



Article

Droplet Deposition and Control of Planthoppers of Different Nozzles in Two-Stage Rice with a Quadrotor Unmanned Aerial Vehicle

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Abstract: Previous studies have confirmed that choosing nozzles that produce coarser droplets could reduce the risk of pesticide spray drift, but this conclusion is based on a large volume of application, and it is easy to ignore how this impacts the control effect. The difference from the conventional spray is that the carrier volume of Unmanned Aerial Vehicle (UAV) is very limited. Little was known about how to choose suitable nozzles with UAV's limited volume to ensure appropriate pest control. Droplet deposition with the addition of adjuvant and the LU110-010, LU110-015, and LU110-020 nozzles and control of planthoppers within nozzles treatments were studied by a quadrotor UAV in rice (Tillering and Flowering stages). Allura Red (10 g/L) was used as a tracer and Kromekote cards were used to collect droplet deposits. The results indicate that the density of the droplets covered by the LU110-01 nozzle is well above other treatments, while the differences in droplet deposition and coverage are not significant. The deposition and coverage were improved with the addition of adjuvant, especially in LU110-01 nozzles' treatment. The control effects of rice planthoppers treated by LU110-01 nozzle were 89.4% and 90.8% respectively, which were much higher than 67.6% and 58.5% of LU110-020 nozzle at 7 days in the Tillering and Flowering stage. The results suggest that selecting a nozzle with a small atomizing particle size for UAV could improve the control effect of planthoppers.

Keywords: droplet deposition; spray nozzle; Unmanned Aerial Vehicle; control of planthoppers

1. Introduction

Rice is one of the most important food crops in the world. The high quality and high yield of rice is of great significance for solving the problems of poverty and hunger. In China, rice cultivation is divided into six areas in terms of climate factors such as sunlight and moisture, and the South China rice cultivation area accounts for 17.6% of the country's total rice cultivation area. Due to abundant

rainfall and long sunshine hours in the growing season, the South China area belongs to a double rice cropping region [1]. Rice planthopper is one of the main pests, including *Nilaparvata lugens* Stal, *Sogatella furcifera* Horvath, and *Laodelphax striatellus* Fallén, which usually gather in the lower layer of rice, consumes nutrients from plants, and affects the growth of rice [2]. Some types of rice planthoppers have no diapause and overwintering characteristics and belong to long-range migratory pests [3]. Rice planthoppers in South China originated from tropical year-round places such as southern Asia and migrate with warm and humid airflow in spring and summer, continuing the migration northward after two generations of early rice breeding in South China [4]. This time is exactly the growth period of early rice in south China, so controlling rice planthoppers is of great significance for rice production. According to statistics from the Chinese Ministry of Agriculture and Rural Affairs in May 2019, rice planthoppers affect 62 million acres in China, and 47.3 million acres need to be controlled. The occurrence of rice planthoppers in South China is the most serious in the country [5]. How to effectively and quickly control rice planthoppers is an urgent problem that farmers need to be concerned.

In recent years, using agricultural drones for crop disease and pest control has developed rapidly in China [6,7]. With the development and improvement of real-time kinematic high-precision positioning technology and flight control technology, almost all agricultural drones have achieved fixed altitude and fixed velocity. In addition, the application of obstacle avoidance technology and terrain following technology has improved the safety and accuracy of drone operations [7–9]. The applicator could be separated from the tanks by UAVs, which could minimize the safety risks of pesticides to the applicator. In addition, there is high operating efficiency in UAVs. The average single operation can reach 0.8–2.8 hectares under different power [6]. Some researchers have studied how to choose suitable operating parameters for different crops and pests with UAV. Chen et al. [10] and Wang et al. [11] reported that drone flight speed and height have a significant effect on the deposition between crop canopies. Qin et al. [12] explored the effects of drone flying height and speed on spray penetration and deposition uniformity of rice canopy. Their results showed that when the flight speed is 5 m/s and the height is 1.5 m, the maximum deposition volume can be obtained in the lower layer of rice canopy and the deposition distribution is better. This study was limited by the drone's flight speed and height instability at that time, but the test results provided data supporting the selection of drone operating parameters. Qin et al. [13] reported better droplet coverage and distribution uniformity for applications using N-3 oil-powered drones at 3.5 m flight height and 4 m/s flight speed. Wang et al. [14] studied the effects of spraying volume on UAV application efficacy, and the results showed that better control of wheat diseases and insect pests were achieved when using coarse droplet size and higher spray volume ($>16.8 \text{ L ha}^{-1}$). However, using different nozzles to obtain different spraying volume actually changed the droplet size in this study. Fang et al. [15] reported that with the increase of the spraying volume of UAV, the residual volume of defoliant in cotton increased. When the spraying volume was lower than 17.6 L/ha, the residual volume was the lowest. Subsequent studies have shown that considering the effects of drift and droplet deposition, the drone's flight speed in the field environment should be less than 6 m/s, and the flight height should be 2 m above the crop canopy [16].

