control Test of Wheat Aphids

According to the results of Section 2.3.2, combined with the operation efficiency of the UAV under different operation parameters, the operation parameters were evaluated and screened to determine which parameters would be used in the wheat aphid control test. The pesticides were configured and used according to the requirements of the local crop protection station.

Test Fields and Pesticide Usage Setting

In order to reduce the difference in aphid distribution in the field before application, the tests were conducted in five adjacent wheat fields. The size of each test field was 50 m × 18 m, and the width of the separation zone between the fields was 2 m.

According to the requirements of the local crop protection station, the dosage of pesticides was 20% *cyanophoxim* (0.9 L/ha), 41% *methiazol* (1.2 L/ha), and 60% *oxystrobin* (150 g/ha); the amount of water was about 10 L/ha; the dosage of the special auxiliary agent for the crop protection UAV was 100 g/10 L; these pesticides were well-mixed before use.

Determination of Wheat Aphid Control Effect

The survey and recording of the aphid population were performed in accordance with NY/T612-2002 Rules for the investigation and forecast of wheat aphides [28], the same as that in Section 2.3.1. To investigate the control effect of aphids, the method was used to investigate the aphid number in each test field before spraying and on the 1st, 3rd, and 7th days after spraying. The overall control effect of aphids was quantified without considering the types or growth stages of aphids. The dropping rate and control effect were obtained according to the number of live aphids in each test field before and after spraying, in accordance with Equations (3) and (4):

$$D = ((N_a - N_b)/N) \times 100\% \tag{3}$$

$$CE = (D_a - D_b)/(100 - D_b) \times 100\% \tag{4}$$

where D is the decline rate of the insect mouth. N_a is the number of live aphids before spraying. N_b is the number of living insects after spraying. CE is the control effect. D_a is the decline rate of the insect mouth in the test field and D_b is the decline rate of the insect mouth in the control field.

2.4. Data Statistics and Processing

All data were analyzed by SPSS 22 (SPSS Inc., an IBM Co., Chicago, IL, USA) statistical software and Excel 2016 (Microsoft Co., Redmond, WA, USA). By comparing via the mean one-way ANOVA (one-way ANOVA) method, the LSD (least significant difference) and

Duncan were selected. The interval was set to 95%, and $p < 0.05$ was considered a significant difference between the two groups.

3. Results

3.1. Distribution of Wheat Aphids and Plant Characteristics

Due to the different sampling points, the quantity of aphids on wheat plants varied greatly. Therefore, the proportion of aphids in the upper, middle, and lower layers of wheat was used to describe the distribution of aphids, as shown in Table 4.

Table 4. Aphid distribution on plants in different time periods.

Time	7:00–7:30	9:00–9:30	11:00–11:30	13:00–13:30	15:00–15:30	17:00–17:30
Upper	1.21%	0.81%	0.68%	0.51%	0.42%	0.46%
Middle	8.18%	7.05%	5.11%	3.19%	3.23%	3.11%
Lower	90.61%	92.04%	94.21%	96.3%	96.35%	96.43%
Temperature	13.5 °C	15.2 °C	21.5 °C	23.6 °C	19.5 °C	18.3 °C

It can be seen from Table 4 that in the wheat flowering stage, aphids mainly distributed in the lower layer of the wheat and accounted for more than 90.61%. There were fewer aphids in the upper and middle layers. At the same time, aphids moved little on the wheat plant in a single day. This was mainly because the wheat ears had not grown up yet, and large amounts of nutrients and water were still concentrated in the lower layer of the wheat, while the wheat aphids fed on wort. In addition, the wet environment in the lower layer of wheat provided good living and reproduction conditions for aphids, so aphids generally gathered in the lower layer of the plant (Figure 4).

Figure 4. Distribution of wheat aphids.

The average LAI of wheat in the flowering stage measured by the hand-held LAI instrument was 6.10. The canopy height of wheat was 65.6 cm. The large LAI and the distribution characteristics of aphids (centralized distribution in the lower layer) put forward higher requirements for the droplet distribution in the lower layer of wheat.

