

# Deposition and biological efficacy of UAV-based low-volume application in rice fields

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**Abstract:** Efficient and accurate application of pesticides can improve biological efficacy, reduce insecticide resistance, and protect the environment. The rapid development of unmanned aerial vehicles (UAV) technology as a new method of pesticide application using low spray volumes demands scientific evaluation compared to conventional practices. The objective of this research was to analyze the effects of spray volume and tank-mix adjuvants on droplet deposition, canopy penetration, and control of rice blast disease and rice leaf roller when applied by UAV technology on rice. An electric backpack sprayer was used as the standard method of application for comparison. Increasing the spray volume and adding an adjuvant significantly increased droplet density, percentage of spray coverage, and control of rice blast and rice leaf roller for the UAV application. The control efficacy of the UAV sprayer was basically equal to or slightly worse than the backpack sprayer. These data indicate that a UAV application made at a spray volume of 18 L/hm<sup>2</sup> with the addition of a methylated crop oil adjuvant at panicle initiation provided excellent blast and leaf roller control.

**Keywords:** UAV, adjuvant, biological efficacy, deposition, low-volume spray, rice

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## 1 Introduction

Use of pesticides has played an important role in the control of agricultural crop pests and the increase of food production<sup>[1]</sup>. In 2018, the export and consumption of pesticides in China were nearly 2.1 and 1.5 million tons, respectively, which makes China the largest pesticide producer and consumer in the world<sup>[2]</sup>. However, according to statistics from the Ministry of Agriculture and Rural Affairs of China, the deposition rate of pesticides was very low only 39.8% in 2019<sup>[3]</sup>. Inefficient use of pesticides leads to reduced pest efficacy, increased pesticide usage, pest resistance, and health and environmental risks.

The deposition rate of a pesticide is closely related to the application equipment. In Europe, ground applicators are mainly used, including tractor-mounted or self-propelled boom sprayers for row crops and air-assisted sprayers for orchards<sup>[4,5]</sup>. In countries with large farmlands such as Brazil, Australia, Canada, and the United States, large-scale, manned aviation spray equipment plays an important role in agrochemical application<sup>[6]</sup>. In just a few years, there has been a large increase in the use of unmanned aerial vehicles (UAVs) in agriculture, especially in Asian countries<sup>[7]</sup>. According to the Statistics of the Chinese Ministry of Agriculture, in 2019 the number of UAV sprayers was close to 50,000, and the operating area was approximately 30 million hectares. Among them, multirotor drones occupied the dominant position in the market.

The rapid popularity of drone technology and the significant increase in sprayed area as well as pesticide quantities has spurred additional research on the use of UAV's for pesticide application. Regarding spray parameter optimization, Qin et al.<sup>[8]</sup> reported that droplet deposition and distribution were closely related to release height and drone velocity, which also affected insect control. In his research, the droplet deposition of HyB-15L UAV (Gaoke Xinnong Technology Co., Ltd., Shenzhen, China) in the lower layer of rice was maximized with a spraying height of 1.5 m and spraying velocity of 5 m/s. Wang et al.<sup>[9]</sup> compared three UAV spray volumes using different nozzles on droplet deposition and pest and disease control efficacy. The conclusion from this study was that the UAV had a comparable deposition and efficacy control at a higher spray volume (>16.8 L/ha) with coarse nozzles. Other

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deposition studies mainly include optimization of parameters on various crops, such as fruit trees<sup>[10,11]</sup>, rice<sup>[12,13]</sup>, and maize<sup>[14]</sup>. According to previous research, the optimum application parameters of different UAVs may vary by crops. In addition to droplet deposition, the drift of small droplets from low volume UAV application has also aroused some concern<sup>[15]</sup>. Wang et al.<sup>[16]</sup> conducted a drift test using a gasoline-powered, single rotor, unmanned helicopter in a pineapple field under various meteorological conditions and found that 90% of the total spray drift was from 3.7 m to 46.5 m. This result was slightly different from that of Xue et al.<sup>[13]</sup>, whose study on single rotor UAV showed 90% of drift droplets were located within a range of 8 m downwind under a wind speed of 3 m/s. With the rapid development of multirotor UAVs, drift tests and simulation analyses from field experiments and FLUENT computational fluid simulations are also crucial. Teske et al.<sup>[17]</sup> used merging algorithms for spray transport with CHARM (Comprehensive Hierarchical Aeromechanics Rotorcraft Model) and AGDISP (AGricultural DISPersal) models to predict the deposition and drift released from a commercial multirotor UAV. The following conclusions can be drawn from their simulations: flight speed was critical, and effectiveness of the spray was compromised above a critical speed. In addition to the flight parameters, the influence of spray volume on deposition and pest control efficacy are also important. However, few studies testing the impact of UAV applications under different spray volume regimes on deposition, canopy penetration and pest efficacy have been reported.