Previous studies focus on the selection of drone parameters. The results have confirmed the feasibility of UAV ultra-low-volume spraying for pest control of crops and promoted the popularization and application of UAV in pest control [7]. However, spraying volume in UAV applications is still limited by the load capacity of the tank. Compared with ground equipment, the biggest difference is the volume of pesticide sprayed per unit area. The average application of ground application equipment (knapsack-type sprayer and boom sprayer) in dry crops (wheat and cotton) is 300–450 L per hectare, and 750 L/hectare was used by stretcher-mounted sprayer in rice, while the average application of drone is 15 L–30 L currently in China [12,14,15,17,18]. Spraying limited volumes while ensuring proper application coverage and pest control is a challenge for UAV applications.

Nozzles and adjuvants are important factors affecting the droplet deposition distribution [19,20]. The addition of adjuvants including surfactants, spreaders, stickers, deposition aids, activators,

humectants, antifoamers, wetting agents, and drift reduction agents etc., can alter spray performance such as the target deposition, spray droplet size, and deposition characteristics [21]. Surfactants in adjuvants could reduce droplet surface tension, which decrease the contact angle between the droplets and the epicuticular wax layer for better droplet contact [22,23]. In addition, the density of droplets has a strong correlation with the type of nozzle and directly affects pest control. Appropriate selection of nozzles and operating parameters could improve the control effect of pests and diseases, while reducing drift and promoting the penetration of droplets in the canopy [20]. Due to the lack of dedicated nozzles currently for UAVs, flat fan nozzles are the most widely used hydraulic nozzles [24]. These nozzles can produce a uniform and stable fan-shaped spray. The spray edges of flat fan nozzles gradually taper, and a narrow spray band is formed when spraying vertically on the ground [25]. However, whether different atomizing particle diameters and adjuvant affects the droplet deposition and the control of pests under the influence of the UAV rotor wind field needs to be further clarified.

In this study, three groups of hydraulic nozzles LU110-01, LU110-015, and LU110-020, which are commonly used in current UAVs [6,7], were selected. The droplets' deposition between the Tillering stage and the Flowering stage of rice and the control effect of rice planthopper were discussed. The objectives of this study were to (1) study the droplet deposition effect between nozzles and adjuvant at the same application volume, and (2) study the control effect of rice planthoppers between nozzles' treatments by ultra-low-volume spray.

2. Materials and Methods

2.1. Field Plots

The test site was located in Taishan City, Guangdong Province (N 22°06'15.12", E 112°47'18.36"). The tested rice variety was Xiangyaxiangzhan, the planting date was April 15 2019, and the planting density was 180,000/ha. The two trials were carried out on May 10 and June 10 2019, which is the season for controlling the rice planthoppers, and the corresponding rice periods were Tillering and Flowering. The average crop height for the Tillering and Flowering rice stages were 65 and 90 cm, respectively. Rice canopy leaf area index were 1.5 and 2.2 for Tillering and Reproductive rice stages respectively, as measured using a CI-100 Plant Canopy Imager (CID Bio-Science, Inc. Camas, WA, USA).

2.2. UAV and Reference Equipment Selection

The drone flight platform is a quadrotor electric plant protection drone-Freedom Eagle 1s (Figure 1, Anyang Quanfeng Aviation Plant Protection Technology Co. Ltd. Anyang, China). This drone has a Global Positioning System (GPS) fully autonomous flight function, which can plan the flight area in the mobile app, set the flight speed, height, and other factors to achieve one-key take-off (Table 1). During the operation, the drone is able to continue to spray pesticide at the breakpoint. The accuracy of the flight height and velocity were controlled within 0.2 m and 0.3 m s⁻¹, respectively. The spray system includes a micro-diaphragm pump (Pulandi Electromechanical Equipment Co., Ltd., Shijiazhuang, China), and 4 hydraulic nozzles (Lechler Inc. Metzingen, Germany). When the height from the canopy is 1.5 m, the effective spray width is 3.5 m.



Figure 1. Freedom Eagle 1s Unmanned Aerial Vehicle (UAV).

Table 1. UAV technical parameters.