3.2. Droplet Depositon in Wheat Canopy

Under different operation parameters, the droplet distribution on the wheat canopy showed great differences. The results of droplet coverage density and the CV of droplet coverage density in the upper and lower layers are shown in Table 5. The change trend is shown in Figure 5.

Table 5. Aphid distribution on wheat plants.

Spraying Date	Treatment	Droplet Coverage Density/(Droplets/cm^2)		CV of Droplet Coverage Density/(%)	
		Upper	Lower	Upper	Lower
22 April 2020	A1	42.04 ± 3.00a	28.53 ± 2.52a	17.07 ± 2.00f	21.00 ± 1.21g
	A2	37.87 ± 2.01ab	24.25 ± 1.88bc	21.20 ± 1.90f	32.30 ± 3.15f
	A3	28.49 ± 2.50de	18.50 ± 2.50def	38.37 ± 4.15cde	43.63 ± 3.85de
	B1	36.49 ± 3.50ab	26.13 ± 2.01ab	21.97 ± 2.36f	37.33 ± 2.08ef
	B2	30.09 ± 1.01cd	21.03 ± 2.00cde	36.30 ± 4.85de	42.30 ± 2.96de
	B3	27.37 ± 4.50def	17.86 ± 1.79ef	44.97 ± 6.40bc	54.17 ± 8.50bc
	C1	34.40 ± 1.40bc	21.53 ± 1.50cd	33.30 ± 2.85e	43.73 ± 3.45de
	C2	24.53 ± 2.50efg	15.65 ± 2.51fg	42.60 ± 4.15cd	49.90 ± 3.25cd
	C3	20.65 ± 2.51gh	9.65 ± 1.52hi	49.83 ± 3.26ab	56.53 ± 5.55bc
	D1	26.07 ± 1.01def	16.01 ± 2.00fg	38.47 ± 1.52cde	49.27 ± 5.90cd
	D2	23.57 ± 3.50fg	12.57 ± 1.91gh	45.27 ± 4.15bc	58.37 ± 5.10b
	D3	16.33 ± 1.53h	8.43 ± 1.51i	54.17 ± 5.05a	67.23 ± 4.80a

Note: Values followed by the same letter in the column do not differ statistically ($p < 0.05$; Duncan's Test).

