Impacts of surfactant-based adjuvants on spray droplet size, drift distance, and deposition efficiency

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Abstract: The application of anti-drift nozzles, such as air-induction nozzles, is the most common recommendation for reducing spray drift; To reduce the risk of coarse droplets bouncing and rolling produced by anti-drift nozzles, various types of adjuvants were screened by comparing their atomization performance, surface tension and contact angle, in order to identify favourable adjuvants that are compatible with anti-drift nozzles. It was found from the study results that the addition of 50% neem crude oil emulsifiable concentrate (neem oil), isomeric alcohol ethoxylates and BYK-405 all significantly decreased distribution span (S) and the percentage of droplet size less than 150 μm ($\Phi Vol_{<150\mu m}$) values, but significantly promoted the median volume (D_{50}) value. And the surface tension measurement results showed that all tested adjuvants significantly reduced the surface tension, while neem oil, FC4430 and silwetl-77 were observed with a most significant effects; Furthermore, all tested adjuvants except BYK-051N could also significantly decrease the contact angle, and the difference between neem oil, FC4430 and silwetl-77 was significant. Wind tunnel test results clearly demonstrated that the application of IDKA (a combination of air-induction nozzle IDK120-01 and neem oil) substantially decreased the drift deposition amount; In addition, the field experiments revealed that IDKA possessed a significantly improved deposition amount per unit area on canopy or bottom, leading to a more effective deposition. These results suggest that the use of IDK120-01 nozzle and neem oil can effectively reduce spray drift, lessen surface tension and enhance spreading.

Keywords: spray drift, unmanned aerial vehicles, air-induction nozzles, surface tension, contact angle
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1 Introduction

Plant protection unmanned aerial vehicles (UAVs) are becoming increasingly popular for controlling crop pests, especially in rice cultivation; In comparison to traditional automatic or semi-manual plant protection equipment, UAVs offer significant advantages in terms of spraying efficiency, performance, and precision[1]. The utilization of plant protection UAVs for plant protection has become increasingly popular due to their ability to prevent rapid outbreaks of insects, diseases and weeds in rice paddy fields. As an emerging technology, UAVs spraying has induced many practical issues, particularly with regard to spray drift[2]. With the increasing environmental awareness, controlling spray drift has become a pressing concern for technology research. The research of spray drift has been focused on the droplet size, nozzle configurations and so on[3]. As the core component of plant protection UAVs, nozzle is the key factor affecting the spray drifts, because nozzles with good spray performance can promote the uniformity and amount of droplet deposition and ultimately improve the spray quality[4]. Dafsari et al.[5] found that the air-induction nozzle could bring about larger droplets including air bubble, which had less drift potential. Air-induction nozzles could produce large droplets containing some air bubbles so as to mitigate spray drift and possibly increase droplet deposit[6].

Although coarse droplets can reduce spray drift, there is a greater risk of bouncing and rolling on the leaves resulting in the deposition reduction[7]. To prevent the loss of droplets due to bouncing or rolling off target, adjuvants can be added to the spray solution. These agents are effective in reducing the surface tension of the liquid, causing droplets to converge and ultimately increase the deposition rate on the plant surface[8,9]. By improving droplet adhesion to the foliage, adjuvants enhance the efficiency of UAV-based spraying operations for pest control and crop protection. In addition to altering surface tension, Ellis et al.[10] performed a detailed study on how different adjuvants affected the atomization performance of nozzles, finding that adjuvants significantly affected the variation of droplet size. The properties of the liquid are also the main factors affecting the effectiveness of pesticide control in previous studies[11,12].

This study uses the ground drift collection method, one of two methods for collecting spray drift, to compare drift potential index across different treatments[13]. The method involves using petri dishes, mylar or filter paper to collect droplets, and is commonly used for this purpose. Bueno et al.[14] and Heidary et al.[12] collected ground drift data at 2.0, 4.0, 8.0, 16.0 and 27.5 m in the field and a

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wind tunnel, respectively, and found that the median volume D_{50} and $\Phi Vol_{<150\,\mu m}$ significantly impacted the spray drift. Wang et al.[15] conducted an analysis of the droplet spectrum and drift potential index of various types of tank-mix adjuvants; Gao et al.[16] compared the spreading performance of Silwetl-77, 6501, JFC, and Greenwet720 to improve the diffusion and adhesion; Meanwhile, Liu et al.[17] focused on the effects of sodium dodecyl sulfate, aerosol OT, and 1% silicone on liquid sheet breakup. In this study, the atomization performance and surface tension of various new adjuvants and their impact on drift deposition and contact angle were assessed. This study aimed to identify adjuvants with optimal spreading, wetting performance, and anti-drift characteristics, which would contribute to ameliorating the theoretical basis for selecting suitable plant protection apparatuses and adjuvants for plant protection UAVs in rice cultivation.

2 Materials and methods

2.1 Materials

A 10.00% cyantraniliprole oil dispersion (trade name: Benevia®) was supplied by DuPont Co., Ltd, Shanghai, China. Allura red (85.00%) was supplied by Shanghai Yuanye Biotechnology Co., Ltd, Shanghai, China. Details of silwetl-77, FC4430, isomeric alcohol ethoxylates, BYK-405 and BYK-051N were summarized in Table 1. Neem crude oil (45.97% oleic acid), obtained by cold pressing neem seeds, and 50.00% neem crude oil emulsifiable concentrate (neem oil) were supplied by Chengdu Lvjin Biotechnology Co., Ltd, Chengdu, China. The tested nozzles were purchased from the market (Table 2).

Table 1 Component identification of the test adjuvants

Trade Name	Registration Holder	Main Ingredient	Type	Possible Properties
Silwetl-77	Momentive, USA	Polyethoxylated heptamethyl trisiloxane	Organosilicone surfactant	Spreader
Neem oil	Green Gold, China	Vegetable oil Oleic acid	Surfactant	Synergist
FC4430	General Electric, USA	Fluorosurfactant	Nonionic polymeric fluorinated surfactants	Wetting agent
Isomeric alcohol ethoxylates	Badische, Germany	Isodecanol ethylene oxide	Non-ionic surfactant	Emulsifier
BYK-405	BYK, Germany	Methylmercuric iodide pyrrolidone	Surfactant	Anti-setting agent
BYK-051N	BYK, Germany	Bubble-breaking polymer	Surfactant	Defoamer

Table 2 Nozzles used in the study at their respective angle and D_{50}, and notable characteristics[a]

Nozzle	Angle, type, D_{50}	Manufacturer	City and country	Nozzle characteristics
IDK120-01	120°, 1, 261 μm	Lechler	Metzingen, Germany	Air-induction nozzle
XR-110-015	110°, 15, 155 μm	TeeJet	Illinois, United States	Anti-drift nozzle

Note: [a] All nozzle treatments were operated at 0.3 MPa.