Many pesticide applications are often tank mixed with spray adjuvants that enhance spreading, canopy penetration, or reduce

droplet evaporation. In addition to spray adjuvants added to the tank there are also commonly used formulation adjuvants present as inert ingredients in commercial pesticide products. Spray adjuvants are materials added to a tank mix to aid or modify the action of an agricultural chemical or the physical characteristics of the mixture. Ultimately spray adjuvants are used to improve the efficacy of pesticides and improve crop protection. Previous studies showed that spray adjuvants have a significant effect on the properties of the solution, further affecting nozzle atomization<sup>[18]</sup>, spray drift, pesticide uptake<sup>[19]</sup>, and biological effects<sup>[20]</sup>. The effect of different adjuvants on spray formations depends on the applied pump pressure in combination with the type of nozzle<sup>[18]</sup>. Despite the multiple functions of adjuvants, there has been little research that has tested the effects of adjuvants on the deposition and efficacy of high-concentration pesticides using UAV application technology.

In this study, two representative spray volumes were compared when tank-mixed with a methylated seed oil adjuvant and their effect on droplet distribution and biological efficacy when applied via UAV in rice fields. Kromekote strips, mylar plates, and flag leaves of rice were used to sample different deposition indicators. The control efficacies on rice blast and rice leaf roller were investigated after the second application.

## 2 Materials and methods

### 2.1 Field plots

The tests were conducted at the Paitan Zengcheng test site, Guangzhou, Guangdong Province, China (latitude 23°46'2378"; longitude 113°8'13573) (Figure 1; Figure 2).

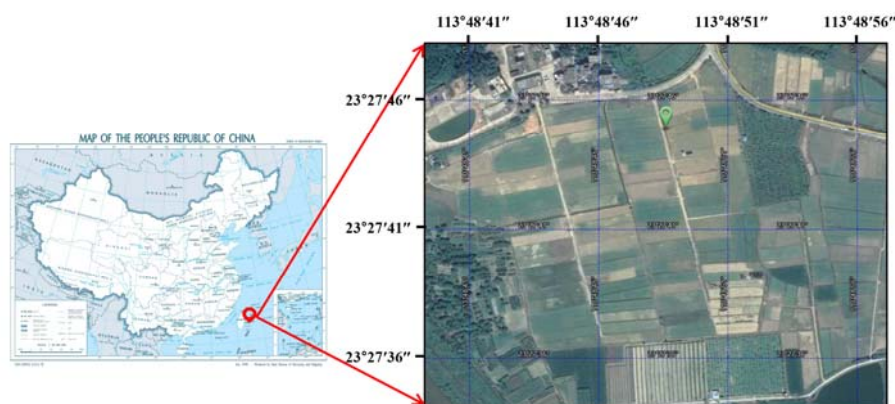


Figure 1 Test field



Figure 2 Flight control platform of UAV

The tested rice variety was “Meixiangzhan” rice, which was in the panicle initiation stage. The tests were performed on 6 June

with rice that was sown nearly 90 days before on 5 March, 2017. Row spacing, plant spacing, plant height, and planting density were 30 cm, 13.3 cm, 73.2±3.1 cm, and 1.33×10<sup>5</sup> clumps/hm<sup>2</sup>, respectively. The rice in the whole test plot grew well and consistently. A total of five treatments were designed in the field test (Table 1).

Treatments 1-4 were sprayed via a UAV-based low-volume application sprayer. Treatment 5 was sprayed via backpack sprayer as a comparison (Figure 3). The total area of the test field was about 5 hm<sup>2</sup>. Each treatment was arranged in a randomized, complete block design with three replications. Each replicate has a treatment area of 3300 m<sup>2</sup> (44 m×75 m).

### 2.2 Sprayers

#### 2.2.1 UAV sprayer

A battery motive TXA four-rotor UAV (TXA, Guangzhou Tianxiang aviation Technology Co., Ltd., Guangzhou, China) (Figure 4) was used in this study.