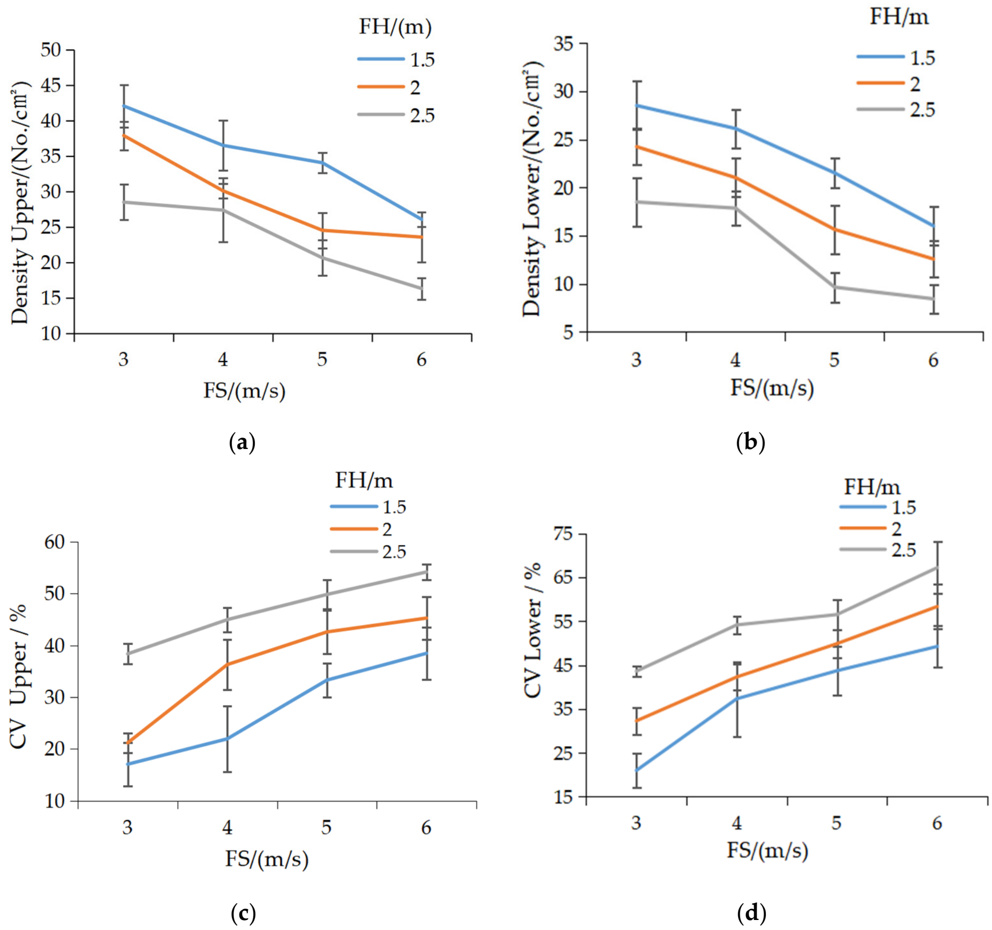

Figure 5. (**a**) Droplet coverage density in the upper layer; (**b**) droplet coverage density in the lower layer; (**c**) CV of droplet coverage density in the upper layer; (**d**) CV of droplet coverage density in the lower layer.

3.2.1. Droplet Coverage Density of Wheat

The droplet distribution on the wheat canopy showed great differences under different operation parameters. The variance analysis results of droplet coverage density in SW are shown in Table 6. The value of sig. indicated the significance of FH and FS factors on the droplet coverage density in the upper and lower layers of wheat during spray operation.

From Table 6, we can see that FH and FS had significant effects on the droplet coverage density in the upper and lower layers.

Table 6. Variance analysis of droplet coverage density.

Factor	Droplet Coverage Density Upper		Droplet Coverage Density Lower	
	Value of Sig.	**Significance**	**Value of SIG.**	**Significance**
FH	5.93×10^{-4}	*	4.6×10^{-5}	*
FS	6.34×10^{-4}	*	3.64×10^{-5}	*

Note: Sig. in the table represents the significance level value of the influence of factors on the results. In this paper, the significance level a = 0.05 is taken [31]. "*" in the table represents that the factors have significant influence on the test results.

As shown in Figure 5a,b, at the same FH, with the increase in FS, the droplet coverage density of WSP in the upper and lower layers showed a downward trend. The maximum droplet density in the upper layer was 42.04/cm^2 (A1 FS: 3 m/s, FH: 1.5 m), and the minimum was 16.33/cm^2 (D3 FS: 6 m/s, FH: 2.5 m/s), with a decrease of 61.2%. The maximum droplet density in the lower layer was 28.53/cm^2 (A1), and the minimum was 8.43/cm^2 (D3), with a decrease of 70.5%. Therefore, in the application process of the crop protection UAV, reducing FS and FH could significantly increase the droplet coverage density in upper and lower layers of wheat.

3.2.2. Uniformity of Droplet Coverage Density

The uniformity of droplet coverage density was measured by the CV of droplet coverage density at each sampling point in SW. The smaller the CV was, the better the droplet coverage uniformity was. Under different operation parameters, the distribution uniformity of droplets in the upper and lower layers of wheat plants showed great differences. The variance analysis results of the CV of the droplet coverage density in SW are shown in Table 7. The value of sig. indicated the significance of FH and FS factors on the CV of droplet coverage density in the upper and lower layers. From Table 7, we can see that FH and FS had significant influence on the CV of droplet coverage density in the upper and lower layers.

Table 7. Variance analysis of CV of droplet coverage density.