2.2 Spraying platform and spraying systems

The test platform included a particle size measurement system and a spray system which can work under the different working pressures. The droplet size measurement system was composed of a laser particle sizer (DP-2, Zhuhai Europe and America Instrument Co., Ltd.) and a computer.

The spray drift test was carried out in the wind tunnel with the dimensions of length×width×height=7.5 m×1.0 m×1.0 m (Anyang Quanfeng Biotechnology Co., Ltd., China) (Figure 1). One end of the air inlet was guided by the comb grid, and the other end had an axial-flow fan with a 0.9 m diameter to produce One end of the air inlet was guided by the comb grid, and the other end had an axial-flow fan with a 0.9 m diameter to produce a stable, continuously adjustable wind speed of 0 to 8 m/s in the working space.

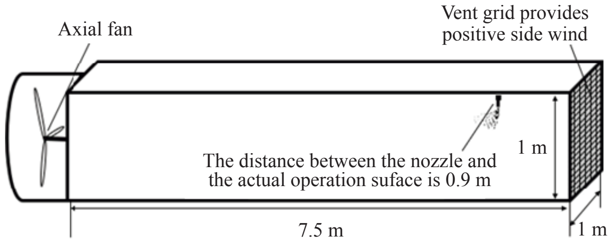


Figure 1 Schematic diagram of open wind tunnel

2.3 Measurement and analysis of atomization performance of different adjuvants

The nozzle (XR-110-015) was vertically installed 2 m above the laser beam in the test area. 10 mL of each adjuvant was diluted with 1 L of water using the pure water as the blank control, and the distribution of droplet particles was measured under 0.3 MPa of spray pressure. Each treatment was performed in triplicate. The droplet size parameters (D_{10}, D_{50}, D_{90}, and $\Phi Vol_{<150\,\mu m}$) were recorded. D_{10} values stand for the 10% cumulative distribution in all droplet diameters, that is, this droplet diameter range accounts for no more than 10% of the total number of droplets; similarly, D_{50} and D_{90} are 50% and 90% of the cumulative distribution of all the droplet diameters, respectively. The distribution span (S) delegates the distribution width of droplet size via the following equation: $S = (D_{90}–D_{10})/D_{50}$; another index, $\Phi Vol_{<150\,\mu m}$, is the percentage of droplet size less than 150 μm for the total droplet volume.

2.4 Measurement of the surface tension of liquids

1 mL of different adjuvant or different volumes of silwetl-77 and FC4430 were diluted with 1 L water, and their surface tensions under unbalanced conditions were detected with a ZL-2 automatic surface tension meter (Shandong Sanpu Kesen Instrument Co., Ltd., China) using the ring method. The monitoring time range was from 0 to 180 s under the condition of (30.1±0.1)°C. All treatments were repeated three times, and the difference in surface tension was within 1 mN/m[18].

2.5 Measurement of the contact angle and evaporation rate of liquids

1 mL of different adjuvant or different volumes of silwetl-77 and FC4430 were diluted with 1 L of water, and their contact angle and evaporation rate of various liquids under balanced conditions were detected with a SD-100S contact angle meter (Dongguan Shengding Precision Instrument Co., Ltd., China), using the SessileDrop[19] and PendantDrop[20] method, respectively. The monitoring time range was from 0 to 3 h under the condition of (25.5±0.2)°C and (56.4±0.5)% by a RS-WS-N01-2C-* humidity transmitter (Shandong Renke Measurement and Control Technology Co., Ltd., China). To prepare for the experiment, fresh rice leaves into 10 mm×10 mm squares were first cut, avoiding the main vein, and fixed them onto microscope slides according to the protocol of Gao et al.[16] Then, a 5 μL droplet was formed at the tip of a microsyringe and gently deposited it onto the prepared leaves. Images were immediately collected after the droplet was deposited, at intervals of 0, 200, 400, and 600 ms, respectively, using a charge-coupled device camera. Finally, SDC-200 software and a five-point fitting method were used to calculate the dynamic changes in

contact angle between the droplet and the rice leaf, which allowed us to estimate the spreading ability. The evaporation rate was measured by the SD-100S contact angle meter as the following steps: A microinjection syringe was used to pick up a small amount of liquid which was then vertically fixed above a temperature-controlled box; The connected water bath and temperature-controlled box were adjusted to 25°C; After the instrument was stabilized, a single droplet of 4 μL was produced by the microinjection syringe controlled by the software and suspended on the needle of the instrument; The software selected video recording mode, and the high-speed camera automatically captured the droplet per second during the whole process of evaporation; The volume change of the droplet with time was obtained by data processing software, and the droplet evaporation rate and droplet evaporation inhibition rate were calculated[21]. Each test was repeated at least three times.

2.6 Effect of different adjuvants and nozzles on the droplet size and the amount of drift deposited

The drift experiment of adjuvants and nozzles was carried out in a wind tunnel (Figure 1). Nine droplet collectors (5 cm × 8 cm mylar and photo paper) were arranged at distances of 1 m, 2 m, and 3 m in the downwind direction from the nozzle's perpendicular plane. Each row consisted of three droplet collectors arranged with a horizontal spacing of 0.3 m. The spray parameters were adjusted according to the ISO22369-2-2010 test procedures and basis before testing. The spray test of ambient temperature was from 28°C to 30°C, and the relative humidity was from 70% to 80%.

5000 mg/L allura red and 0.5 g/L Benevia® were added into the pure water, then the different adjuvants (10 g/L) or equal volumes of water were added to create solution A (neem oil), solution B (FC4430), solution C (silwetl-77), and solution D (blank control). Different treatments, including XR-110-015 plus solution D (abbreviated with XRD), IDK120-01 plus solution A (abbreviated with IDKA), IDK120-01 plus solution B (abbreviated with IDKB), IDK120-01 plus solution C (abbreviated with IDKC), IDK120-01 plus solution D (abbreviated with IDKD) were used to spray under a condition of a 2 m/s wind speed and a 0.3 MPa pressure in the wind tunnel. Each treatment was performed in triplicate. When the droplets were dried, the mylar and photo paper were put into disposable gloves, then transferred into a black bag in a cool environment for evaluating the atomization and drift performances for each treatment.