**Table 1 Spray application parameters of five different treatments**

Treatment	Application rate /L·hm <sup>-2</sup>	Spray speed /m·s <sup>-1</sup>	Flow rate /L·min <sup>-1</sup>	Spray swath /m	Adjuvant	Spraying equipment	Objective
T1	9.0	6	0.65	4	No adjuvant	UAV Sprayer	Deposition and biological efficacy test
T2	9.0	6	0.65	4	Maifei 1%		
T3	18.0	3	0.65	4	No adjuvant		
T4	18.0	3	0.65	4	Maifei 1%		
T5	450	≈0.5	1.2	≈0.9	No adjuvant	Electric Knapsack Sprayer	Only biological efficacy test
T6					Untreated control		



Figure 3 Electric knapsack sprayer

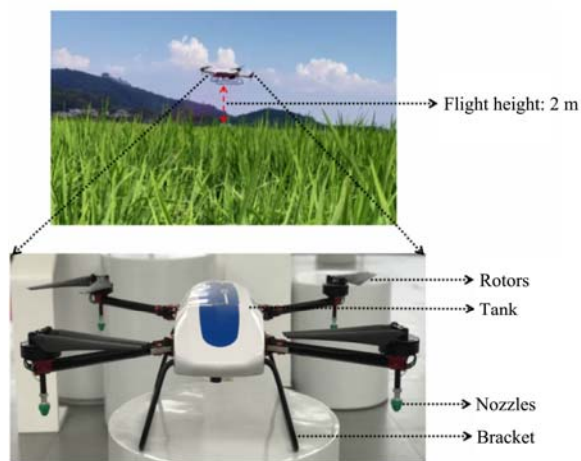


Figure 4 Unmanned aerial vehicle (UAV)

The parameters of the UAV are shown in Table 2. The UAV was powered by 12,000 mAh Li-Po batteries. The flying time was 15-20 min with the full tank load. The flight speed was 2-6 m/s, and there were four vertically downward hydraulic nozzles (ST110-01, Teejet spraying system Co., Ltd.) mounted directly under each rotor. During the application, only two nozzles located at the rear of the UAV dispersed the spray.

**Table 2 Parameters of the UAV sprayer (R10)**

TXA-UAV	Parameters
Vehicle mass/kg	14.9
Max takeoff weight/kg	25.4
Vehicle length × width × height/mm	1205 × 1215 × 380
Battery type and capacity	Lithium, 12,000 mAh
Nozzles type, numbers	Hydraulic nozzles (ST110-01), 4 (only 2 used in test)
Spray swath/m	4
Tank capacity/L	10
Maximum flow rate/L·min <sup>-1</sup>	1.3
Spraying angle	Vertical downward

The chemicals were transferred from the tank to the nozzles by a micro diaphragm pump. The flow rate was 0.32 L/min for each

nozzle (ST110-01, Lechler Inc, Germany) with a spray pressure of 2 bar. The accuracies of the flight height and flight velocity were controlled by a well-trained operator. The flight height was nearly 2.0 m, and the effective spraying width was 4.0 m. Two industry-representative spray volumes of 9.0 L/ha and 18.0 L/hm<sup>2</sup> were achieved at the flight speed of 3 m/s and 6m/s.

### 2.2.2 Backpack sprayer

A electrical backpack sprayer with a hollow cone nozzle ( $\phi=1.0$  mm) was used in the test. The pressure pump provided a pressure nearly of 3 bar and a flow rate nearly of 1.2 L/min. The spray volume of the backpack sprayer was established based on label recommendations of 450 L/hm<sup>2</sup>. The backpack sprayer followed a swinging application pattern with walking speed about 0.3 m/s.

## 2.3 Spray deposition measurements

### 2.3.1 Spray liquid

Prior to the application, a water-soluble colorant, allure red, was added in the solution as tracer at a usage of 75 g/hm<sup>2</sup>. Refer to 2.4 for detailed information on the pesticides and adjuvants.

### 2.3.2 Droplet density and percentage of spray coverage

Two Kromekote strips (1600 cm × 5 cm) were used to sample the droplet density and percentage of spray coverage distribution at an interval of 15 m along the same flight path (Figure 5a). Kromekote strips were arranged below the upper canopy, about 5 cm down from the top of the rice canopy (Figure 5c). The sampling strip was perpendicular to the flight line, and it was fixed and straightened by the fixing device. The sampling position was located in the middle of the spray area, occupying a total of four spray widths. After the application was completed, the strips were divided every 20 cm. The divided strips were scanned at a resolution of 600 dpi with a scanner, and imagery software DropletScan (USDA, UAS) was utilized to extract and analyze the droplet density and percentage of spray coverage of the Kromekote strips.

