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Article

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Posted Date: November 19th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11539175/v1

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Additional Declarations: No competing interests reported.

Effects of Spray Adjuvants on Droplet Deposition, Effective Spray Width, and Field Control Efficacy in UAV-Based Rice Pest Management

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Abstract: Unmanned aerial vehicle (UAV) spraying is widely used for rice pest management, but improving droplet deposition uniformity and field control efficacy remains challenging. This study evaluated six commercial spray adjuvants for UAV-based control of rice stem borers using a DJI T30 platform. Droplet spreading, deposition density, spatial uniformity, effective spray width, and field control efficacy were assessed under different operating conditions. The results showed that spray adjuvants influenced droplet deposition patterns and effective spray width. Activator 90 achieved a deposition density of 30.0 drops/cm² and the lowest coefficient of variation (CV, 44.6%), indicating relatively uniform deposition. Analysis of the operating parameters showed that application rate and adjuvant treatment significantly affected effective spray width ($P < 0.001$), while flight height also had a significant effect ($P = 0.03$); flight speed was not significant ($P = 0.12$). The greatest measured effective spray width was 5.9 m at an application rate of 22.5 L/ha. In field trials, Activator 90 achieved control efficacies of 84%, 88%, and 89% at 7, 14, and 21 days after application, respectively, and the lowest final disease injury rate (1.26%). These findings indicate that appropriate spray adjuvant selection can improve droplet deposition uniformity and field control performance in UAV-based rice protection. The identified operating conditions provide a reference for optimizing UAV spraying, although their applicability should be validated for other platforms and field conditions.

Keywords: Unmanned aerial vehicle, Rice, Spraying adjuvant, Droplet deposition, Rice stem borers

1. Introduction

The challenges of pesticide drift, evaporation, and poor leaf adhesion during spraying can substantially reduce effective pesticide deposition and control efficacy, thereby limiting pesticide-use efficiency [1–3]. In 2015, the Ministry of Agriculture and Rural Affairs launched the Action Plan for Zero Growth in the Use of Chemical Fertilizers and Pesticides by 2020, aiming to curb the excessive growth of agricultural chemical inputs and promote more efficient and sustainable pesticide use [4–6]. Importantly, "zero growth" refers to controlling the growth of pesticide consumption through improved application efficiency and reduced unnecessary inputs, rather than eliminating pesticide use altogether [7–9]. Therefore, improving pesticide deposition and utilization efficiency through precision application technologies has become an important approach to reducing unnecessary chemical inputs while maintaining effective crop protection.

Owing to the low efficiency of manual pesticide spraying and the substantial environmental pollution caused by excessive pesticide use, the combination of agricultural unmanned aerial vehicles and spray adjuvants has achieved precise, efficient, and low-cost pesticide application[10-14]. He et al. investigated the effects of spray adjuvants and application volume on the deposition density, deposition amount, and effective deposition rate of droplets at different positions in the rice canopy. The results of an unmanned aerial vehicle spraying experiment revealed that the addition of spray adjuvants can significantly increase the deposition amount and effective deposition rate of droplets[15].

Lan et al. investigated the effects of spray adjuvants on the surface tension of the solution, the contact angle of the medicine on corn leaves, and the deposition characteristics of droplets and compared the deposition characteristics of different adjuvants sprayed by unmanned aerial vehicles[16]. Han et al. investigated the distribution of deposition amounts on the canopies and ground of hilly citrus trees under the precision operation mode of agricultural unmanned aerial vehicles and the effect of different spray adjuvants[17]. Guo et al. conducted pesticide spraying experiments using unmanned aerial vehicles to analyse the effects of different adjuvants on the distribution of droplet deposition on the rice canopy and the effect of adjuvant-assisted unmanned aerial vehicles in controlling rice blast disease[18]. Wang et al. compared the performance of various types of tank-mixed adjuvants by analysing the droplet profiles, drift potential index (DIX), field deposition and control of wheat rust and aphids in a wind tunnel to elucidate the spray characteristics and control of these adjuvants in aerial sprays[19]. Yan et al. explored the effects of aerial spray adjuvants on droplet deposition and distribution in wheat and tested the research hypothesis that the use of aerial spray adjuvants could reduce wheat mycotoxin contamination while improving Fusarium head blight of wheat control[20].

However, most previous studies have focused on either individual adjuvants or specific crop types, with limited comparative research on standardized UAV platforms using multiple spray adjuvants under uniform field conditions. In particular, systematic evaluations of the effects of commonly used adjuvants on droplet deposition characteristics, spray coverage, and pest control efficacy in rice paddies are scarce. While these adjuvants are extensively applied in agricultural practices, their relative performance under UAV-based spraying conditions, especially for controlling the rice stem borers, remains ambiguous. Therefore, this study aims to fill this research gap by systematically evaluating six commercial adjuvants through integrated laboratory and field trials, with the specific objectives of (1) characterizing their dynamic spreading behaviour on rice leaves; (2) quantifying their effects on UAV spray droplet deposition density and uniformity; (3) determining optimal operational parameters for effective spray width when the best-performing adjuvant is used; and (4) evaluating field control efficacy against a rice stem borers. We hypothesized that compared with nonadjuvant treatments, adjuvant treatments would significantly affect droplet spreading characteristics, improve deposition quality while improving uniformity, increase effective spray width under optimized parameters, and ultimately provide superior pest control efficacy. The findings are expected to establish selection criteria and operational guidelines for precision UAV pesticide application in rice production systems.

2. Materials and methods

2.1. Materials

The experiments were conducted in the National Modern Agricultural Demonstration Zone of Wujiang, Jiangsu Province, which is very suitable for the growth of crops such as wheat, rice, rapeseed, and aquatic plants. The terrain is flat without mountains, making full mechanized management easy throughout the process[21]. The rice variety used was Nanjing 46, which was transplanted by machine and had a plant height of 25–35 cm. The tested pesticides and varieties were Kangkuan (20% chlorantraniliprole suspension concentrate) at a dose of 150 mL/ha and the spray-specific adjuvants Silwet L-77 (surfactant), Sylgard 309 (oil-based spreader-sticker), Activator 90 (surfactant/sticker), TM07 (deposition aid), LI-700 (spreading agent), and Aeromate 480 (drift reducer/adhesion promoter) at a dose of 150 mL/ha. These adjuvants were chosen on the basis of their suggest roles in modulating droplet behaviour, increasing foliar retention, and reducing drift under field conditions. This study was provided by the Institute of Plant Protection, Chinese Academy of Agricultural Sciences. The physical properties of the spray adjuvants are listed in Table 1.