The atomization performance was evaluated using a scanner (Epson, V600) to scan the size and density of droplet particle on the photo paper. Data such as D_{10}, D_{50}, D_{90}, and estimated drift deposition amounts were analyzed with the software DepositScan (ARS Headquarters Co., Ltd, Washington, United States)[22].

Ground drift deposition amounts were detected using the following method: 0.3067 g of Allura red was accurately weighed and dissolved in 100 mL of deionized water and further diluted to the standard solution with concentrations of 191.69, 95.84, 47.92, 23.96, 11.98, 5.99, 3.00 and 1.50 mg/L. Then, the absorbance values were detected with a microplate reader (Migu Molecular Instruments (Shanghai) Co., Ltd., CMax Plus) at 514 nm. The Allura red on the mylar was eluted with 5 mL of deionized water, and its absorbance was measured at 514 nm with a microplate reader.

The deposition percentage per pv and anti-drift effect RT were detected via an industry standard, the MH_T1050-2012 aircraft spray drift field measurement method, with the following equation:

$$\text{Drift deposition percentage per mylar pv}=(\rho_1 V_1)/(tV_2\rho_2)\times 100\%$$

$$\text{Anti}-\text{drifteffectRT}=\frac{\sum(\text{pvC}\times\text{driftdistance})-\sum(\text{pvT}\times\text{driftdistance})}{\sum(\text{pvC}\times\text{driftdistance})}\times 100\%$$

where, ρ_1 is the concentration of allura red of the drift deposition, mg/L; ρ_2 is the concentration of the Allura red of the test solution and control solution, mg/L; V_1 is the volume of deionized water dissolved on the mylar, L; V_2 is the nozzle flow, L/min; t is the spray time, min; pvC is the drift deposition percentage of nozzle XR-110-015 at different drift distances; pvT is the drift deposition percentage of the test nozzle at different drift distances.

2.7 Comparison of spray effect of different treatments of UAV in the field

During the peak period of rice tillering (July 1, 2020), the UAVs (DJI MG-1P, Shenzhen DJI Innovation Technology Co., Ltd.) sprayed 1 L dosage of solution A, C and D onto 600 m^2 with XR-110-015 and IDK120-01 nozzles, separately. Their isolation zone between the two communities was 300 m^2, each treatment had 3 repetitions. The flight parameters were respectively set to an altitude of 1.5 m, and a direction of perpendicular to the wind. The meteorological data during operation were 24.33°C air temperature, 86.87% air humidity, and 1.81 m/s northeast wind speed. Before the operation, the collection cards (5 cm×8 cm mylar) were arranged on the canopy, medium and bottom layers of crop, and their coefficient variation was used to evaluate the spray penetration rate. Afterwards, 10 rice plants at 5 randomly selected points were collected and measured, the deposition amount of Allure red on a rice plant was regarded as effective deposition, and the theoretical deposition was also calculated. The effective deposition rate was equal to the value, the effective deposition divided by the theoretical deposition.

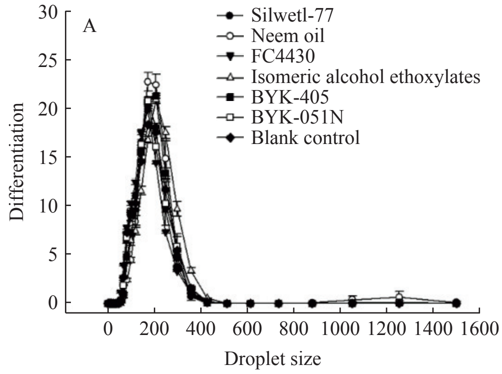
2.8 Data analysis

The values of S, $\Phi\text{Vol}_{<150\,\mu m}$, D_{50}, anti-drift effect, surface tension and contact angle of droplets deposited by different adjuvants were compared by using analysis of variance (ANOVA) followed by Tukey's test for multiple comparisons (p<0.05) with the SPSS version 17.0 software package (IBM) and were plotted by Sigmaplot 12.5. And the values of S, $\Phi\text{Vol}_{<150\,\mu m}$, D_{50}, the drift deposition amounts and the drift amounts of droplets deposited by different adjuvants and nozzles drifted at different distances were compared by using analysis of multivariate followed by Tukey's test for multiple comparisons (p<0.05) with the SPSS version 17.0 software package (IBM).

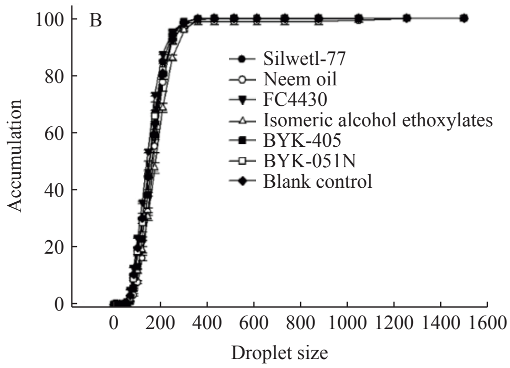
3 Results

3.1 Effect of different adjuvants on atomization performance

When the XR-110-015 nozzle sprayed the solution containing different adjuvants at a pressure of 0.3 MPa, the S values of neem oil (0.76) and BYK-405 (0.85) were the lowest, followed by the treatments of isomeric alcohol ethoxylates (0.93) and silwetl-77 (0.91), they all were significantly higher than those of BYK-051N (0.98), FC4430 (0.97) and the blank control (0.98) (p<0.05) (Table 1). Compared with the blank control (155.55), the D_{50} values of neem oil (169.61) and isomeric alcohol ethoxylates (179.97) were significantly promoted (p<0.05); the D_{50} values of silwetl-77 (153.26), BYK-405 (163.23) and BYK-051N (154.36) were comparative to the blank control and were higher than that of FC4430 (142.92) (p<0.05). The value of $\Phi\text{Vol}_{<150\,\mu m}$ of FC4430 (53.47) was significantly higher than those of other treatments (p<0.05); in contrast, the lowest values of $\Phi\text{Vol}_{<150\,\mu m}$ were neem oil and isomeric alcohol ethoxylates observed with the value of 32.52 and 30.88, respectively (Figure 2, Table 3).