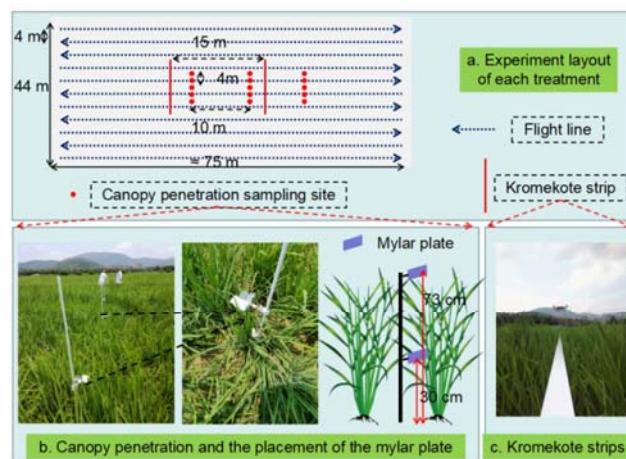


Figure 5 a. Experiment layout of each treatment; b. Canopy penetration and the placement of the mylar plate; c. Kromekote strips

### 2.3.3 Canopy penetration and deposition on the flag leaves

Before application in each treatment, canopy penetration sample collectors were placed at each plot in five equally spaced sample sites (Figure 5a; 5b). Refer to Figure 5, each sampling strip has a total of 5 sampling sites, which was 4 m apart. The samplers were sampled once with three repetitions, and an interval of 10 m was set to each repetition. Sampling was arranged at the center of the plots to avoid cross-contamination between plots, as shown in Figure 5a. Sample collectors at each site consisted of two mylar plates (40×80 mm). The mylar plates were fixed horizontally through double-headed clamps on a plastic rod. One mylar plate was arranged at a height equivalent to the head of the rice canopy. Another one was arranged in the lower part of the canopy, which was 30 cm above the ground.

After application, 10 flag leaves from randomly chosen plants and two mylar plates of different canopy positions at each sampling site were collected and placed in labeled plastic zip-lock bags. Ten flag leaves were combined and bagged as one sample. For each plot, there were 15 rice flag leaf samples and 30 mylar plates. All samples were placed in zip-lock bags along with a label describing the treatment, replication, and location information. A light-proof seal box was used for storing samples after collection and transporting them to the laboratory for analysis.

Each mylar plate and the rice sample were washed in 0.02 L and 0.2 L of distilled water in the collection bags, respectively. To allow the dye to dissolve into the water solution, samples were agitated and vibrated for 10 min. After shaking and elution, a sample portion of the wash effluent was filter through a 0.22 μm membrane and the filtered wash effluent was poured into a cuvette to measure the absorbance value by a UV2100 ultraviolet and visible spectrophotometer (LabTech, Co. Ltd., Beijing, China) at an absorption wavelength of 514 nm<sup>[21]</sup>. Spray deposition was quantified through comparison with similarly determined dye concentrations from spray tank samples and the area of the

respective samples. Deposition on the mylar plate was expressed as a quantity of dye deposited per unit area (μg/cm<sup>2</sup>). Deposition on the flag leaves was expressed as quantity of tracer per leaf (μg/leaf). To better reflect the amount of liquid deposited, deposition on the flag leaves was also expressed in μL/leaf, which was calculated from the quantity of dye per leaf (μg/leaf) divided by the concentration of the tracer (g/L).

The climatic conditions were recorded using a Kestrel 5500 digital meteorograph (Loftopia, LLC, USA), which recorded temperatures of 33.9-36.3°C, a relative humidity of 53.7%-69.5%, and wind velocities of 0.00-1.78 m/s (Table 3).

**Table 3 Weather condition during the deposition test**

Treatment	Temperature/°C	Humidity/%	Wind speed (Average/m·s <sup>-1</sup> )
T1	33.9~35.8	59.5~68.4	0.04~2.48 (1.22)
T2	34.0~34.2	62.9~68.1	0.64~4.36 (1.78)
T3	34.9~35.4	53.7~64.9	0.02~0.39 (0.72)
T4	34.3~34.2	57.5~63.2	0.39~2.65 (1.17)
T5	34.2~36.1	57.2~69.5	0.00~3.83 (1.13)

### 2.4 Control pests and diseases

To study the effects of spray volume and adjuvants on pest control performance, the first spraying was conducted on 6 June, 2017, and the second application 14 days later. The pesticides sprayed were Pyraclostrobin 9% aqueous capsule suspension (Seltima<sup>®</sup>, BASF<sup>®</sup>) and Chlorantraniliprole, a 350 WDG (water dispersible granule) (Altacor<sup>®</sup> Insect control FMC<sup>®</sup>) for controlling rice blast disease and rice leaf roller, respectively (Table 4). The adjuvant used in the test was Maifei (BeijingGrand AgroChem Co., Ltd, Beijing, China). The main component of Maifei is a methylated crop oil specially designated for aerial application. In each application, five treatments were applied by both the UAV and the backpack sprayers as described above. To more accurately analyze the effect of pesticide application, an untreated control was also included.