Adjuvant Name	Surface Tension (mN/m)	Viscosity (mPa·s)	Density (g/cm³)
Activator 90	20.5	1.05	0.98
TM07	23.8	1.30	1.01
Sylgard 309	22.0	1.10	1.00
Aeromate 480	28.7	2.50	1.05
Silwet L-77	18.9	0.95	1.00
LI-700	30.5	2.80	1.06

Table 1. Physical property parameters.

This spraying operation uses a T30 plant protection unmanned aerial vehicle (UAV) manufactured by DJI Innovation Technology Co., Ltd. of Shenzhen. The specific parameters of the plant protection UAV are shown in Table 2. The T30 UAV body is constructed of lightweight materials and has high strength and rigidity. The UAV controller is the core control system of T30 and can adjust and monitor the parameters of plant protection operations. The UAV controller is equipped with multiple motors and propellers and provides powerful lifting and flight capabilities. GPS navigation technology is used to accurately locate and control the position and flight trajectory of the UAV. The dispensing system uses intelligent dispensing technology, which can automatically adjust the proportion of liquid medicine according to the needs of different crops. The structure of the DJI T30 is shown in Figure 1.

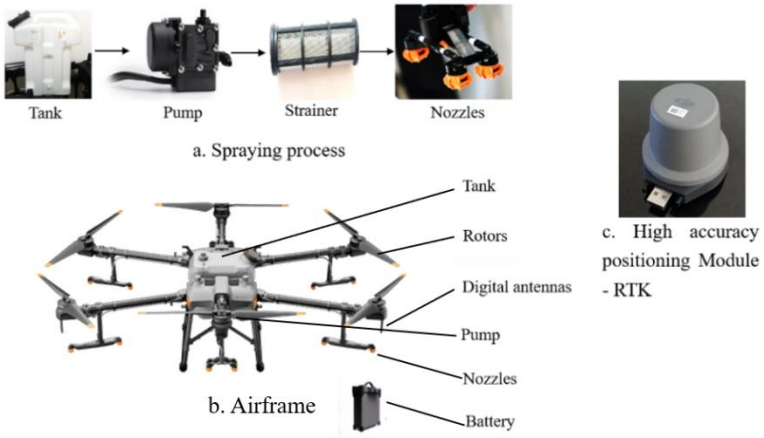


Figure 1. T30 plant protection UAV.

Parameters	Specification
UAV model	DJI Agras T30
Operation tank volume	30 L
Maximum operating flight speed	7 m/s
Maximum spray flow	7.2 L/min
Nozzle model	SX11001VS (standard)
Atomized particle size	130–250μm
Maximum effective spray width	4–9 m
Water pump	Plunger pump
RTK/GNSS positioning	Supported

Table 2. Main parameters of the T30 plant protection UAV.

2.2. Methods

2.2.1. Preliminary Evaluation of Spray Adjuvants

A 10 μL pipette was used to dispense the solutions of Silwet L-77, Sylgard 309, Activator 90, TM07, LI-700, and Aeromate 480 onto rice leaves. The spreading behaviour and time required to reach an apparently stable spreading state were observed and recorded. This preliminary assessment was performed qualitatively and did not include quantitative measurements of spreading diameter, spreading area, or spreading rate.

2.2.2. Spray Droplet Deposition Test

In accordance with the actual field conditions, common parameters for the plant protection UAV were selected for testing the uniformity of mist droplet deposition and field efficacy in a 1.3 ha rice field, which was divided into 8 plots. The design parameters are listed in Table 3. Sampling was performed at five points in the upper part of the crop in each plot. The experimental machinery operation and sampling point layout are shown in Figure 2.

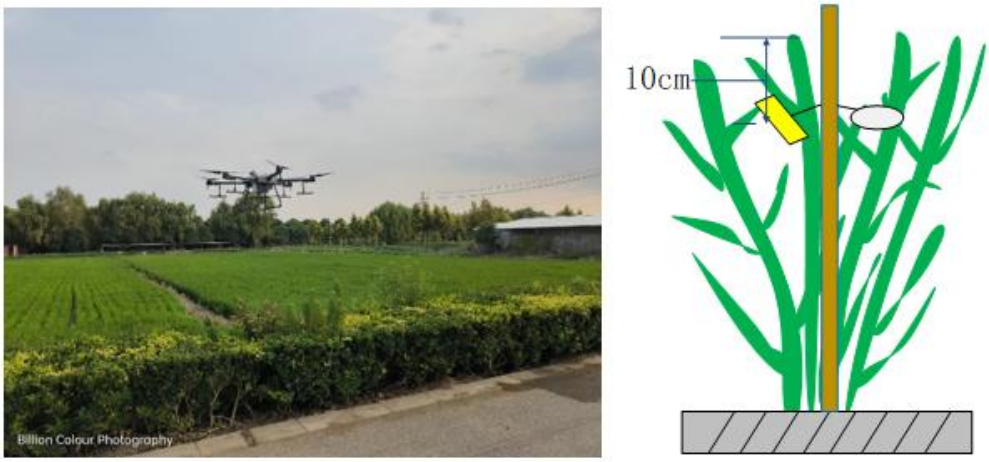


Figure 2. Machine operation and sampling point layout.