a. Percentage of the number of different particle size in total droplets



b. Cumulative percentage of the number of droplet smaller than a certain particle size to the total droplets

Figure 2 Distribution characteristics of spray droplets of different adjutants under XR-110-015 and 0.3 MPa

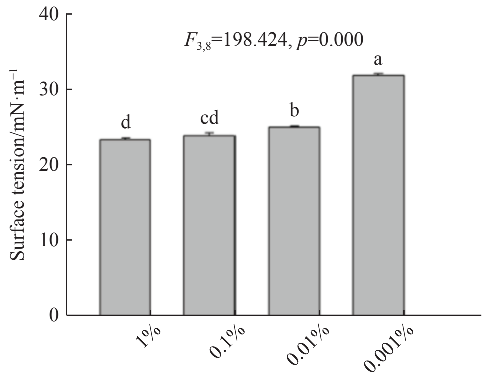
Table 3 The spray droplet characteristics of different adjutants

Adjutants	S±SD	D_{50}±SD	$\Phi Vol_{<150\,\mu m}$±SD
Silwetl-77	0.91 ± 0.01^{b}	153.26 ± 1.02^{c}	45.98 ± 0.76^{b}
Neem oil	0.76 ± 0.02^{d}	169.61 ± 1.87^{b}	32.52 ± 0.93^{d}
FC4430	0.97 ± 0.01^{a}	142.92 ± 0.47^{d}	53.47 ± 0.37^{a}
Isomeric alcohol ethoxylates	0.93 ± 0.01^{b}	179.97 ± 1.80^{a}	30.88 ± 0.98^{d}
BYK-405	0.85 ± 0.01^{c}	163.23 ± 0.77^{b}	38.64 ± 0.47^{c}
BYK-051N	0.98 ± 0.001^{a}	154.36 ± 4.73^{c}	45.10 ± 3.48^{b}
Water	0.98 ± 0.01^{a}	155.55 ± 0.57^{c}	44.94 ± 0.37^{b}
$F_{6,14}$ values	70.19	33.19	30.289
p-values	0.000	0.000	0.000

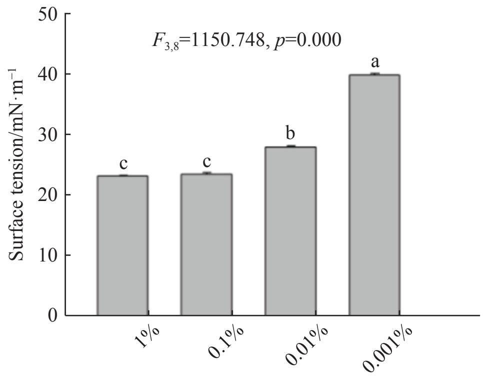
Note: SD is standard deviation. Means within a row followed by different lowercase and uppercase letters are significantly different using the paired bootstrap test procedure (p<0.05).

3.2 Effect of different adjuvants on the surface tension of liquids

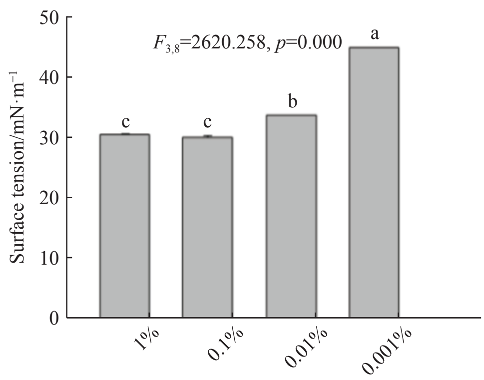
There was a significantly decreased tendency on the surface tension with the increased concentrations of silwetl-77 (Figure 3a), FC4430 (Figure 3b) and isomeric alcohol ethoxylates (Figure 3c). The surface tensions of 0.001% concentration of silwetl-77 (32.0 mN/m), FC4430 (39.8 mN/m) and isomeric alcohol ethoxylates (44.8 mN/m) were the strongest (p<0.05), followed by the 0.01% concentration of silwetl-77 (25.1 mN/m), FC4430 (27.9 mN/m) and isomeric alcohol ethoxylates (33.6 mN/m) (p<0.05), and finally the 0.1% (24.0 mN/m, 23.4 mN/m, 30.0 mN/m) and 1% (23.4 mN/m, 23.0 mN/m, 30.4 mN/m) concentrations of the tested adjuvants with no noticeable difference between each other (p>0.05).



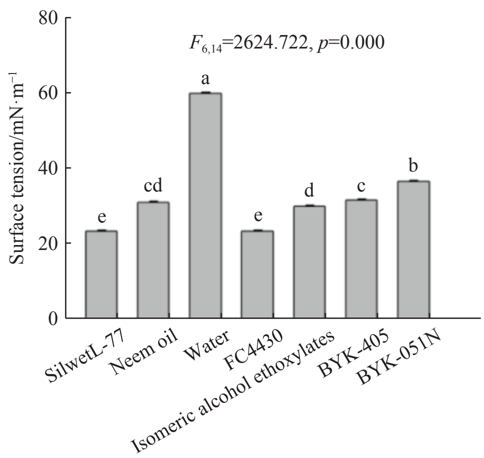
a. Different concentration of silwetl-77