**Table 4 Pesticide usage and application date**

Application date	Pesticide (Product name)	Product use rate	Label recommended rate	Control pest
First application: 6 June	9% Pyraclostrobin microcapsule suspending agent (BASF Corporation)	720 mL/ha	672~876 mL/hm <sup>2</sup>	Rice blast
Second application: 20 June	Chlorantraniliprole (Altacor <sup>®</sup> 350 WDG Insect Control)	80 g/ha	70~90 g/hm <sup>2</sup>	Rice leaf roller

The evaluation of rice blast and rice leaf roller control was conducted according to pesticide field efficacy test criteria of “GB/T 17980.19-2000 Pesticide-Guidelines for field efficacy trials (I) Fungicides against leaf diseases of rice” and “GB/T 17980.2-2000 Pesticide--Guidelines for the field efficacy trials (I)--Insecticides against rice leaf roller”. The control efficacy investigation was carried out 7 days after the second application.

$$\text{Rated of rolled leaf (\%)} = \frac{\text{The number of rolled leaves}}{\text{The number of total leaves investigated}} \times 100 \quad (1)$$

$$\text{Control efficacy (\%)} = \frac{\text{Rate of rolled leaf in control group} - \text{Rate of rolled leaf in experimental group}}{\text{Rate of rolled leaf in control group}} \times 100 \quad (2)$$

The control efficacy of rice blast was calculated based on the following formula 3 and formula 4.

$$\text{Disease index (\%)} = \frac{\sum (\text{Number of diseased leaves at each grade} \times \text{Representative value of the specific grade})}{\text{Total number of investigated leaves} \times \text{Representative value of the highest grade}} \times 100 \quad (3)$$

$$\text{Control efficacy (\%)} = \frac{\text{Disease index in control group} - \text{Disease index in experimental groups}}{\text{Disease index increment in control group}} \times 100 \quad (4)$$

### 2.5 Data analysis

A factorial design was conducted for both experiments. The averages were compared using *t*-tests at 5% probability. Significant differences between treatments were calculated using

analysis of variance (ANOVA) and Duncan's test at a significance level of 95% with SPSS v22.0 (SPSS Inc, an IBM Company, Chicago, IL, USA). The coefficient of variation (CV), used as an indicator to reflect the dispersion of the deposition data, is given



below:

$$CV = \frac{S}{\bar{X}}, S = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{X})^2}{n-1}} \quad (5)$$

where,  $S$  is the standard deviation;  $x_i$  is the deposition from each sampling datum;  $\bar{X}$  is the average deposition from all sampling data;  $n$  is the total number of samples.

Graphs were drawn using the Origin 8.0 (OriginLab Co., LTD, Northampton, MA, USA) software package.

### 3 Results

#### 3.1 Droplet density and percentage of spray coverage

The effects of spray volume and addition of adjuvant on multi-swath deposition are shown in Figure 6.

Droplet density and percentage of spray coverage changed depending on the sampling position, and the changed rules of two

deposition indicators were similar. Under the combined influence of the spraying system, environmental wind, rotor wind, droplet density and percentage of spray coverage fluctuated greatly during application. The coefficient of variation (CV) for droplet density and percentage of spray coverage were in the ranges of 59.9%~75.5% and 64.7%~94.1%, respectively. Both increasing the spray volume and adding adjuvant significantly increased the droplet density and percentage of spray coverage. However, there was no significant interaction effect between the spray volume and the use of adjuvant (Table 5). Adding adjuvant increased the percentage of spray coverage by 52.3%~54.3% and increased the droplet density by 26.8%~40.1%, respectively. When the spray volume was increased from 9 L/ha to 18 L/hm<sup>2</sup>, the percentage of spray coverage increased 57.5%~59.5%, and the droplet density increased 36.6%~50.9%, respectively.