Classification	Parameters
Total Weight (kg)	12 ± 1
Size (m)	1.37*1.37*0.65
Battery capacity (mA)	16,000*2
Working efficiency (ha)	0.7–1.0
Runtime (min)	≥10
Operation method	Remote Control or Mobile
Boom length (cm)	90.5
height above crop canopy (m)	1–3
Number of nozzles	4
Unit flow (L/min)	1.92–2.36
Load capacity (L)	10
Spraying width (m)	3–5

According to the Xuan's research [26] and the practical recommendation of the application operator, the application volume of the drone was 15 L/ha. The nozzles used in the test were LU110-01, LU110-015, and LU110-020, and their flow rates were corrected under the pressure of 250 KPa based on the principle of the same spraying volume (Table 2). In terms of formula 1, the spraying speeds are 3.3 m/s, 5 m/s, and 6.1 m/s, respectively.

$$q = \frac{QVD}{600} \quad (1)$$

where Q is spraying volume per unit area (L/ha), q is flow rate of total nozzles (L/min), V is flying velocity (km/h), and D is effective spraying width (m).

Table 2. UAV spray operation parameters.

Nozzles	Flow Rate of Total Nozzles (L/min)	Spraying Volume (L/ha)	Height (m)	Velocity (m/s)	Spray Width (m)
LU110-01	1.04	15	1.5	3.3	3.5
LU110-015	1.58			5	
LU110-02	1.93			6.1	

2.3. Experimental Treatment

The experiment was divided into two processes: spray deposition test and control effect of rice planthoppers test. All experimental tests are carried out in a fixed area, zone a, b, c, and d, where zone a, b, and c correspond to the different nozzle treatments, and where zone d was used as a blank control in control effect of rice planthoppers test. Each zone was conducted in 2400 m² (20 *120 m) field with 10 m between each treatment as a buffer zone.

2.3.1. Characterization of Spray Deposition

The six treatments (Table 3) were applied on May 10 and June 10, respectively. 1% methylated vegetable oil adjuvant (Anyang Quanfeng Biological Technology Co. Ltd. Anyang, China) was added in treatments 1, 3, and 5, and only water with tracer was used in treatments 2, 4, and 6. Each nozzle treatment (LU110-01, LU110-015, LU110-02) correspond to zones a, b, and c. Artificial samplers were placed at equally spaced sample sites across the center of each zone. Each sample site was 1 m apart and spanned a total of 10 m. The sample sites were repeated two times along the spray direction, with an interval of 10 m between each repetition (Figure 2). The artificial samplers were fixed on a single part of the Tillering stage, and double parts (upper layer and lower layer) of Flowering rice in accordance with the height of rice (Figure 3).

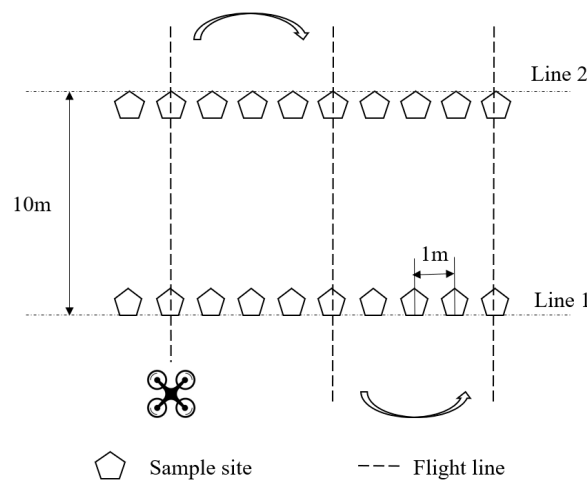


Figure 2. Experimental layout of each plot, in relation to the UAV sprayer.

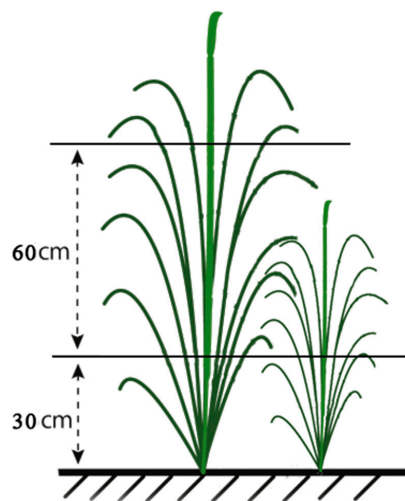


Figure 3. Artificial samplers at each sampling position within the two-stage rice canopy.

Table 3. Treatments in spray deposition test.

Treatment	Zone	Nozzles	Add Adjuvant
1	a	LU110-01	Y
2			N
3	b	LU110-015	Y
4			N
5	c	LU110-02	Y
6			N

Allura Red (Zhejiang Jigaode Pigment Technology Co., Ltd, 10g/L) was used as a tracer and Kromekote card (Elifo paper Co., Ltd, Beijing, China) as a droplet test card [27]. Different from water-sensitive paper, the Allura Red itself has a color. When the droplets drop on the Kromekote card, there would be a mark produced [28]. The Kromekote card was carefully picked down using clean tweezers and sealed in Ziploc bags for qualitative analysis, i.e., droplet deposition, coverage, and droplet density. The collected samples were analyzed in the laboratory of the National Center for International Collaboration Research on Precision Agricultural Aviation Pesticides Spraying Technology (NPAAC), South China Agricultural University.