b. Different concentration of FC4430



c. Different concentration of isomeric alcohol ethoxylates



d. 0.1% concentration of different adjuvants

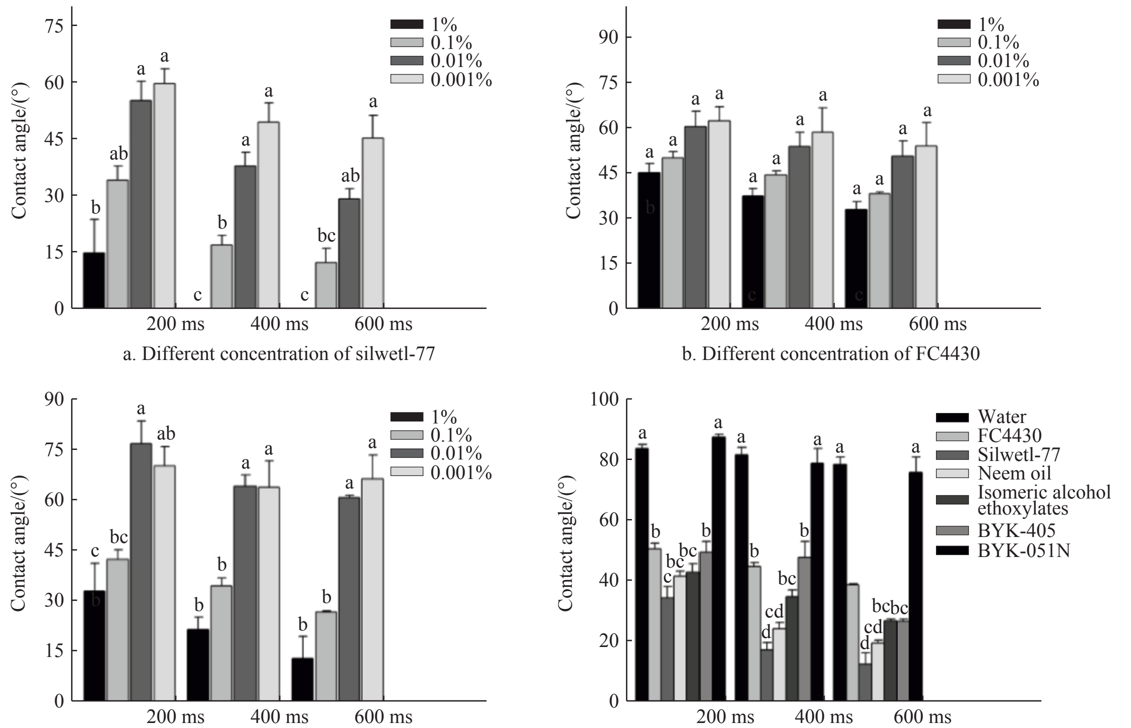
Note: Different letters above bars indicate significant differences (p<0.05), and the same letter are not significantly different (p>0.05) according to Tukey's multiple range test.

Figure 3 Effects of different adjuvants on surface tension of liquids

The addition of 0.1% concentration adjuvants had a significant effect on the surface tension. The surface tension of water (59.8 mN/m) was significantly greater than those of the other solutions added with different adjuvants ($p<0.05$), for example, those of BYK-051N (36.7 mN/m) and BYK-405 (31.7 mN/m), while those of silwetl-77 (23.4 mN/m) and FC4430 (23.4 mN/m) was the lowest among the treatments. Additionally, the surface tension of solutions with neem oil neem oil (31.1 mN/m) or isomeric alcohol ethoxylates (30.0 mN/m) also had significantly decreased the surface tension compared with water (Figure 3d).

3.3 Effect of different adjuvants on the contact angle between liquids and rice

The contact angles were measured to assess the effect of different concentrations of adjuvants on the wettability of the rice crop surfaces. The contact angles were decreased with increasing concentrations of silwetl-77 (Figure 4a), FC4430 (Figure 4b) and isomeric alcohol ethoxylates (Figure 4c) at 200, 400, and 600 ms, which of the 1% concentration of silwetl-77 was the lowest, at 200, 400, and 600 ms with 14.80°, 0.00°, and 0.00° respectively, followed by the 0.1% (34.04°, 16.85°, and 12.21°), 0.01% (55.09°, 37.81°, and 29.11°, respectively), and 0.001% concentration (59.71°, 49.37°, and 45.21°) at 200, 400, and 600 ms, respectively (Figure 4A). Meanwhile, the contact angle of 1% FC4430 (32.936°-45.241°) at 200, 400, and 600 ms was the lowest, followed by the 0.1% (38.294°-50.108°), 0.01% (50.657-60.507°) and 0.001% concentration (53.941°-62.347°) with no striking difference between each other ($p>0.05$) (Figure 4b). Further, the contact angle of 1% (12.765°-32.867°) and 0.1% (26.533°-42.377°) isomeric alcohol ethoxylates at 200, 400, and 600 ms, with no significant difference between each other ($p>0.05$), all were lower than those of 0.001% concentration (63.813°-70.223°) (Figure 4c). Overall, higher adjuvant concentrations led to lower contact angles and improved surface wetting, which could increase the effectiveness of pesticide applications.



a. Different concentration of silwetl-77

b. Different concentration of FC4430

c. Different concentration of isomeric alcohol ethoxylates

d. Different concentration of FC4430

Note: Different letters above bars indicate significant differences ($p<0.05$), and the same letter are not significantly different ($p>0.05$) according to Tukey's multiple range test. The $F_{3,8}$ values of the contact angle of 0.1% concentration of different adjuvants at 200 ms, 400 ms, 600 ms were 70.249, 57.582, 104.475, and the p-values on the contact angle of 0.1% concentration of different adjuvants at 200 ms, 400 ms, 600ms were 0.000, 0.000, 0.000, respectively. The $F_{3,8}$ values of the contact angle of different concentration of silwetl-77 at 200 ms, 400 ms, 600 ms were 12.675, 42.076, 26.792, and the p-values on the contact angle of different concentration of silwetl-77 at 200 ms, 400 ms, 600 ms were 0.002, 0.000, 0.000, respectively. The $F_{3,8}$ values of the contact angle of different concentration of FC4430 at 200 ms, 400 ms, 600 ms were 4.430, 3.749, 4.265, and the p-values on the contact angle of different concentration of FC4430 at 200 ms, 400 ms, 600 ms were 0.041, 0.060, 0.045, respectively. The $F_{3,8}$ values of the contact angle of different concentration of isomeric alcohol ethoxylates at 200 ms, 400 ms, 600 ms were 11.647, 19.347, 28.986, and the p-values on the contact angle of different concentration of FC4430 at 200 ms, 400 ms, 600 ms were 0.003, 0.001, 0.000, respectively.

Figure 4 Effect of different adjuvants on the contact angle of liquids

The addition of 0.1% concentration adjuvants had significant effects on the contact angle of the solution at 200, 400, and 600 ms, among which of water at 200, 400, and 600 ms (83.40°, 81.32°, and 78.04°, respectively) were significantly higher than those of the other treatments ($p<0.05$). The contact angles of silwetl-77 (34.04°, 16.85°, and 12.21°) and neem oil (41.05°, 23.75°, and 19.19°) were the lowest with no striking difference between each other ($p>0.05$) (Figure 4d and Figure 5).