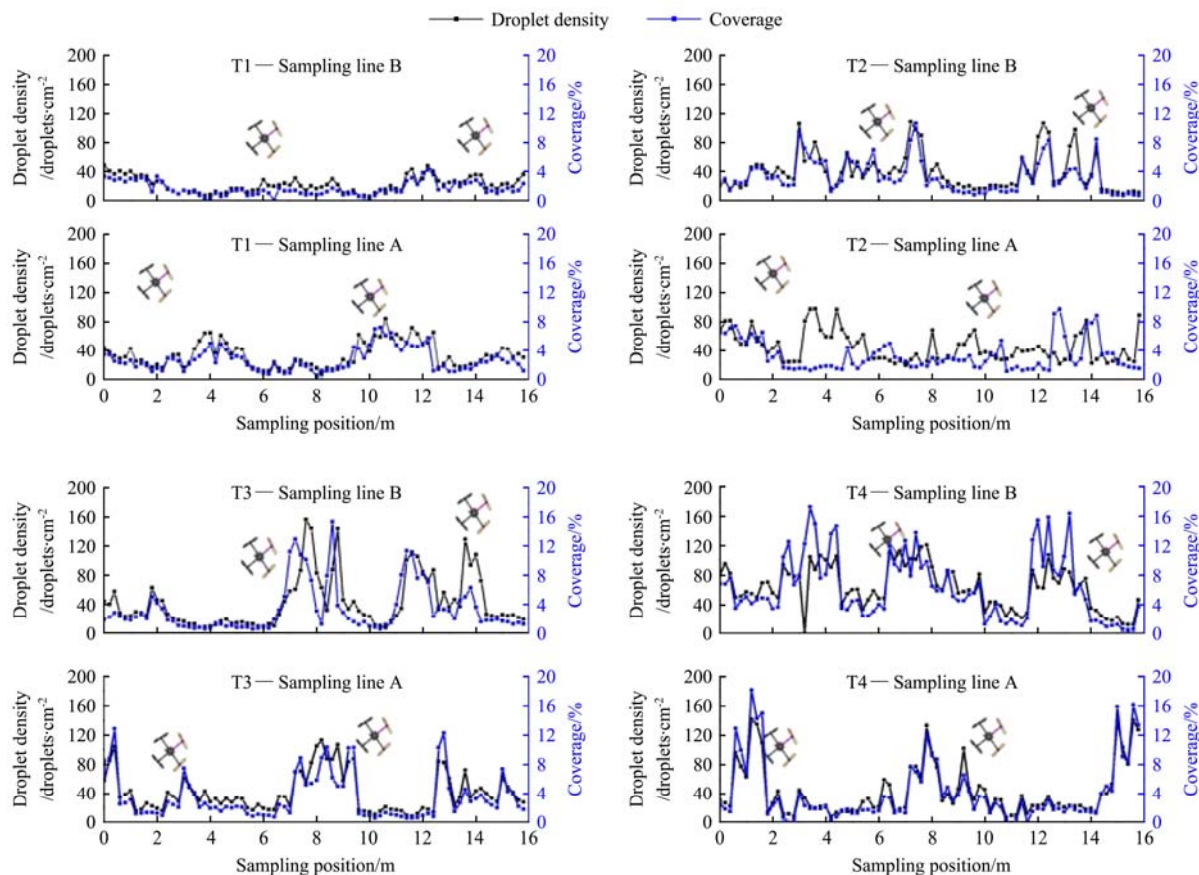


Figure 6 Effects of spray volume and addition of adjuvant on multi-swath droplet density and coverage

**Table 5** Effects of spray volume and adjuvant on droplet deposition

Spray volume /L·hm <sup>-2</sup>	Adjuvant	Droplet density (droplets/cm <sup>2</sup> )	Percentage of spray coverage %
9.0	0	27.9±1.2 Bb	2.14±0.11 Bb
9.0	1%	39.1±1.8 Ba	3.26±0.17 Ba
18.0	0	42.1±2.5 Ab	3.37±0.25 Ab
18.0	1%	53.4±2.7 Aa	5.20±0.35 Aa
Spray volume		**	**
Adjuvant		**	**
Spray volume×Adjuvant		Ns	Ns

Note: Data in the table are mean ± SD. Different uppercase or lowercase letters in the same column indicate significant difference at different spray volume under the same adjuvant or at different adjuvant under the same spray volume at  $P < 0.01$  level by  $t$  test, respectively. \*\* indicate extremely significant difference  $P < 0.01$  level, and Ns indicate no significance.

#### 3.2 Deposition on the flag leaves

Figure 7 shows the deposition on the flag leaves of rice (Figure 7a. deposition in  $\mu\text{g}/\text{leaf}$ ; b. deposition in  $\mu\text{L}/\text{leaf}$ ). The highest deposition ( $\mu\text{g}/\text{leaf}$ ) occurred at a spray volume of 9 L/hm<sup>2</sup> with adjuvant, followed by a spray volume of 18 L/hm<sup>2</sup> with adjuvant. However, the differences between the depositions were not significantly different. Adding an adjuvant significantly increased the deposition ( $\mu\text{g}/\text{leaf}$ ) compared to the treatments without adjuvant. Droplet deposition (the amount of liquid deposited,  $\mu\text{L}/\text{leaf}$ ) was calculated from deposition (the quantity of dye deposited,  $\mu\text{g}/\text{leaf}$ ) and the concentration of the tracer (g/L), which was closely related to the amount of spray volume. For UAV application, the highest deposition ( $\mu\text{L}/\text{leaf}$ ) was achieved at a spray volume of 18 L/ha with adjuvant. Because the volume of the backpack sprayer was ten times higher

than that of the UAV, the deposition ( $\mu\text{L}/\text{leaf}$ ) was correspondingly 10 times higher.