The droplet deposition, coverage, and density are important parameters of droplet deposition [29]. Kromekote cards were scanned at a resolution of 600 dpi with a scanner, and imagery software DepositScan (USDA, Wooster, OH, USA), was utilized to extract and analyze the droplet deposition, coverage, and deposits on the Kromekote card. The ratio of the pixel number of the droplets covered to the analyzed zone gives the coverage of the droplets on the sample card. The droplet density refers to the number of droplets per unit area on the crop surface and is usually expressed as the number of droplets per square centimeter.

2.3.2. Control Effect of Rice Planthoppers Test

Four treatments (treatment 1, 3, 5, and blank control) were applied on May 10 and June 10 respectively, which were consistent in zone a, b, c, and d. DuPont™ Exirel™ Insect Control 900 ml/ha were sprayed with Freedom Eagle 1s.

The survey and recording of rice planthoppers were carried out according to pesticide field efficacy test criteria. In each part of the zones a, b, c, and d, a parallel jump method was used for investigation. Each area selected 30 clumps of rice as a survey sample and patted the base of the rice by hand. The overall control effect against rice plant hopper was calculated without regard to the types or instar of rice plant hopper. Based on the spray application and incidence of the blank control, six assessments of plant hopper were carried out during the tests. The first assessment was carried out prior to the first spray application on 9 May, and the second and third assessments were carried out on 11 and 17 May. The tests were also carried out 1 and 7 days after the second spraying.

$$R(\%) = \frac{PT0 - PT1}{PT0} \times 100 \quad (2)$$

where R is the dropping rate of insects, PT0 is the number of live insects before spraying, and PT1 is number of live insects after spraying.

$$E(\%) = \frac{R_{PT} - R_{CK}}{1 - R_{CK}} \times 100 \quad (3)$$

where E is the correction control effect, R_{PT} is the dropping rate of insects in the spraying zone, and R_{CK} is the dropping rate of insects in the controlled zone.

2.4. Nozzle Droplet Size Test

The droplet size distribution of LU110-01, LU110-015, and LU110-02 with water were tested in NPAAC. Data acquisition and calculation of droplet size were performed using a DP02 laser particle size analyzer (Euro-American Instrument Co., Ltd, Zhuhai, China). The nozzle height was 0.6 m, and the distance between the transmitter and receiver of the laser particle size analyzer was 1.2 m. The temperature was 32 °C, the relative humidity was 60%, and the pressure was 250 KPa. Each test was repeated three times.

2.5. Environment Test

The environmental parameters were collected by the kestrel weather station (Model NK-5500, Nielsen-Kellerman Co., Boothwyn, PA, 209 USA) with a collection frequency of 2 s, and include temperature, humidity, wind direction, wind speed, etc. The results showed that the temperature and humidity conditions remained relatively stable during the test from Table 4. The natural wind was the transverse wind perpendicular to the route. The average wind speed was less than 6 m/s, which met the requirements of drone operations [16,26].

Table 4. Meteorological parameters.

Date	Treatment	Mean Temperature °C	Mean Humidity %	Mean Wind speed m/s
May 10	1,2	28.8 ± 0.10	72.4 ± 0.45	1.1 ± 0.30
	3,4	29.3 ± 0.23	69.0 ± 0.55	0.9 ± 0.21
	5,6	29.4 ± 0.30	73.4 ± 1.30	1.1 ± 0.42
June 10	1,2	30.5 ± 0.35	82.7 ± 0.69	1.5 ± 0.52
	3,4	29.9 ± 0.21	83.5 ± 1.20	1.1 ± 0.83
	5,6	29.7 ± 0.19	85.1 ± 1.75	1.7 ± 0.75

2.6. Statistical Analysis

Statistical Product and Service Solutions (SPSS v. 25.0, SPSS Inc., Chicago, IL, USA) was used for all statistical analysis. A *p*-value of <0.05 was considered to be statistically significant. No adequate way to transform the droplet deposition, droplet density and coverage results into a normally distributed dataset was found. For this reason, the non-parametrical Kruskal–Wallis tests were used to analyze deposition data [30]. The data (dropping rate of insect and control efficacy) were compared by analysis of variance (ANOVA). Duncan’s multiple comparisons was used for multiple comparisons.

3. Results

3.1. Droplet Size Distribution

The results from the DP02 laser particle size analyzer showed that the droplets DV0.5 value of LU110-01, LU110-015, and LU110-02 was 132.8, 146.6, and 167.0 µm, respectively (Table 5). The Dva values are the droplet diameters (µm), where (a × 100)% of the spray volume is contained in droplets smaller than this value. DV0.5 means interchangeably VMD (Volume Median Diameter), which is a recognized factor of the quality of spraying [31]. The droplet sizes were classified based on the ASAE (American Society of Agricultural Engineers) S-572 standard.