3.4 Effect of different adjuvants on the evaporation rate of liquids

There were significantly positive linear correlations between the volume of silwetl-77, FC4430, neem oil, or water and experimental time. The curve had the high coefficient R^2 (0.901-0.999) and adjusted coefficient R^2_{adj} (0.812-0.998), suggesting the over 90.1% variability from the tested model. Meanwhile, the slopes of water, FC4430, neem oil and silwetl-77 were about 0.003

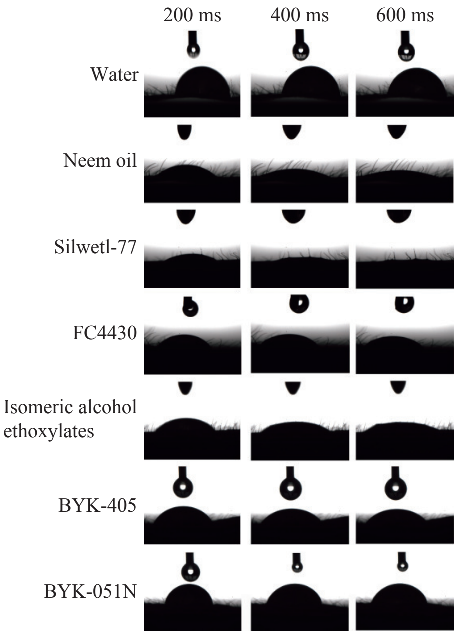


Figure 5 Contact angles of different adjuvants at 200 ms, 400 ms, and 600 ms

with the almost same evaporation rates, they were higher than that of Isomeric alcohol ethoxylate (0.002) and lower than those of BYK-405 (0.004) and BYK-051N (0.005) (Table 4). Based on the observation, 5 μL of 1% silwetl-77 and neem oil solutions could fully spread in a short time.

3.5 Drift deposition of different treatments at different distances

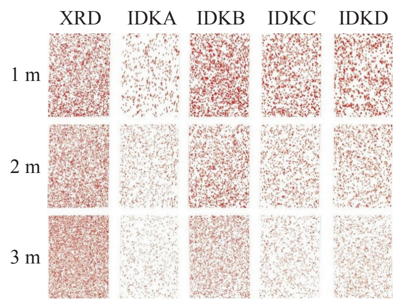
The deposited droplet particles of different treatments at different distances were analyzed by scanning the photo paper (Figure 6), and the results are listed in Table 5. The results indicated that there was an extremely significant difference among different treatments in the droplet volume D_{50}, S values and estimated drift deposition amounts (p<0.01, respectively); Additionally, the D_{50}, S value and estimated drift deposition amount of IDKA (240.00 μm, 0.48, 0.26 μL/cm^2, respectively) were the least, followed by those of IDKC (307.26 μm, 0.68, 0.62 μL/cm^2, respectively) and IDKB (320.74 μm, 0.71, 0.76 μL/cm^2, respectively), and they all were significantly lower than the XRD treatment (342.33 μm, 0.96, 1.30 μL/cm^2, respectively). Meanwhile, The D_{50}, S values and estimated drift deposition amounts of different drift distances were extremely different (p<0.01), among which of 3 m (236.96 μm, 0.63, 0.45 μL/cm^2, respectively) and 2 m (278.67 μm, 0.68, 0.56 μL/cm^2, respectively) were significantly lower than that of 1 m (393.69 μm, 0.85, 1.20 μL/cm^2, respectively). Among multiple factors, the interaction between factors A and B was extremely significant (A×B, F=9.89, df = 8, p=0.000<0.01).

Table 4 The evaporation rate of different adjutants

Adjutants	Lineweaver-burk curve	Correlated index (R^2)	Adjusted coefficient (R^2_{adj})	F	Slope (95% confidence interval)
Water	V = (4.627±0.007) – (0.003± 0.00) t	0.998	0.995	$F_{1,28}$=5759.31***	0.003***
FC4430	V = (3.435±0.008) – (0.003±0.00) t	0.996	0.992	$F_{1,28}$=3526.22***	0.003***
Neem oil	V = (4.663±0.006) – (0.003±0.00) t	0.997	0.995	$F_{1,12}$=2219.40***	0.003***
Silwetl-77	V = (3.649±0.005) – (0.003±0.00) t	0.999	0.998	$F_{1,27}$= 15 163.22***	0.003***
Isomeric alcohol ethoxylates	V = (4.640±0.026) – (0.002±0.00) t	0.901	0.812	$F_{1,13}$=55.995***	0.002***
BYK-405	V = (4.365±0.019) – (0.004±0.00) t	0.992	0.985	$F_{1,28}$=1784.39***	0.004***
BYK-051N	V = (4.360±0.017) – (0.005±0.00) t	0.995	0.991	$F_{1,28}$=2922.94***	0.005***

3.6 Effect of different treatments on the drift deposition amounts and the percentage of drift deposition per mylar

The standard curve of the absorbance and concentration of allure red was obtained (Y= 0.0132X+0.0356, R^2=0.9996). The drift deposition amounts of different treatments at different distances were measured by eluting the mylar, and the drift deposition percentages per mylar (pv) of each treatment were calculated according to the formula above. The results indicated that the drift deposition amounts and pv value were extremely significant among different treatments (p<0.01), those of the XRD (1.26 μg/cm^2, 0.06%, respectively) were significantly higher than the IDKD (0.82 μg/cm^2, 0.04%, respectively) and IDKC (0.84 μg/cm^2, 0.04%, respectively), and those of the IDKA (0.70 μg/cm^2, 0.04%, respectively) were significantly lower than others; the drift deposition amounts and pv value of different distance were extremely significant (p<0.001), while those of 1 m (1.24 μg/cm^2,



Note: XRD: XR-110-015 plus solution D; IDKA: IDK120-01 plus solution A (neem oil); IDKB: IDK120-01 plus solution B (FC4430); IDKC: IDK120-01 plus solution C (Silwetl-77); IDKD: IDK120-01 plus solution D (Blank control), respectively.