Factor	CV Upper		CV Lower	
	Value of Sig.	**Significance**	**Value of Sig.**	**Significance**
FH	2.88×10^{-4}	*	1.02×10^{-4}	*
FS	6.32×10^{-4}	*	4.56×10^{-5}	*

Note: Sig. in the table represents the significance level value of the influence of factors on the results. In this paper, the significance level a = 0.05 is taken [31]. "*" in the table represents that the factors have significant influence on the test results.

As shown in Figure 5c,d, with the increase in the FS and FH, the droplet distribution uniformity gradually became worse, while the value of CV became larger. The minimum value of CV in the upper layer was 17.43% (A1 FS: 3 m/, FH: 1.5 m), and the maximum value was 54.17% (D3 FS: 6 m/s, FH: 2.5 m/s). The minimum value of CV in the lower layer was 24.2% (A1), and the maximum value was 67.23% (D3). Meanwhile, under the same operation parameters, the CV in the lower layer was larger than that in the upper layer. From this analysis, we can see that the reduction in FH and FS could significantly improve the droplet distribution uniformity in the upper and lower layers of the wheat canopy during the spraying operation.

3.3. Control Effect of Wheat Aphids

3.3.1. Operation Parameter Screening for Aphids Control Test

The droplet distribution and operation efficiency under different operation parameters were the reference basis for the selection of operation parameters. Without considering the dosing and operation site conversion of the crop protection UAV, the equation of pure flight operation efficiency of the crop protection UAV is as follows:

$$OE = FS \times SW \tag{5}$$

where *OE* is the pure flight operation efficiency of the UAV, *FS* is the flight speed, and *SW* is the corresponding spraying width.

However, in the actual field operation, due to the different SWs under different operation parameters, the number of flight routes that need to be set for the same field is also different. When switching routes, the UAV will automatically accelerate, decelerate, and reverse, which increases the time for a single operation. Taking a single field (50 × 18 m) as the test site for operation efficiency, the operation efficiency of the UAV under different operation parameters was measured, and the results are shown in Table 8.

Table 8. Actual operation efficiency.

Treatment	FS/ (m/s)	FH/ m	SW/ m	Routes	Flight Time/ s	Operation Efficiency/ (ha/min)
A1	3	1.5	3	6	130	0.042
A2	3	2	2.8	6		
A3	3	2.5	2.7	6		
B1	4	1.5	2.5	7	124	0.044
B2	4	2	2.3	8	142	0.038
B3	4	2.5	2.2	8		
C1	5	1.5	2.1	9	151	0.036
C2	5	2	2.1	9		
C3	5	2.5	2.0	9		
D1	6	1.5	2.0	9	144	0.038
D2	6	2	1.9	9		
D3	6	2.5	1.8	9		

According to the actual operation efficiency under different operation parameters, combined with the droplet distribution on wheat plants, the operation parameters for the control test were selected. In all groups, B1 (FS: 4 m/, FH: 1.5 m) had the highest working efficiency (0.044 ha/min) and A1 (FS: 3 m/, FH: 1.5 m) was the second highest (0.042 ha/min); A1 had the highest quality in coverage density and uniformity of droplets in both layers and B1 was the second highest, so A1 and B1 were selected for the wheat aphid control test.

3.3.2. Control Effect of Wheat Aphids

The control effect of wheat aphids under these two groups of operation parameters is shown in Table 9.

From the results of Table 9, the average control effect of aphids under A1 operation parameters was 92.05% at 7 days after application, that of B1 was 81.75%, and the control effect of A1 was 10.3% higher than that of B1. According to the distribution characteristics of aphids and the analysis of droplet deposition of two sets of parameters in wheat fields, the droplet coverage density in both layers and the uniformity of droplet density in the upper layer had all reached a high level, and there was no significant difference between them, while the droplet distribution uniformity in the lower layer had a significant difference. Therefore, it could be considered that the main reason for the difference in aphid control effect was the uniformity of droplet coverage density in the lower layer of wheat. The control effect of wheat aphids can be significantly improved by increasing the uniformity of the droplet coverage density in the lower layer.