Table 5. Droplet size distribution results.

Nozzles	D _{V0.5} µm	D _{V0.1} µm	D _{V0.9} µm	Droplet Classification
XALU110-01	132.8 ± 5.2	63.7 ± 1.1	180.2 ± 2.1	Fine
LU110-015	146.6 ± 3.8	63.5 ± 3.2	197.6 ± 1.9	Fine
LU110-02	167.0 ± 6.7	67.4 ± 2.1	222.4 ± 3.2	Fine

3.2. Droplet Deposition

Figure 4 shows the spray deposition of LU110-01,015,02 nozzles in two periods. There was no significant difference in the distribution of deposition amount between rice canopies at each nozzle treatment ($p > 0.079$). The amount of deposition slightly increases from LU110-01 to LU110-02 in the Tillering stage, while there was no difference in the Flowering stage. LU110-01 nozzle with adjuvant obtained a larger droplet deposition amount of $0.32 \mu\text{l}/\text{cm}^2$ on the upper layer, and LU110-015 had the smallest droplet deposition amount on the lower layer, only $0.08 \mu\text{l}/\text{cm}^2$. With the addition of adjuvant, the droplet deposition of the Tillering stage and upper layer of the Flowering stage (TY with LU110-01,02; FY with LU110-01,015,02) increased significantly, while slight changes were obtained in the lower layer. Especially in LU110-01 nozzle treatment, deposition amount was increased from $0.24 \mu\text{l}/\text{cm}^2$ to $0.41 \mu\text{l}/\text{cm}^2$ with adjuvant in the Tillering stage.

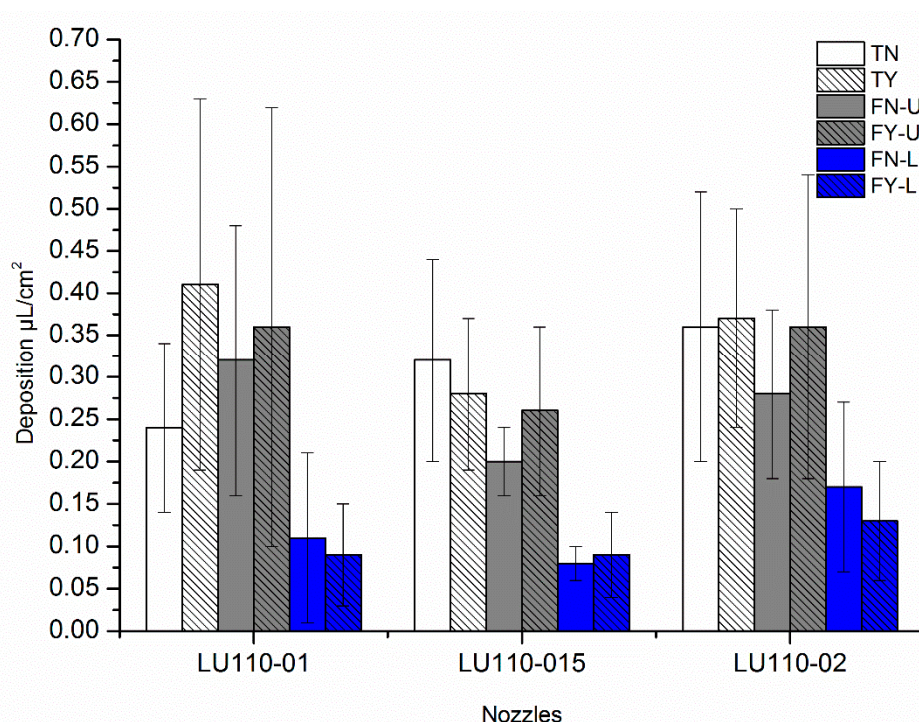


Figure 4. Droplet deposition under different nozzles in two-stage rice. Where TN is the treatment of Tillering stage without adjuvant, TY is the treatment of Tillering stage with adjuvant, FN-U is the treatment of Flowering stage without adjuvant (upper layer), FY-U is the treatment of Flowering stage with adjuvant (upper layer), FN-L is the treatment of Flowering stage without adjuvant (lower layer), and FY-L is the treatment of Flowering stage with adjuvant (lower layer).