Figure 6 Performance parameters of deposition droplets with different adjuvants and nozzle models at different drift distances

Table 5 Multiple comparison of D_{50}, span distribution (S) and estimated drift deposition of deposited droplets

Treatment	D_{50} (μm)±SD	S±SD	Drift deposition±SD/(μL·cm^{-2})	Drift distance/m	D_{50} (μm)±SD	S±SD	Drift deposition±SD/(μL·cm^{-2})
XRD	342.33±122.31^{a}	0.96±0.12^{a}	1.30±0.66^{a}	1	393.69±78.46^{a}	0.85±0.18^{a}	1.20±0.60^{a}
IDKA	240.00±53.75^{c}	0.48±0.18^{c}	0.26±0.24^{c}	2	278.67±39.12^{b}	0.68±0.19^{b}	0.56±0.35^{b}
IDKB	320.74±69.60^{ab}	0.71±0.17^{b}	0.76±0.43^{b}	3	236.96±34.25^{c}	0.63±0.25^{b}	0.45±0.37^{b}
IDKC	307.26±75.71^{b}	0.68±0.18^{b}	0.62±0.41^{b}				
IDKD	305.19±57.41^{b}	0.78±20.00^{b}	0.75±0.43^{b}				

Note: SD is standard deviation. Means within a row followed by different lowercase and uppercase letters are significantly different using the paired bootstrap test procedure (p<0.05). XRD: XR-110-015 plus solution D; IDKA: IDK120-01 plus solution A; IDKB: IDK120-01 plus solution B; IDKC: IDK120-01 plus solution C; IDKD: IDK120-01 plus solution D, respectively.

0.06%, respectively) was the least significant among the treatments, followed by 2 m (0.87 μg/cm², 0.04%, respectively), 3 m (0.64 μg/cm², 0.03%, respectively). The interactions between factors *A* and *B* on the drift deposition amounts and pv value were significant (p<0.05) (Table 6).

Table 6 Multiple comparisons of drift deposition amounts and drift deposition percentage per mylar (*Pv*)

Treatment	Drift deposition amounts± SD (μg·cm^{-2})	*Pv*±SD (%)	Drift distance/ m	Drift deposition amounts ± *SD* (μg·cm^{-2})	*Pv*±*SD* (%)
XRD	1.26±0.39^{a}	0.06±0.02^{a}	1	1.24±0.41^{a}	0.06±0.02^{a}
IDKA	0.70±0.61^{d}	0.04±0.03^{c}	2	0.87±0.40^{b}	0.04±0.02^{b}
IDKB	0.97±0.44^{b}	0.05±0.02^{ab}	3	0.64±0.39^{c}	0.03±0.02^{c}
IDKC	0.84±0.36^{cd}	0.04±0.02^{bc}			
IDKD	0.82±0.30^{cd}	0.04±0.02^{bc}			

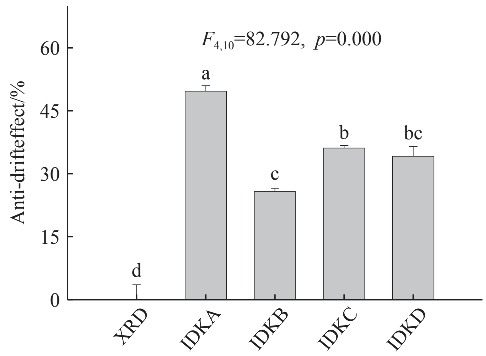
Note: *SD* is standard deviation. Means within a row followed by different lowercase and uppercase letters are significantly different using the paired bootstrap test procedure (p<0.05). XRD: XR-110-015 plus solution D; IDKA: IDK120-01 plus solution A; IDKB: IDK120-01 plus solution B; IDKC: IDK120-01 plus solution C; IDKD: IDK120-01 plus solution *D*, respectively.

3.7 Anti-drift effect of different treatments

The anti-drift effect of different treatments was shown in Figure 7. For the same solution, IDKD (34.18%) increased significantly compared with the results of XRD (0.00%). For the same nozzle, the anti-drift effects of solution A (neem oil, IDKA) (49.69%) were significantly higher than those of solution B (FC4430, IDKB) (25.73%), solution C (silwetl-77, IDKC) (36.14%), and solution D (blank control, IDKD) (p<0.05). The treatment IDKA (IDK120-01 + neem oil) had a significantly higher anti-drift effect than those with other treatments (Figure 7).

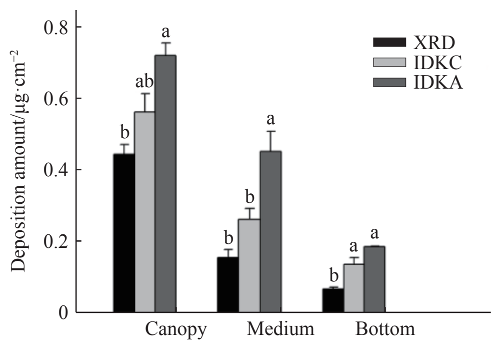
3.8 Spray effect of different treatment of UAV in the field

The spray effect of different treatment of UAV in the field was shown in Figure 8. For the deposition amount, IDKA at different layers (0.722, 0.454, and 0.186 μg/cm², respectively) were all significantly higher than the results of XRD (0.445, 0.156, and 0.068 μg/cm², respectively); However, IDKC (0.136 μg/cm²) was only increased significantly at the bottom of the crop, compared to the XRD, it was also enhanced at the canopy and medium layer with insignificant difference (0.564 and 0.262 μg/cm², respectively) (Figure 8a). In regard to penetration rate, its result of IDKA (0.488) was more outstanding than that of IDKC (0.562) and XRD (0.725),

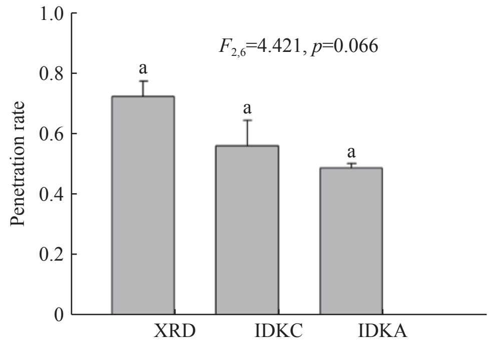


Note: Different letters (a, b, c, d) above bars indicate significant differences (p<0.05), the same letter is not significantly different (p>0.05) according to Tukey's multiple range test. XRD: XR-110-015 plus solution D; IDKA: IDK120-01 plus solution A (neem oil); IDKB: IDK120-01 plus solution B (FC4430); IDKC: IDK120-01 plus solution C (Silwetl-77); IDKD: IDK120-01 plus solution D (Blank control), respectively.