Treatment code	Machine type	Operating height	Operating speed	Spray Volume	Pesticides and adjuvants	Area (ha)	Remarks
1	T30 Plant Protection UAV	2.0 m	4 m/s	15 L/ha	Pesticides +Silwet L-77	0.20	In each plot, five water-sensitive papers were randomly placed for field observation
2					Pesticides +Sylgard 309	0.21	
3					Pesticides +Activator 90	0.11	
4					Pesticides +TM07	0.29	
5					Pesticides +LI-700	0.25	
6					Clearwater	0.09	
7					Pesticides	0.09	
8					Pesticides +Aeromate 480	0.15	

Note: During the experiment, the recorded meteorological conditions were characterized by a wind speed of 0.2–2.2 m/s, an air temperature of 30.2–32.3 °C, and a relative humidity of 56.1–67.8%.

Table 3. Experimental design.

Meteorological conditions, including wind speed, air temperature, and relative humidity, were recorded using a small weather station during each spraying operation. The measurements were conducted at approximately crop-canopy height and are reported for the corresponding experiments.

2.2.3. Effective spray width test

The effects of four factors, including the flight height A (1.5 m, 2 m, 2.5 m, and 3 m), flight speed B (3 m/s, 4 m/s, 5 m/s, and 6 m/s), application rate per ha C (15 L/ha and 22.5 L/ha), and adjuvant Activator 90 (with an adjuvant and without an adjuvant), on the effective spraying width of the T30 plant protection UAV were investigated. The experimental process is shown in Figure 3, with a total of 15 poles arranged at intervals of 0.5 m, each with water-sensitive paper attached. The T30 plant protection UAV flew along the centerline, and the operation parameters are listed in Table 4.



Figure 3. Layout of the effective spray width position.

Treatment code	With or without adjuvant	Application rate per ha (L)	Operating height (m)	Operating speed (m/s)
1	Without adjuvant	15	1.5	3
2				4
3				5
4				6
5			2	3
6				4
7				5
8				6
9			2.5	3
10				4
11				5
12				6
13			3.0	3
14				4
15				5

16				6
17		22.5	2	3
18				4
19	With adjuvant	15	2	3
20				4
21				5
22				6
23			2.5	3
24				4
25				5
26				6

Table 4. Design of effective spray width operating parameters.

2.2.4. Pest control trials in the field

In accordance with the "Guidelines for Field Efficacy Trials of Pesticides Part 1: Insecticides for the Control of Rice Stem Borers (GB/T 17980.1—2000), the efficacy investigation was conducted on August 7 (7 days after spraying, tillering stage), August 14 (14 days after spraying, preflowering stage), and August 22 (21 days after spraying, mid-flowering stage)[22-23]. Ten sampling points were randomly selected in each plot, and each point was investigated for an area of 0.25 m^2. The investigation encompasses 2–5 m^2 of rice fields, and the number of tillers, blight plants, leaves, and affected plants (rolled leaves) were recorded[24-26].

2.3. Data processing

After the experiment, the water-sensitive papers were collected, labelled, and sealed for preservation. The results are shown in Figure 4 and were returned to the laboratory for analysis. The water-sensitive papers were scanned using a scanner (resolution 600 dpi) and processed using the image processing software Photoshop for edge processing. A specific area was cropped and saved in JPG format and then analysed using DepositScan software[27-28].

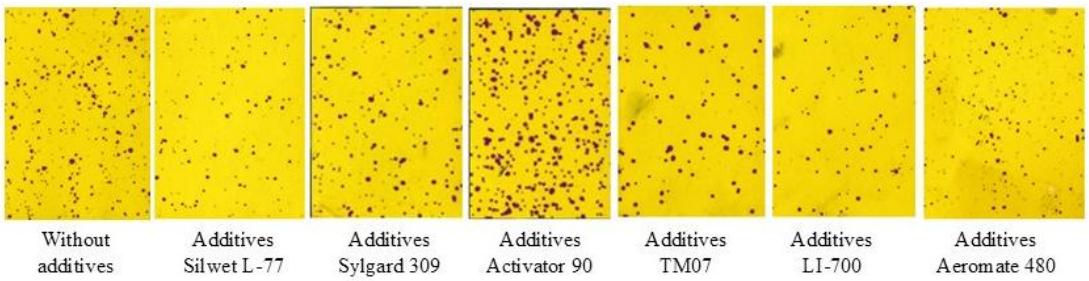


Figure 4. Distribution of droplets with different adjuvants.

The coverage rate on the sampling card can be obtained by calculating the ratio of the number of fog droplet pixels in the analysis area of the image to the analysis area. The calculation formula is[29-31]:

$$\delta = \frac{\sum_{i=0}^{M}\sum_{j=0}^{N} f(i,j)}{M \times N} \times 100\%$$

where M represents the width of the analysis area in pixels, N denotes the height of the analysis area in pixels, and f(i, j) indicates the grey value flag of the pixel in the image analysis area at coordinates (i, j) relative to the pixel. If the pixel is black, then f(i, j)=1; otherwise, f(i, j)=0.

The coefficient of variation V is used as a measure of the uniformity of the droplet distribution, where V is calculated using the following formula[32-33]:

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

where S represents the standard deviation, X_i denotes the number of droplets per unit area of each sampling card, $\bar{X}$ indicates the average number of droplets per unit area of the sampling card, and n represents the total number of sampling cards per layer.

In accordance with the industry standard "Technical Specification for Quality Evaluation of Agricultural Unmanned Aerial Vehicles", a sedimentation density of ≥15 drops/cm² is used as the boundary of spray coverage to determine the width of coverage [34-36]. The coverage rates are listed in Table 5.

Treatment code	Effective spray width (m)	Natural wind speed (m/s)	Relative humidity %	Average temperature °C
1	5	0.8–1.8	56.6%	32.3
2	3.5	0.5–1.5		
3	3.5	1.0–1.7		
4	4	0.5–2.0		
5	3.5	0.5–1.0	65.2%	31.5
6	3.5	0.7–1.5		
7	4	0.5–1.3		
8	3	1.0–1.6		
9	4.5	1.0–2.0	56.1%	31.8
10	3.5	0.5–1.7		
11	5	0.3–1.0		
12	3.5	1.0–2.1		
13	4.5	0.7–1.9	67.8%	30.6
14	4	0.7–2.2		
15	5.5	0.2–1.1		
16	5	0.3–1.4		
17	7	0–0.8	58.4%	32.3
18	5	0–1.1		
19	4.5	0.4–1.0	60.5%	30.2
20	4	0.3–0.9		
21	5	0.2–1.0		
22	5.5	0–0.7		
23	5.5	0.4–1.2	62.8%	30.7
24	5.5	0.3–0.9		
25	5	0.5–1.0		
26	7	0.3–1.1		

Table 5. Effective spray width for different treatments.