3.3. Droplet Density

According to the Kruskal–Wallis test, the type of nozzle has a significant effect on the droplet coverage density of each treatment ($p < 0.001$). There is a significant difference between the nozzle type LU110-01 with LU110-015 and LU110-02, and no difference between LU110-015 and LU110-02. LU110-01 had the largest droplet density in the upper and lower layers of rice in the Flowering stage, and LU110-015 had the lowest value in the Tillering stage, which were 35.48 and $7.37/\text{cm}^2$, respectively. As shown in Figure 5, the droplet covering density increases in turn as the nozzle's atomizing particle size decreases. Consistent with the change in the amount of droplets' deposition, the density of the droplets in the upper layer of the canopy is twice that of the lower layer (Figure 5 FN-U and FN-L, FY-U and FY-L). Existing standards [16] for the coverage of spray droplet density of UAV sprays believe that the density of droplet coverage per square centimeter should reach 15 or more. According to this standard, the coverage densities of LU110-015 and LU110-02 in the lower layer of rice canopy cannot

meet the requirements (Figure 5, FN-L and FY-L). Adding adjuvant has little effect on the density of droplets (Figure 5, TN and TY, FN-U and FY-U, FN-L and FY-L).

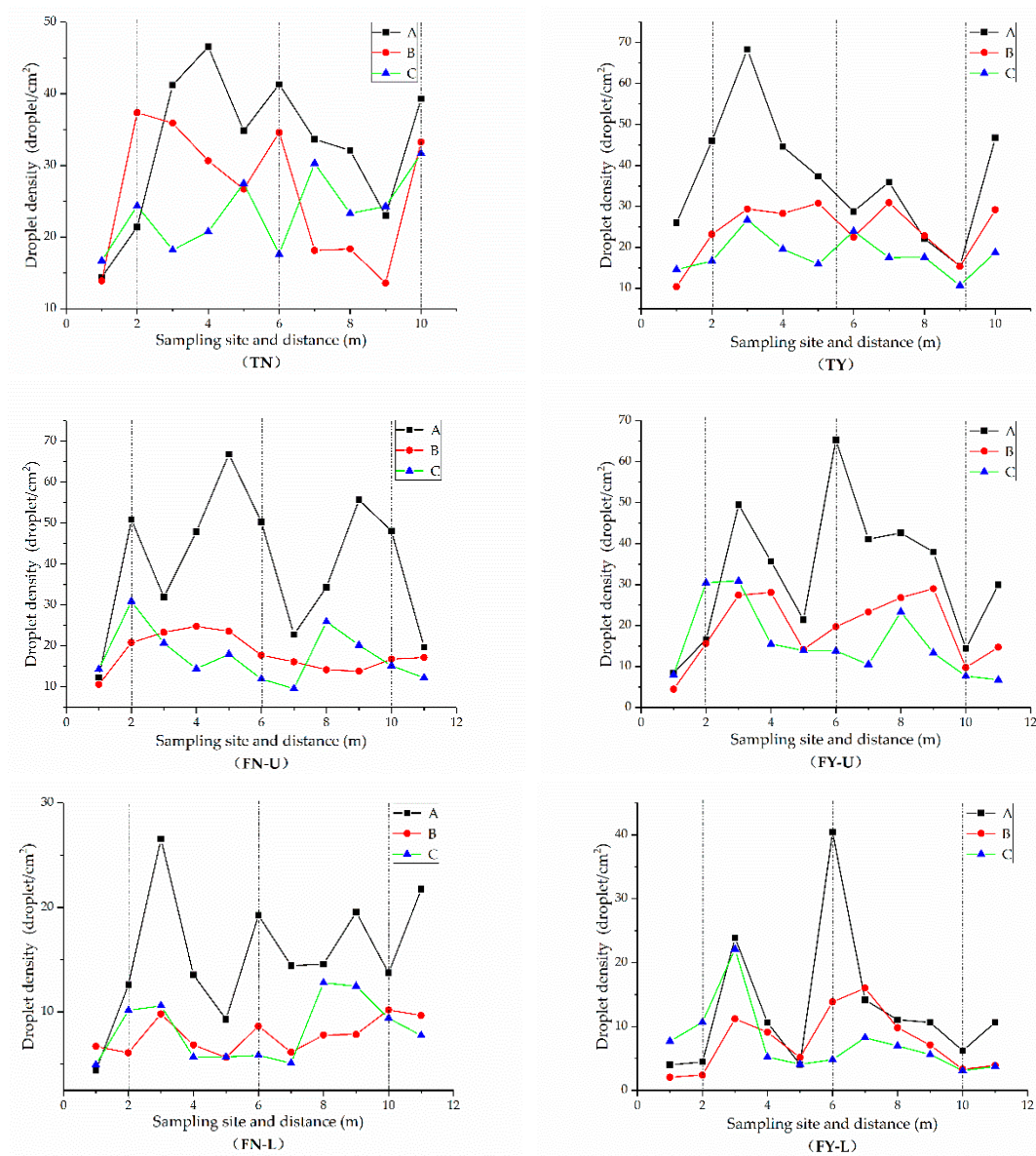


Figure 5. Droplet density under different nozzles in two-stage rice. Where A, B, and C is treatment of LU110-01, LU110-015, and LU110-02 respectively.