Table 9. Aphid control effect under different operation parameters.

Field	FS/(m/s)	FH/m	N_a/(No./100 Plants)	N_b(No./100 Plants)			Control Effect(%)		
				1 Day	3 Days	7 Days	1 Day	3 Days	7 Days
1	3 m/s	1.5 m	1624	403	175	170	75.6	89.5	90.8
2			1763	525	276	134	71.1	86.9	93.3
3	4 m/s	1.5 m	1526	525	275	325	66.2	82.4	81.3
4			1417	603	317	287	58.2	78.2	82.2
5	CK		1438	1464	1475	1505		/	

Note: N_a is the number of live aphids before spraying. N_b is the number of living insects after spraying.

4. Discussion

Because of the difference in crop LAI and diseases and insect pest occurrence location, in the application of pesticide spraying, the operation parameters should be adjusted and selected to achieve better control effects.

In the research of UAV operation parameters and droplet deposition characteristics, many studies have been carried out on the relationship between FS, FH, droplet coverage density in the upper and lower layer, and the uniformity of droplet coverage density in the upper layer [19–23]. These studies show that reducing the FS and FH of the UAV can improve the deposition coverage density of droplets in the upper and lower layers of crops and the uniformity of droplet coverage density in the upper layer. It is also found that the spray deposits density decreases dramatically from the top to the bottom of the canopies, which is similar to the results of Zhu et al. [32]. There are few studies on the relationship between the uniformity of droplet coverage density in the lower layer and the operation parameters, and the problem of droplet overlap at the junction of SW has not been considered in the arrangement of sampling points. On the basis of previous research results, this paper innovated the droplet sampling method, taking the middle route as the droplet sampling route, concentrating the sampling points in a SW range, and fully considering the overlap of SW ranges in the actual operation process, which could reflect the droplet distribution characteristics in the SW range more accurately in the actual spraying application. In terms of the droplet distribution, it was found that with the increase in FH and FS, not only did the droplet coverage density in the upper and lower layers decrease gradually, but so did the uniformity of droplet coverage density in the upper and lower layers. The increase in FS increased the wind speed in the forward wind field, and the increase in FH lengthened the settling time of droplets in the air, which aggravated the evaporation and drift of droplets during the settling process, thus leading to the decrease in droplet coverage density and the deterioration in uniformity in the upper layer, which are basically consistent with previous research results [33]. The droplet coverage density in the lower layer also dropped with the increase in FS and FH. On the one hand, with the increase in FH, the disturbance of the wind field to the wheat canopy was weakened, which reduced the droplet settlement in the lower layer. On the other hand, with the increase in FS, the time of the wind field acting on the wheat canopy and the exposure time of the lower layer of wheat was shortened, which also reduced the droplet settlement in the lower layer.

The CV of droplet coverage density in the lower layer was mainly related to the disturbance of the crop canopy caused by the crop protection UAV. Xu et al. [34] found that the droplet coverage density in the area below the rotor of the crop protection UAV was largest and gradually decreased to both sides. During the spraying operation, the wind field of the crop protection UAV directly blew to the wheat canopy, which made the wheat canopy circularly open to both sides with the route as the center. The exposed area of the lower layer of wheat was largest in the middle part, and the two sides gradually became smaller. This situation also made the droplet coverage density in the lower layer the highest around the route and the lowest on the edge. At the same FS, with the increase in FH, the wind field acting on the wheat canopy became smaller, the exposure of the lower layer of wheat at the edge of the SW became smaller, and the difficulty of droplet penetration increased. The difference between the coverage density in the lower layer of the edge part and the middle part became larger, which led to the poorer uniformity of droplet coverage density in the lower layer. At the same FH, with the increase in FS, the moving speed of the wind field on the wheat canopy also increased, and the exposure time of the lower layer of the wheat was shortened, especially on the edge of the SW. The shortened exposure time enlarged the difference in droplet coverage density in the lower layer between the boundary part and the middle part of the SW, which made the uniformity of droplet coverage density in the lower layer worse.