The field efficacy was calculated according to the following formula[37]:

$$W = \frac{D}{T} \times 100$$

$$R = \frac{C}{T} \times 100$$

$$E = \frac{CK - PT}{CK} \times 100$$

where W represents the blight heart rate, %; D denotes the number of blight heart plants investigated; T indicates the total number of plants investigated; R represents the rolling leaf rate, %; C denotes the number of rolling leaves investigated; T indicates the total number of leaves investigated; E represents the control efficacy, %; CK denotes the blight heart rate or rolling leaf rate in the blank control area after spraying; and PT indicates the blight heart rate or rolling leaf rate in the spraying area.

2.4. Basic Information Record

The crop growth and weather conditions, which are listed in Table 6, were recorded.

Meteorological conditions	**Small weather station records**		
Soil type	Mainly composed of yellow pine soil with heavy soil viscosity	Neutral to slightly alkaline, less acidic	Direct seeding
Soil cover	Weeds	Rice straw	
Varieties to be tested	Southern Japonica 46	Spacing between plants and rows	
Application fertility period	Seedling stage - plucking		

Table 6. Basic information record form.

3. Results and Analysis

3.1. Effects of different adjuvants on the spread of rice

Based on visual observation of the droplet spreading behaviour shown in Figure 5, Activator 90 exhibited the most rapid and visually extensive spreading, followed by TM07, Sylgard 309, Aeromate 480, Silwet L-77, and LI-700. Activator 90 and Silwet L-77, which had the lowest surface tensions (20.5 and 18.9 mN/m, respectively), showed rapid visible spreading, reaching an apparently stable spreading state within 1–2 s. In contrast, LI-700, which had the highest surface tension (30.5 mN/m) and viscosity (2.80 mPa·s), showed the slowest visible spreading and required approximately 4–5 min to reach a limited and apparently stable coverage state. It should be noted that the spreading assessment in this preliminary experiment was based on qualitative visual observation and spreading time rather than quantitative measurements of spreading diameter, spreading area, or spreading rate. Therefore, the ranking reported above should be regarded as a qualitative comparison of spreading behaviour rather than a quantitative ranking of spreading performance. Future studies should employ image-based measurements to quantify droplet spreading area, equivalent diameter, and spreading rate, thereby providing a more objective assessment of the spreading characteristics of different adjuvants.

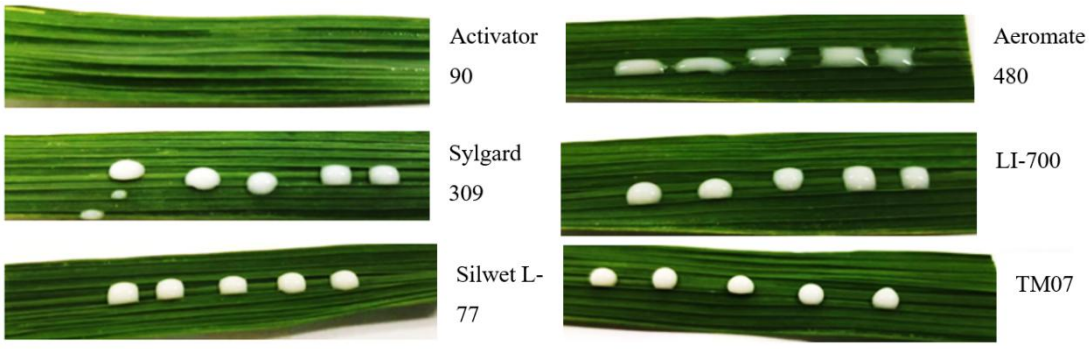


Figure 5. Visual comparison of droplet spreading behaviour of different adjuvants on rice leaves.

Note: Images were captured when the droplets reached an apparently stable spreading state. The spreading assessment was based on visual observation and spreading time; quantitative spreading area, diameter, and spreading rate were not measured in this preliminary experiment.

3.2. Droplet deposition of different adjuvants

Figure 6a shows the field deposition conditions, while Figure 6b–c compare droplet deposition density and spatial uniformity among treatments. Activator 90 achieved a deposition density of approximately 30 drops/cm² and the lowest CV (44.6%), indicating the most uniform deposition. TM07 and Sylgard 309 also showed relatively low CV values. In contrast, Aeromate 480 exhibited a higher deposition density (42.3 drops/cm²) but a higher CV (60.1%), demonstrating that greater deposition does not necessarily ensure better uniformity. Figure 6d further illustrates this trade-off between deposition density and uniformity, with Activator 90 showing the lowest CV among the treatments. Figure 6e presents the available physicochemical data, showing lower surface tension and viscosity for Activator 90 than for Aeromate 480. These differences may partly explain their contrasting deposition patterns. Overall, Activator 90 provided the best balance between deposition density and spatial uniformity under the tested conditions.