3.4. Coverage

There was no significant difference in the coverage between the nozzle treatments at a significant level of 0.05. However, there is a certain difference in the coverage between rice canopies. The droplet coverage in the upper layer of rice is much higher than that in the lower layer in the Flowering stage. The LU110-02 nozzle treatment achieved the highest coverage in the upper and lower layers, 4.94% and 1.96%, respectively (Table 6). With the addition of adjuvant, the coverage of all the treatments were obviously improved, except treatments 4 and 6 in the Tillering stage. The coverage of LU110-01 nozzle treatment reached the maximum in all treatments, which was 6.11%.

Table 6. Coverage of all the treatments in two-stage rice.

Treatment	Tillering Stage	Flowering Stage	
		Upper layer	Lower layer
1	4.16 ± 1.7	4.88 ± 2.5	1.64 ± 1.4
2	6.11 ± 2.7	5.47 ± 3.5	1.67 ± 1.1
3	4.86 ± 1.6	3.15 ± 0.6	1.24 ± 0.3
4	4.31 ± 1.4	3.88 ± 1.6	1.42 ± 0.8
5	4.94 ± 2.1	3.79 ± 1.4	1.96 ± 1.2
6	4.81 ± 1.4	4.60 ± 2.2	2.01 ± 1.1

¹ According to results of the Kruskal–Wallis test, all the treatments were $p > 0.374$.

3.5. Control Effect of Rice Planthoppers

Control efficacy (%) of rice planthoppers evaluated at 1 and 7 days after two applications are shown in Table 7. There was no significant difference in the dropping rate of insects and control effect of the rice planthoppers on the first day after the treatment. Whereas there was a significant difference between the nozzle control LU110-01 and the nozzle LU110-02 on the seventh day. On the first day after first spray, the dropping rate of insects of all the treatments was above 91%, which reflected the control effect on rice planthoppers. From the perspective of the control effect, the LU110-01 nozzle treatment obtained the best control in two applications, which were 89.4% and 90.8% respectively, at 7 days, which was significantly better than the LU110-015 and LU110-02 nozzle treatments.

Table 7. Control efficacy of rice planthoppers.

	Period	Date	LU110-01	LU110-015	LU110-02
Control efficacy	Tillering stage	1d	84.8 ± 4.3 a	80.3 ± 5.6 a	81.4 ± 4.9 a
		7d	89.4 ± 4.7 a	74.4 ± 9.8 ab	67.6 ± 19.9 b
	Flowering stage	1d	23.6 ± 12.7 a	32.0 ± 11.3 a	21.2 ± 27.5 a
		7d	90.8 ± 8.4 a	78.3 ± 12.7 ab	58.5 ± 18.9 b
dropping rate of insects	Tillering stage	1d	93.7 ± 1.3 a	92.2 ± 1.7 a	91.4 ± 2.0 a
		7d	94.8 ± 1.1 a	88.2 ± 2.3 ab	84.7 ± 6.5 b
	Flowering stage	1d	42.6 ± 9.5 a	48.9 ± 8.5 a	40.8 ± 20.7 a
		7d	88.9 ± 10.2 a	73.5 ± 15.4 ab	49.4 ± 23.1 b

¹ Data followed by different small letters in the same rows are significantly different among different treatments at $p < 0.05$ by Duncan's multiple comparisons.

One day after the second spray, the dropping rate of insects of each treatment was less than 50%, which may be related to the occurrence of small-scale rainfall in the area 8 hours after spraying. The high humidity environment after the rain was conducive to the reproduction and spread of rice planthoppers. Because the pesticide used in the test was a systemic pesticide, and the density of the rice planthoppers was not significantly higher than that before the treatment, there was no supplementary spray. At seven days after treatment, the effects of each treatment were quite different. The efficacy of LU110-01 nozzle treatment is 90.8%, but LU110-02 nozzle treatment is less than 58.5%.

4. Discussion

The results showed that the droplet density between the nozzles are significantly different, and there are no significant differences in deposition and coverage between nozzles. Droplet number densities were strongly correlated to the droplet size categories of the nozzles. Where the smaller the $Dv0.5$, the greater the droplet number density [32,33]. In addition, in Wolf's study, multiple nozzle types (Fine, Medium, Coarse) were compared in four laboratory trials and one field trial [20]. They concluded that significant differences were found among compared nozzle treatments in the amount of coverage attained in the bottom of the soybean canopy except the lower application volume (140 L/ha). In his study, there were no significant differences in deposition and coverage with lower

application volume, corroborating the findings from this study. The application volume of the drone was 15 L/ha, which is far from 140 L/ha. So, there is a little impact on deposition and coverage between nozzles under ultra-low volume spray.