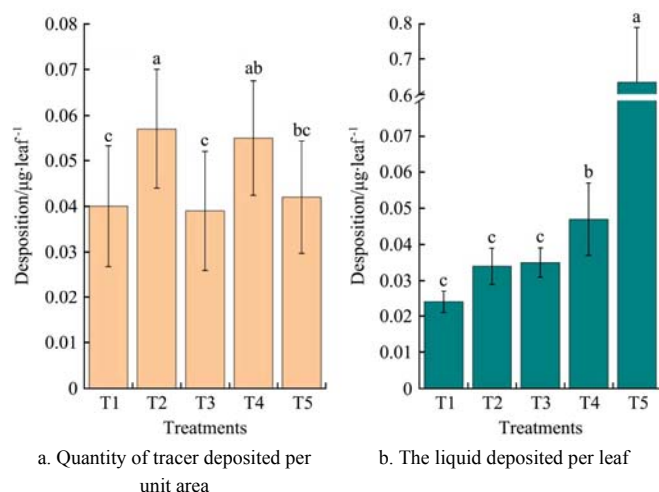


Figure 7 Deposition on the flag leaves

### 3.3 Canopy penetration

Canopy penetration data from mylar plates are shown in Table 6. The droplet penetration of the UAV was 47.1%, which was significantly lower than that of the backpack sprayer. Although the downwash airstream from the UAV was beneficial in disturbing the leaves which may benefit droplet penetration. However, this force only played a role in the initial stage of droplet release. Due to the relatively high application height (2 m), the droplets lose their initial kinetic energy due to air resistance during the deposition process. When reaching the upper canopy of the rice, the droplets were only affected by gravity and air resistance. Due to occlusion of the leaves, more droplets were deposited on the upper canopy, which affects the penetration of the droplets to the inner canopy.

**Table 6 Comparison of droplet penetration in canopy between knapsack and UAV sprayer**

Sprayer	Canopy	Deposition $\mu\text{g}/\text{cm}^2$	Coefficient of variance/%	Penetration ratio/%
UAV	Upper	0.171	85.9	47.1
	Lower	0.080	98.3	
Backpack sprayer	Upper	0.145	24.7	68.8
	Lower	0.100	52.7	

Note: The penetration of the droplets was calculated as the deposition of the lower canopy divided by the upper canopy.

### 3.4 Control efficacy

The ultimate goal of aerial application is to achieve satisfactory crop protection by proper selection of the application parameters including application timing, pesticide type, tank mix partners, environmental parameters, and proper selection of spray system equipment. In this study, the control efficacy of fungus was relatively low, ranging from 44.7% to 62.7% (Figure 8). This was mainly because the disease was less severe in the blank control when the environment changed after the second application. Among all treatments, the best disease control efficacy, 62.7%, was achieved with UAV application at a spray volume of 18 L/ha with adjuvant. For insecticides, rice leaf roller control efficacy was relatively high, ranging from 84.3% to 96.3% (Figure 8). The UAV application at 18 L/hm<sup>2</sup> was not significantly different from the backpack sprayer.