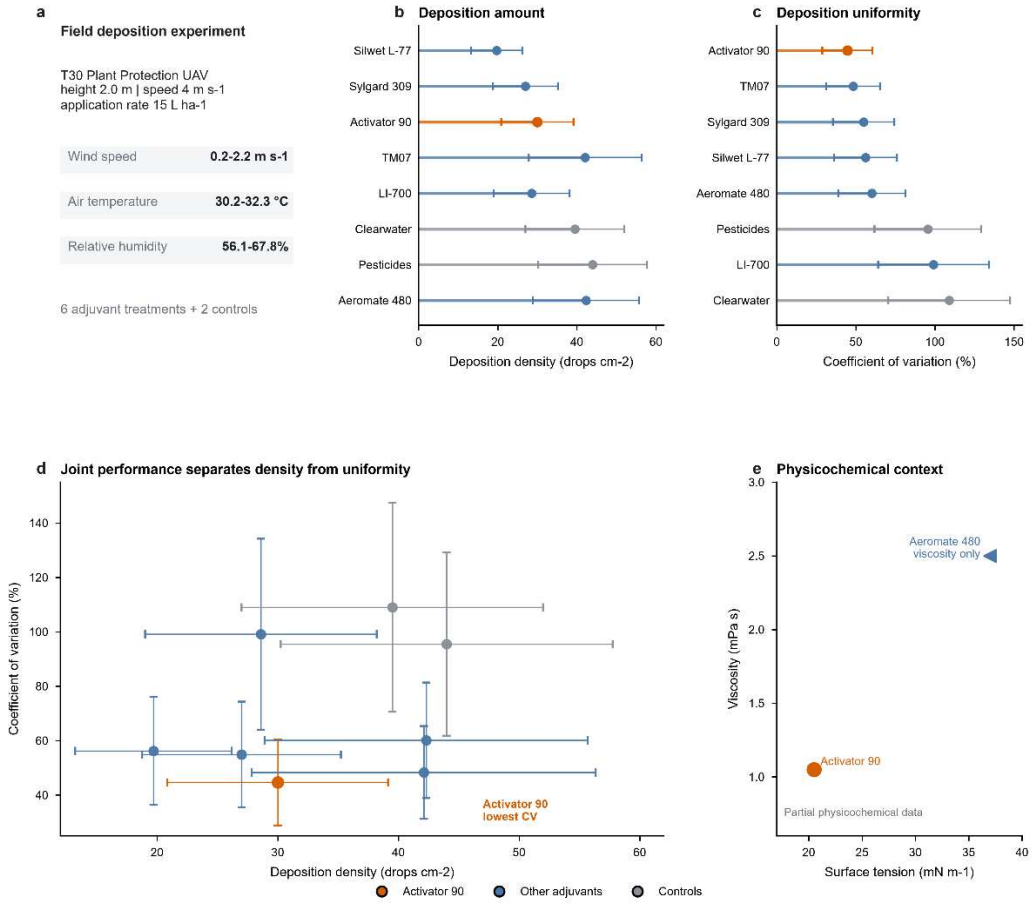


Figure 6. Effects of spray adjuvants on droplet deposition density and spatial uniformity in the upper rice canopy.

The differences in droplet deposition among the tested adjuvants likely resulted from the combined effects of surface tension, viscosity, and interfacial behaviour. Lower surface tension generally promotes droplet spreading and wetting on rice leaves, while viscosity can influence droplet deformation, breakup, transport, and retention. Appropriate interfacial properties may further improve adsorption and retention at the liquid–leaf interface. However, the deposition results indicate that surface tension alone cannot explain adjuvant performance. For example, although Silwet L-77 had the lowest surface tension, it

did not achieve the best deposition uniformity or field efficacy, whereas Activator 90, with relatively low surface tension and moderate viscosity, achieved the lowest CV (44.6%) and the highest control efficacy. These results suggest that the overall performance of an adjuvant depends on the combined effects of spreading, retention, droplet transport, and deposition rather than on a single physicochemical property. Such interactions may also influence drift risk and ultimately determine the amount of pesticide reaching the target canopy and the resulting field control efficacy.

Figure 7 shows the lateral distribution of droplet deposition density at flight speeds of 3, 4, 5 and 6 m/s, with and without spray additives, at a flight height of 2.5 m and an application rate of 15 L/ha. The spatially averaged deposition density was higher with the additive at all four tested speeds, but the magnitude and consistency of the response varied across the transect. At 3 m/s, the mean increased from 29.60 to 44.60 pcs/cm², with increases at 12 of the 15 lateral positions. At 4 m/s, the mean increased from 19.20 to 62.07 pcs/cm², and deposition was higher at every sampled position. By contrast, the increase at 5 m/s¹ was modest (19.07 to 23.73 pcs/cm²), with increases at 8 positions and decreases at 7. At 6 m/s¹, the mean increased from 21.60 to 42.53 pcs/cm², with higher deposition at all 15 positions. These patterns indicate that the additive-associated change in deposition depended on both flight speed and lateral position.