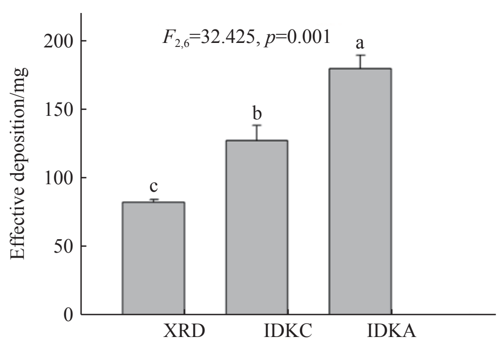
Figure 7 Comparison of anti-floating effect of different treatment



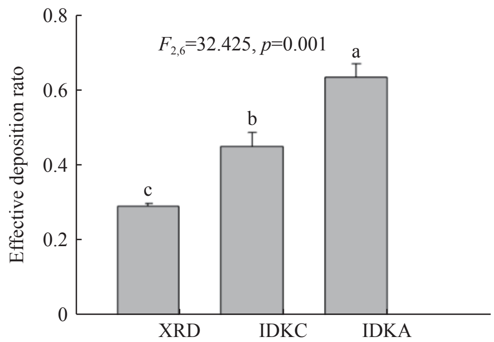
a. Deposition amount of different treatment at layer



b. Penetration rate of different treatment



c. Effective deposition of different treatment



d. Effective deposition rate of different treatment

Note: The $F_{2,6}$ values of the deposition amount of different treatment at canopy, medium, and bottom layer were 12.604, 15.000, 24.551, and the p-values on the deposition amount of different treatment at canopy, medium, and bottom layer were 0.007, 0.005, 0.001, respectively. Different letters above bars indicate significant differences (p<0.05), the same letter is not significantly different (p>0.05) according to Tukey's multiple range test. XRD: XR-110-015 plus solution D; IDKA: IDK120-01 plus solution A (neem oil); IDKC: IDK120-01 plus solution C (Silwetl-77), respectively.

Figure 8 Comparison of spray effect of different treatment of UAV in the field but their difference was not significant (Figure 7b). With regard of effective deposition and effective deposition rate, the results of IDKA (180.558 μg and 0.638, respectively) was more significantly protruding than that of IDKC (127.842 μg and 0.452, respectively) and XRD (82.935 μg and 0.293, respectively) as shown in Figures 8b and 8c.

4 Discussion

Since the drift was closely related to the droplet size[23], the smaller a spray droplet, the longer it remained airborne and the higher the possibility of drifting by crosswind; Moreover, smaller droplets could evaporate before deposition[24]. The results showed that the estimated drift deposition amount and percentage of drift amount at 3 m was significantly lower than those at 1 m and 2 m, which had smaller D_{50} values. Kirk[25] reported that D_{50} had a profound influence on droplet drift. The results also suggested that neem oil could significantly decrease the S and $\Phi\text{Vol}_{<150\,\mu\text{m}}$ value compared with that of the blank control while also showing a significant increase in its D_{50} value, resulting in a lower drift deposition percentage. This was consistent with the results of Stainier et al.[26], Preftake et al.[27] and Santos et al.[28] During the high deformation processes in a spray nozzle, the addition of the adjuvant SDS could shift the droplet size distribution to larger droplet sizes[29]. Fornasiero et al.[30] also found that normal nozzles with anti-drift adjuvant or low-drift nozzles could decrease potential drift. However, Ferguson et al.[24] found that the addition of adjuvant DRT oil was an effective way to reduce the drift potential across all nozzle types, but the greatest reduction in drift potential could be achieved by changing the nozzle type.

The results showed that the estimated drift deposition amount and the drift percentage of air-induction nozzle IDK120-01 were significantly lower than those of anti-drift nozzle XR-110-015. Air-induction nozzles can promote the formation of larger and less homogeneous droplets, without considerably affecting the velocity of the droplets. However, Feng et al.[31] found that large droplets (D_{50} 491 μm) have slightly reduced retention in corn, even though it had significantly increased absorption, promoting the translocation of glyphosate to the growing sink tissues.

The complex process of spraying the chemical liquid on the organism's surface and generating biological effects included atomization, spray delivery, impact, wetting, retention, drug diffusion and biological effects[26,32]. The addition of adjuvants has become increasingly important to enhance the effectiveness of sprayed chemical solutions by altering their properties, such as reducing droplet drift, evaporation, and improving droplet spreading on leaf surfaces of plants[33]. The spray adjuvants can change the properties of the solution, which was beneficial to the wetting and spreading of the droplets on the target while reducing the loss of control agents[34], because of lower surface tension. Carvalho et al.[35] found that the emulsifiable concentrate formulation, which resulted in the lowest surface tensions, was more effective in decreasing the drift able fines than the water-dispersible granules and suspension concentrate formulations. Dechelette et al.[29] found that the addition of associative SDS decreased the dynamic surface tension, slightly increased the initially zero shear viscosity, substantially enhanced the extensional properties of the solutions, and substantially reduced the spray drift. The results also showed that the addition of neem oil and silwetl-77 significantly reduced the surface tension of the liquids. The smaller the surface tension was, the better the droplet spread[36], as the droplet surface tension decreases, the maximum spreading ratio increases[37]. The results also showed that the contact angle increased with the increase of surface tension owing to the decrease of concentration. When adjuvant lowered droplet surface tension, it improved wetting (lower contact angles) and enhanced spreading[38]. Abbott et al.[39] observed that this response was variable, and therefore liquid surface tension was of little predictive value for estimating the spread area. Generally, both these approaches can provide sufficient and uniform fruit coverage of insecticides[30].

5 Conclusions

The spray atomization performance of different adjuvants was evaluated by the droplet size measurement system, and found that the addition of adjuvants would modify the distribution span S, $\Phi\text{Vol}_{<150\,\mu\text{m}}$ and D_{50}, and those of the 50% neem oil possessed a greatest change in all the treatments. The surface tension of different adjuvants measured by an automatic surface tension meter showed that the addition of neem oil and silwetl-77 could significantly decrease the surface tension, especially for silwetl-77, with the contact angle decreasing. In the wind tunnel, we found that there were negative correlations between the drift distance, D_{50} and percentage of drift amount; the IDKA (IDK120-01+neem oil) significantly decreased the drift deposition amount. And the anti-drift effect and spray effect of nozzle IDK120-01 plus neem oil was significantly stronger than that of other spray methods. These results suggest that the addition of neem oil could be an effective way to reduce the spray solution drift with all nozzle types and improved wetting and enhanced spreading.

Acknowledgments

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