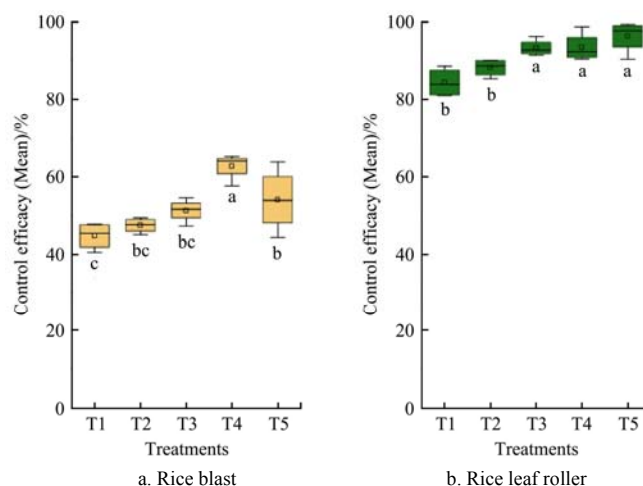


Figure 8 Control efficacy on rice blast and rice leaf roller

## 4 Discussion

The test results showed that both spray volume and adjuvant had significant effects on droplet deposition and control efficacy when applied in rice by a UAV at low spray volumes, application in a rice field. Spray volume and droplet size are important factors in application technology and should be defined prior to spraying<sup>[22]</sup>. The requirements for different spray volumes often vary with the type of agrochemical<sup>[23]</sup>, leaf area index<sup>[24]</sup>, and application technology<sup>[25]</sup>. Insufficient spray volume will lead to a relatively low degree of percentage of spray coverage, which has adverse effects on the control of insect pests and diseases. Currently no spray coverage quality standard exists for the various multi-rotor UAV applicators. To improve effectiveness, a greater number of spray droplets per unit area is assumed to lead to a higher probability of maximizing pest control. The recommended values from Syngenta Crop Protection AG (Basel, Switzerland) research recommends at least 30-40 droplets/cm<sup>2</sup> for contact activity for post-emergence herbicide applications, 20-30 droplets/cm<sup>2</sup> for insecticide or pre-emergence herbicide applications, and 50-70 droplets/cm<sup>2</sup> for fungicide applications to provide satisfactory control<sup>[26]</sup>. Excessive spray volume may also cause issues. There is a saturation point (point of runoff) for droplet deposition on target crops. Beyond this value, the droplets will runoff. This can be exacerbated when spreading surfactants are added to the spray tank. After the runoff ends, the droplets reach the maximum stable retention on the leaves, which is only about half of the point of runoff<sup>[27]</sup>. This easily leads to significant reductions in deposition due to runoff in the case of large-volume applications. Additional time is also spent filling tanks that may be crucial to completing a spray operation in a required time period. Therefore, it is important to choose a suitable spray volume to improve work efficiency while ensuring adequate control efficacy for different sprayers and targets. The results of this trial indicate that droplet deposition and pest control significantly improved when the spray volume was increased from 9 liters/ha to 18 liters/hectare.

Canopy penetration is defined as the ability of sprayed droplets to move through a canopy to provide adequate control of insect and disease pests<sup>[28]</sup>. How to maximize canopy penetration has been examined in various cropping systems, application technologies, and techniques<sup>[29-32]</sup>. However, as an important influencing factor, the effects of different droplet sizes on canopy penetration were not consistent. In some studies, finer droplets were more easily captured on the upper portion of the canopy<sup>[31,32]</sup>.

Knowledge of physics suggests that objects with more mass under the influence of gravity would experience greater momentum. A greater momentum will cause the droplets to move deeper into dense canopies<sup>[33]</sup>. On the contrary, some studies indicated smaller droplets penetrated canopies better<sup>[23,34]</sup>. Further, decreasing the droplet size will enhance performance on difficult-to-wet plants, especially for monocotyledons with a predominantly vertical structure<sup>[23]</sup>. In this test, UAV canopy penetration was lower than that of the backpack sprayer, which might lead to less control of pests such as plant hoppers that feed lower on the rice stem and disease organisms that may flourish in the deeper denser canopy.

Adjuvants are often added to a tank mix to improve the performance of the active ingredient or modify the physical characteristics of the mixture<sup>[18]</sup>. The results of previous research showed that adjuvants influence the mechanism of spray formation by altering relevant physical properties including surface tension, shear and extensional viscosity. Although the use of adjuvants in pesticide sprays is common, their function and impact on spray quality is not always known. Their influence on deposition, retention, translocation movement into the leaf, translocation through the plant, and activity against the target pest may be different among crops and pests<sup>[19]</sup>. Our test results show that adding a methylated seed oil adjuvant can significantly improve deposition on the targets. This result is consistent with other studies<sup>[19,35]</sup>. However, the mechanisms on how adjuvants affect deposition and improves the performance of the active ingredient with different methods of application, such as with UAV technology, requires further study.

Effective pest control depends on proper application practices that deliver a quality spray. Variables including pest species, location on the plant, product attributes, adjuvant selection, spray system configuration, and environment conditions all may have a significant effect on UAV application deposition and pest control efficacy<sup>[36]</sup>. Past research has proven the feasibility of low-volume spraying via UAVs in agrichemical applications to control pests and diseases<sup>[15,21,37,38]</sup>. However, further improving deposition and optimizing application parameters are areas for further research.

## 5 Conclusions

The effects of spray volume and the addition of a methylated seed oil adjuvant on spray distribution and pest control were investigated comparing UAV application technology to conventional backpack sprayer in rice. For UAV application, increasing both the spray volume and adding an oil adjuvant significantly increased the droplet density and percentage of spray coverage. The effect of increasing spray volume on biological efficacy was more critical than adding adjuvants. Spray volume had a significant effect on the amount of liquid deposited ( $\mu\text{L}/\text{leaf}$ ), but it had no significant effect on the quantity of tracer ( $\mu\text{g}/\text{leaf}$ )—a conclusion that was reversed for the adjuvant. Further increasing canopy penetration is important to improve pest control via UAV application. A spray volume of  $18 \text{ L}/\text{hm}^2$  with addition of methylated crop oil via UAV application can effectively improve droplet deposition and pesticide efficacy at the panicle initiation stage of rice, which is meaningful for more efficient crop protection and reduced need for large spray volumes.

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