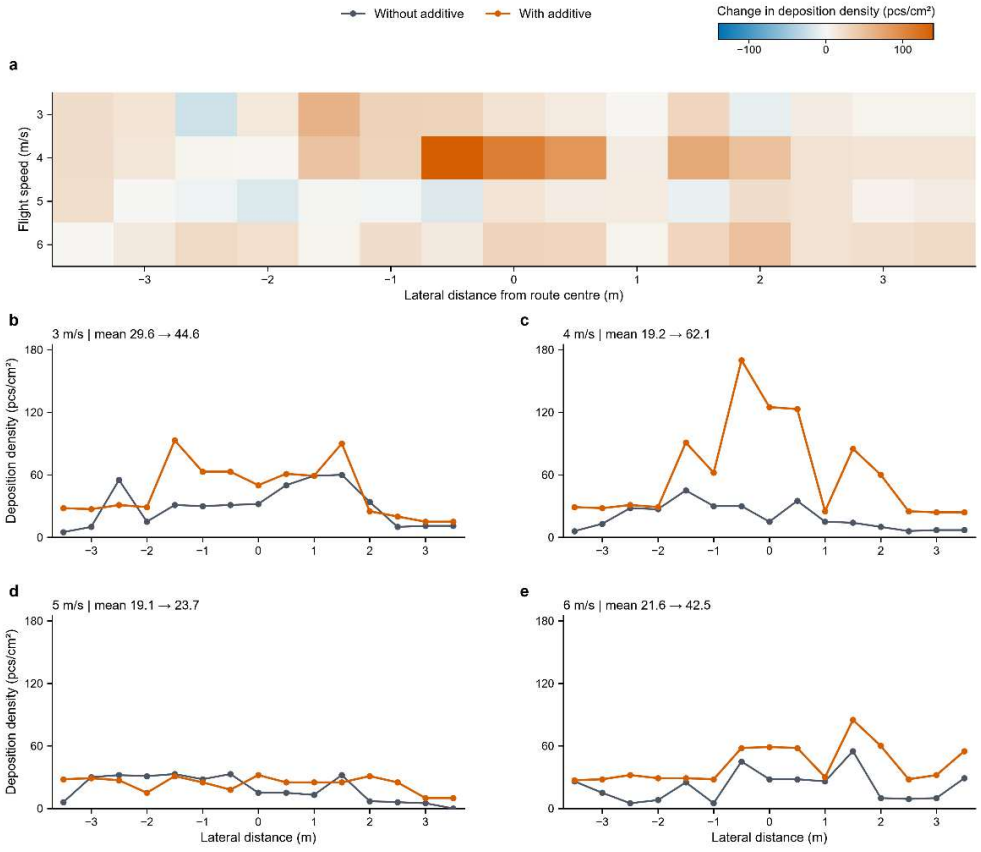


Figure 7. Effects of spray adjuvants and flight speed on the spatial distribution of droplet deposition in rice crops.

When plant protection UAVs are used for pest and disease control, droplet deposition coverage, droplet density, and sedimentation uniformity significantly affect the effectiveness of pest control[39]. Previous studies have shown that spraying uniformity is challenging with UAVs for crop protection, because factors such as rotor wind fields and nozzle positions can affect the uniformity of spraying[40]. The results of this study re-

vealed that the use of adjuvants further improved the uniformity, which significantly affected the effectiveness of pest and disease control. Therefore, when UAVs are selected for spraying operations, suitable spray adjuvants should be chosen as much as possible.

3.3. Spraying effect of different adjuvants

Figure 8a presents the factorial experimental design and factor levels. ANOVA results (Figure 8b) showed that application rate and adjuvant treatment significantly affected effective spray width (both $P < 0.001$), followed by flight height ($P = 0.03$), whereas flight speed had no significant effect ($P = 0.12$). Effect sizes (Figure 8c) further highlighted the importance of application rate (partial $\eta^2 = 0.58$) and adjuvant treatment (0.52). As shown in Figure 8d, the largest observed spray width was obtained at a flight height of 2.5 m, an application rate of 22.5 L/ha, and with Activator 90. Overall, application rate and adjuvant selection were the key factors influencing effective spray width under the tested conditions.

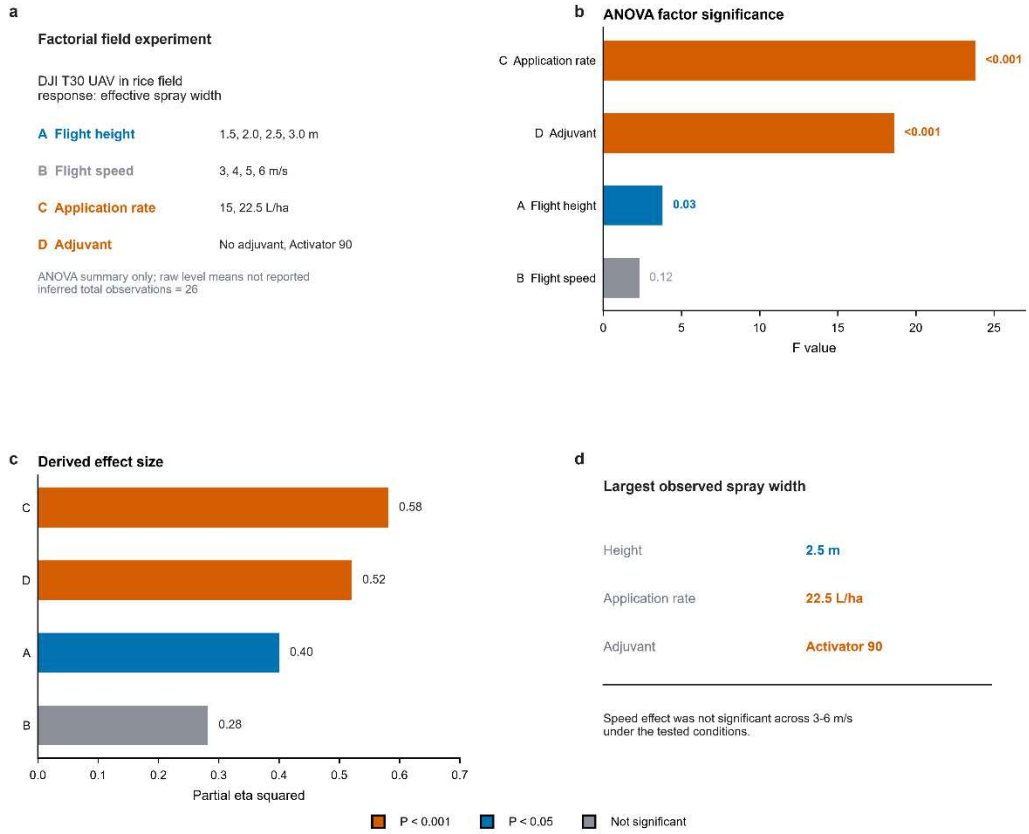


Figure 8. Effects of UAV operating parameters and spray adjuvant treatment on effective spray width.

Figure 9 shows the effects of UAV operating parameters and spray adjuvant treatment on effective spray width. As shown in Figure 9a, effective spray width increased from 4.0 m at a flight height of 1.5 m to a maximum of 5.0 m at 2.5 m, before decreasing to 4.7 m at 3.0 m. In Figure 9b, spray width varied only modestly with flight speed, reaching a minimum of 4.2 m at 4 m/s and remaining at 4.7 m at 5–6 m/s. Figure 9c shows that increasing the applica-tion rate from 15 to 22.5 L/ha increased effective spray width from 4.4 to 5.9 m. As shown in Figure 9d, adding adjuvant increased the measured width from approximately 4.35 to 5.25 m. These patterns indicate that application rate and adjuvant treatment produced larger changes in effective spray width than flight speed under the tested conditions, while the optimal tested flight height was 2.5 m.