In the research of crop protection UAV operation parameters and pest control effects, researchers mainly study the relationship between operation parameters and spray quality. As researchers believe that droplet deposition structure plays a major role in pest control [35,36], the control effect was taken as a means to verify the superiority of spray parameters [24–27], and the research on the characteristics of insect pests and diseases and the targeted optimization of spray parameters are often neglected. In the actual growth process of wheat, the characteristics of wheat plants in different growth stages are quite different, and the occurrence locations and characteristics of different diseases and insect pests are also different. Only by comprehensively considering this situation can the suitable parameters be selected to achieve better control effects. In the flowering stage, the LAI is large and the aphids gather in the lower layer. Only by increasing the coverage density and distribution uniformity of droplets in the lower layer can the control needs be met better. Under the operation parameters of A1 and B1, the droplet coverage density in the upper and lower layers of wheat both reached a large value, and the difference was within 6%, with no significant difference (Table 5). The CVs of droplet coverage density in the upper layer were both less than 22%, which achieved a good uniformity and also showed no significant difference (Table 5). However, in terms of the uniformity of droplet coverage density in the lower layer, A1 was significantly higher than B1, and the CV of A1 was 16.3% lower than that of B1. The droplet distribution uniformity in the lower layer of A1 was much better than that of B1. Aphids were mainly concentrated in the lower layer of wheat in the flowering stage, and the better droplet distribution uniformity in the lower layer could control aphids more effectively; therefore, the average control effect of A1 aphids was 10.3% higher than that of B1 7 days later. It could be seen that for the diseases and insect pests whose harm is concentrated in the lower layer, it is necessary not only to increase the deposition density of droplets in the upper layer and lower layers, but also to improve the uniformity of the droplet distribution in the lower layer, to obtain the ideal control effect.

5. Conclusions

In this study, the P20 four-rotor crop protection UAV was used as the test equipment. Based on the growth characteristics of wheat and the field distribution characteristics of aphids in the flowering stage, the droplet distributions under different operation parameters were tested, and the suitable operation parameters for aphid control were screened with the actual operation efficiency and control effect as the assessment goal. At 7 days after pesticide application, the control effect of A1 on aphids was over 90.8%, which effectively restrained the harm of the rapid propagation of aphids on wheat growth.

Through this test, we found that the droplet distribution characteristics of the crop protection UAV showed great differences under different operation parameters. Generally, the reduction in FS and FH can effectively improve the droplet deposition quantity and the droplet distribution uniformity in crop groups, thus improving the quality of spraying. For the situation where the crop has high LAI and the insect pests are concentrated in the lower layer, it is necessary not only to increase the deposition quantity of droplets in the upper and lower layers, but also to ensure the droplet distribution uniformity in the upper and lower layer, to obtain the ideal control effect. In the actual crop protection UAV pesticide application operation, the quality and efficiency of operation need to be given sufficient attention at the same time. Only by taking both into account can we maximize the advantages of the crop protection UAV in crop protection operations and promote the sustainable development of the crop protection UAV industry.

In different growth stages of wheat, the characteristics of wheat plants and associated diseases and insect pests would make a great difference. In the future, more tests should be carried out to optimize the operation parameters of the crop protection UAV in different growth stages, to ensure the control effect of diseases and insect pests in the whole growth period of wheat.

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

Funding: This research was funded by the China Agriculture Research System of MOF and MARA (grant no. CARS-12); the Agricultural Science and Technology Innovation Project of the Chinese Academy of Agricultural Sciences, Jiangsu Province and Education Ministry Co-sponsored Synergistic Innovation Center of Modern Agricultural Equipment Project (grant no. XTCX1004); Crop Protection Machinery Team (grant no. CAAS-ASTIP-CPMT); Key Research and Development Plan of Jiangsu Province (grant no. BE2020385); the Central Public-Interest Scientific Institution Basal Research Fund (grant no. Y2022XK31).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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

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