In this study, the deposition and coverage were improved with the addition of adjuvant, especially in the LU110-01 nozzles treatment. Previous studies reported that plant oils in adjuvants may increase the viscosity of the spray and reduce the number of small droplets, so they would reduce the smaller droplets move off-target, and improve deposition in artificial samplers [21,22,34]. There are lower percentages of smaller droplets in the LU110-02 nozzle than the LU110-01 nozzle in this study, so a slight change was observed with the addition of adjuvant in these treatments.

There was a strong correlation between the droplet density and the control effect of rice planthoppers in this study. In the LU110-01 nozzle treatment, the control effect of rice planthoppers was consistent with the effect of the density of droplets deposited on rice, which were better than other treatments. Gu explored the influence of droplet densities and spray methods on the efficiency of chlorpyrifos against brown planthopper [35]. His results showed that when the coverage density of the fan nozzle TP6501E was increased from 7.7/cm² to 55.4/cm², the control effect of brown planthopper was increased from 71.88%, 74.61%, and 77.11% to 90.58%, 92.12%, and 92.78%, with 48% chlorpyrifos EC 41.21, 51.52, 61.82 mg/m², respectively. He considered that high droplet density can ensure satisfactory efficiency at low doses when sprayed laterally. Prokop [36] studied the influence of droplet spectra on the efficiency of contact fungicides, whose results suggest that as the number of droplets per unit area increases, the disease prevention effect increases at the same time, which is consistent with the results of this study.

Rice planthoppers' stings harm rice crown plexus, and carry plant virus disease, which affects the normal growth of rice, causing rice plant roofing in severe cases [37]. Most rice planthoppers live in the base of the stem of rice. Therefore, in the chemical control, spray deposition should reach the bottom canopy layers of rice. However, existing studies have found that during the application of UAVs, the canopy penetration is poor, and the droplet deposition in the lower canopy is lower than that in the upper canopy [38]. The average droplet density in the upper layer was 23.38/cm², while the deposition in the lower layer was only 10.60/cm² in this study. How to improve the effect of droplet distribution by UAVs in the lower and middle layer of the crop is worthy of discussion. The solution proposed in this research is to use a nozzle with a small particle size, which can ensure a high droplet density in the middle and lower layers. In addition, Xu et al. [33] considered that when the amount of application liquid increased from 300 L/hectare to 900 L/hectare, the density of the droplets sprayed by the four nozzles ST11001, ST11002, TR8001, and TR8002 at the base of rice increased by 8.21, 8.54, 7.79, and 9.69 times, respectively. He et al. [38] indicated that increasing the amount of liquid application can significantly increase the droplet deposition density and adding spray adjuvant (plant oils) can significantly increase the droplet deposition amount and effective deposition rate. Existing studies have shown that increasing the volume of spray according to the state of the canopy could also improve droplet coverage. Emilio Gil [39] designed a mobile app model DOSAVIÑA. This tool could recommend a suitable spray volume based on the canopy structure of the vine, and even spray pressure, operating speed, and the number and type of nozzles for some fruit trees. This research not only explored the effect of droplet coverage between crop canopies, but also helped to reduce the amount of pesticide application and provide decision support for precise application. Wang et al. [14] reported that spray volume and nozzles significantly influenced the control efficacy of both the UAV and electric air-pressure knapsack sprayer, but the study did not distinguish between the spray volume and the type of nozzles. Future research should be focused on the relationship between the type of nozzles and the volume of application liquid on the canopy deposition effect, and establish the correlation between the canopy structure, the volume of application liquid, and the type of nozzles to achieve the best management practice.

5. Conclusions

In this study, the same spraying volume was used to compare the effect of droplet deposition and control of rice planthoppers of different nozzle treatments (LU110-01, LU110-015, and LU110-02) by UAV during the Tillering and Flowering stages of rice. The results showed that the droplet density between the nozzles are significantly different. The density of the droplets covered by the LU110-01 nozzle were well above other treatments, and the differences in deposition and coverage were not significant. The deposition and coverage were improved with the addition of adjuvant, especially in the LU110-01 nozzles' treatment, while little effect was observed on the density of droplets. The amount of droplet deposition in the lower layer of rice is only 30% of the upper layer, and the density of the droplet coverage is 50% in the Flowering stage. The control effects of rice planthoppers treated by the LU110-01 nozzle were 89.4% and 90.8% respectively, which were much higher than 67.6% and 58.5% of LU110-020 nozzle at seven days in the Tillering and Flowering stages. Therefore, it is considered that, without considering the risk of drift, the LU110-01 nozzle can be used to obtain better deposition distribution and rice planthoppers control effects.

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