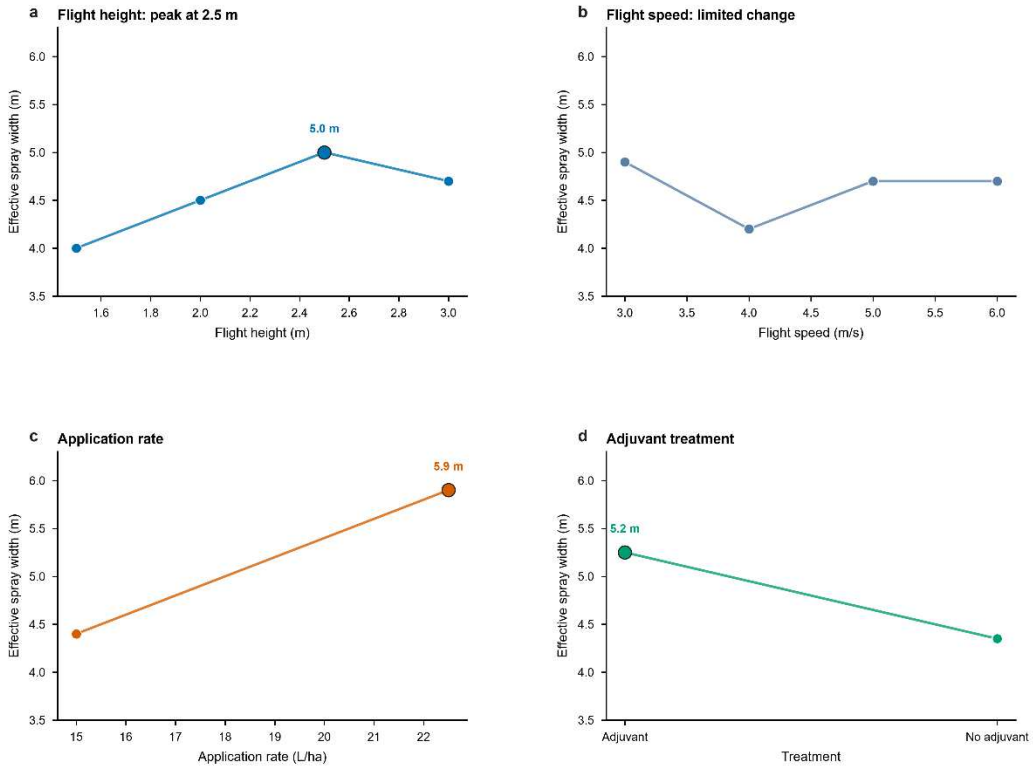


Figure 9. Effects of UAV operating parameters and spray adjuvant treatment on effective spray width.

The wider spray swath observed at 22.5 L/ha may reflect increased deposition near the lateral edges. However, effective spray width also depends on nozzle configuration, droplet properties, downwash airflow, and environmental conditions; these results therefore apply to the tested DJI T30 conditions.

3.4. Field Control Efficacy of Different Adjuvants against Rice Stem Borers

The field efficacy results in Figure 10 reveal how physical properties ultimately translate to biological effectiveness. The high average control efficacy (87%) observed for Activator 90 may be associated with its relatively low surface tension and moderate viscosity, which may favour droplet spreading and retention on rice leaves. The moderate efficacy of Sylgard 309 (78%), despite its relatively low surface tension (22.0 mN/m), suggests that surface tension alone does not determine field efficacy, and other formulation-related factors may also contribute. The lower efficacies of LI-700 and Aeromate 480 (77% each) may be related to their relatively high viscosity and surface tension. Higher viscosity may increase droplet retention and reduce susceptibility to drift; however, excessive viscosity may also restrict droplet spreading, penetration, or redistribution on target surfaces. The observed differences in field efficacy should also be interpreted in the context of the meteorological conditions during application. Wind speed and relative humidity can affect droplet transport, evaporation, and retention on rice foliage, thereby influencing the amount of active ingredient reaching the target. Therefore, the efficacy values obtained in this study represent the performance of the tested adjuvants under the environmental conditions recorded during the field trial.

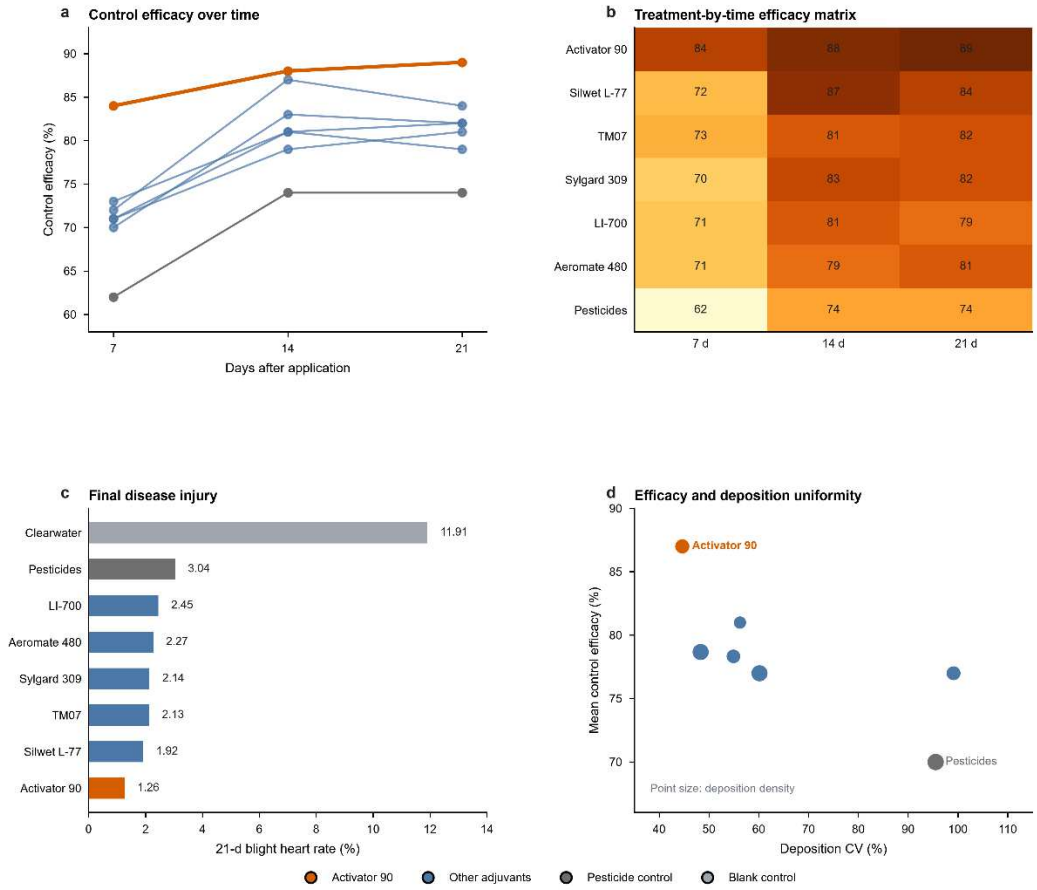


Figure 10. Temporal dynamics of field control efficacy of different spray adjuvants against rice stem borers.

Figure 10a shows that control efficacy increased from 7 to 14 days after application and then generally stabilized. Activator 90 consistently achieved the highest efficacy (84%, 88%, and 89% at 7, 14, and 21 days, respectively), whereas the pesticide-only treatment reached 62%, 74%, and 74%. As shown in Figure 10b, Activator 90 maintained the highest efficacy at all three assessment times, while the other adjuvants generally produced intermediate values. Figure 10c confirms this pattern: Activator 90 had the lowest final disease injury rate (1.26%), followed by Silwet L-77 (1.92%), TM07 (2.13%), Sylgard 309 (2.14%), Aeromate 480 (2.27%), and LI-700 (2.45%); the pesticide-only and clearwater treatments showed higher injury rates of 3.04% and 11.91%, respectively. These results indicate that Activator 90 provided the strongest and most sustained field control under the tested conditions.

Figure 10d further illustrates the relationship between mean control efficacy and deposition uniformity. Activator 90 combined the highest mean efficacy (approximately 87%) with a relatively low deposition CV (about 45%), whereas the pesticide-only treatment showed lower efficacy (approximately 70%) and a higher CV (about 95%). The other adjuvants generally showed intermediate mean efficacy, despite variation in deposition CV and density. This pattern suggests that more uniform droplet deposition may contribute to improved field control, although efficacy is also likely influenced by other formulation and application factors.

This outcome suggests that droplet distribution uniformity may contribute substantially to pest control under the tested conditions.Excessively high coefficients of variation (such as 95.5% for the pesticide-only treatment) indicate clustered droplet distribution within the canopy, creating extensive uncovered or inadequately covered ‘safe zones’ where pests can survive and reproduce. Conversely, Activator 90 improved deposition

uniformity, which may help reduce areas with insufficient droplet coverage. This maximizes the elimination of pest refuges, achieving more thorough population control.

4. Conclusion

Indoor experiments in this study revealed that when different adjuvants were added to the pesticide solution and droplets were applied to the rice leaves, significant differences in the spreading characteristics and spreading time were observed. On the basis of their spreading performance, the overall ranking was as follows: Activator 90 > TM07 > Sylgard 309 > Aeromate 480 > Silwet L-77 > LI-700. This observed difference may be associated with differences in the physicochemical properties of the adjuvants, particularly surface tension, which is consistent with recent research indicating that low surface tension adjuvants (e.g., Activator 90) can rapidly disrupt the interfacial energy between the droplet and the leaf surface, facilitating fast spreading.

Field spray width tests showed that, under the specific operating conditions tested, the measured effective spray width was greater at the higher application volume, and adjuvant addition was also associated with increased effective spray width. This may be related to changes in spray-liquid physicochemical properties and their effects on droplet transport and deposition. The effective spray width first increased and then decreased with increasing flight height, reaching a maximum at 2.5 m, which may be related to the interaction between UAV downwash airflow and droplet sedimentation trajectories. Under the tested conditions, the combination of a 2.5 m flight height, 22.5 L/ha application volume, and adjuvant addition resulted in the greatest measured effective spray width; however, this optimal combination is specific to the DJI T30 and the experimental conditions used in this study.

Analysis of the droplet deposition density and the coefficient of variation (CV) of the upper crop layer elucidated the distribution patterns of deposition with and without different adjuvants. Overall, the data revealed that adjuvants significantly reduced the CV and improved the uniformity of the droplet distribution. Activator 90 achieved the lowest CV (44.6%) and showed the most uniform droplet deposition among the tested adjuvant treatments.There was no significant difference in the improvement effect between Silwet L-77 and Aeromate 480, whereas LI-700 performed the worst. These findings highlight that in modern precision pesticide applications, deposition uniformity is as crucial as, if not more critical than, absolute deposition density because uniform coverage decreases the number of control blind spots. This finding further highlights the importance of deposition uniformity in achieving effective coverage.

Field efficacy trials confirmed that the addition of adjuvants significantly increased the control efficacy of chlorantraniliprole against the rice stem borers. During the 21-day investigation period, the average control efficacy for adjuvant-treated plots was 77%–87%, whereas it was only 70% for the treatment without adjuvant. The synergistic effects of the different adjuvants were ranked as follows: Activator 90 > Silwet L-77 > TM07 > Sylgard 309 > Aeromate 480 = LI-700. This ranking was broadly consistent with the observed differences in deposition uniformity, suggesting that more uniform droplet deposition may contribute to improved field control efficacy under the tested conditions.

Funding: This research was funded by the Special Funding for Suzhou Polytechnic Institute of Agriculture Innovative Research Team (CXTD202403); Project of the Future Industry Research and Development Program of Liaoning Province (2026JH40/10200045); National Natural Science Foundation of China (Grant No. 31971804).

Data Availability Statement: The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare that they have no conflicts of interest. The founding sponsors played no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Statement: Permission was obtained from the relevant authorities and stakeholders to conduct this study in the agricultural field.

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