

Research Article

Reducing Spray Drift and Increasing Spreading Effect of the Thifluzamide Through the Use of Adjuvants and Nozzles

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Abstract

Spray drift, as a practical issue during Unmanned Aerial Vehicle (UAV) spraying, has a negative impact on the environment, and the use of air-induction nozzles or anti-drift adjuvants are the most common recommendations for reducing drift. To screen the adjuvants for favourable atomization performance and anti-drift effect, we evaluated the spray atomization performance of different adjuvants by the droplet size measurement system. From the wind tunnel results, we commented on the relationship among the atomization performance, drift distance and drift deposition, and determined the drift percentage of different nozzles and the surface tension of liquids with different adjuvants. The results showed that the addition of adjuvants would modify the distribution span S , $\Phi Vol_{<150\mu m}$ and the volume medium diameter D_{50} : $\Phi Vol_{<150\mu m}$ and D_{50} of the Maifei treatment decreased and increased the most of all the treatments. There were negative correlations between the drift distance, D_{50} and percentage of drift amount. The adjuvants Maifei and the nozzle IDK120-015 significantly decreased the drift deposition amount. And the anti-drift effect of nozzle IDK120-015 plus Maifei was significantly stronger than that of other nozzles or adjuvants. In addition, the addition of adjuvants could significantly decrease the surface tension, especially for Maifei. These results suggest that the addition of Maifei is an effective way to reduce the spray drift for all nozzle types and lessen the surface tension. These data help to provide a theoretical basis for selecting suitable nozzles and adjuvants for plant protection UAVs.

Keywords: Spray drift; Unmanned aerial vehicles; Anti-drift adjuvants; Air-induction nozzles; Anti-drift effect; Surface tension

Introduction

Pesticides are commonly sprayed using manual sprayers in China. However, in 2002, the Ministry of Agriculture of China organized different local plant protection departments to survey plant protection sprayers in the field and found that there was serious running, dropping, dropping and leaking phenomena of various manual sprayers (100 million of the social holdings), resulting in the effective utilization rate of pesticides being less than 30% [1]. Compared with traditional automatic or semi-manual plant protection equipment, plant protection Unmanned Aerial Vehicles (UAVs) have the advantages of high spraying efficiency, performance, and precision; thus, plant protection UAVs are increasingly being applied in the control of crop pests [2], especially for rice protection. Due to the canopy overlap, occurring in rice cultivation, crop spraying using automatic or semi-manual machines is inconvenient for controlling diseases, insect pests and weeds. Qin et al. [3] found that the deposition and distribution of droplets in the lower layer were higher and more uniform when crop spraying was executed by UAVs and the insecticidal efficacy and the persistence period were greater than those achieved with a hand lance operated from a stretcher-mounted sprayer. The popularization of plant protection UAVs provides a useful operating platform for preventing rapid outbreaks of pests and diseases in rice paddy fields and for upgrading technology for rice

protection.

As an emerging technology, UAV spraying for crop protection can induce many practical issues; especially spray drift [2]. Due to the influence of air operation conditions and air flow, compared with ground-based plant protection aircraft, plant protection UAVs were more likely to produce spray drift [4]. Spray drift not only reduces the effective utilization rate of pesticides but also poses a serious threat to the safety of personnel, adjacent crops and the environment. With the increasing environmental awareness of the public, controlling spray drift will inevitably be the focus of spray technology research. Aerial spray drift has been studied regarding spray droplet size, nozzle configurations and so on [5,6]. As the core component of plant protection UAVs, the nozzle is the key factor affecting the spray drifts because a nozzle with good spray performance can improve the uniformity and amount of droplet deposition and ultimately improve the spray quality [7]. Flack et al. [8] found that when the leeward side of the air-induction nozzle JAP110-015 was tilted, it could reduce the drift by 39% compared with the drift of the conventional fan nozzle, and when the upwind side was inclined, the drift was decreased by 18.6%. Therefore, choosing the right nozzle is one of the key factors in improving the reducing spray drift.

In addition to the nozzle, the properties of the liquid were also the main factors affecting the atomization performance in previous

studies [9-11]. Butler-Ellis et al. [12] mentioned that the adjuvants were the main factors that affected the atomization performance of sprinklers. When a certain concentration of adjuvants was added, the spray angle and fan width decreased relative to those parameters measured without including adjuvants to the liquid. Ellis et al. [13] performed a detailed study on how different adjuvants affected the atomization performance of hydraulic spray nozzles, analyzed the changes in droplet size and liquid film length for different types of spray nozzles under the conditions of adding different adjuvants, and analyzed the drift index of spray droplets after atomization. Although the surface tension and viscosity of the medicinal solution during atomization were not known, there was a relationship between these properties. Additionally, some scholars studied the effects of nozzle type, size and pressure on the atomization performance [14] and the breaking mechanism of the liquid film [15-18].

The collection methods of spray drift could be divided into the ground drift collection method and the air drift collection method [19]. The ground drift collection method mainly uses petri dishes, Mylar and filter paper to collect the droplets [20]. Smith et al. [21] and Heidary et al. [11] collected ground drift data at 2, 4, 8, 16 and 27.5 m in the field and a wind tunnel, respectively, and found that the median volume D₅₀, $\Phi\text{Vol}_{<150\mu\text{m}}$ and downwind distance significantly impact spray drift.

In this paper, we evaluated the spray atomization performance of different adjuvants and their effects on drift deposition by adapting plant protection UAV nozzles and screened adjuvants and nozzles with good atomization performance and good anti-drift effects to lay the foundation for reducing pesticide application *via* increased efficiency. The atomization performance of different types of nozzles was detected for different adjuvants during the spray process, and the relationship between atomization performance and drift deposition was analyzed by comparing the effects of different atomization properties of the nozzles and adjuvants on the drift deposition, providing a theoretical basis for selecting suitable plant protection apparatuses and adjuvants for plant protection UAVs in rice cultivation.

Materials and Methods

Materials

A 240g/L thifluzamide suspension (trade name: Mansui) was used as the fungicide agent and was supplied by Nissan Chemical Co., Ltd, Shanghai, China. Allura red (85%) was supplied by Shanghai Yuanye Biotechnology Co., Ltd, Shanghai, China. SilwetL-77 and 10% FC4430 (Fluorosurfactant) dipropylene glycol monomethyl ether solution were supplied by General Electric Co., Ltd, Boston, America and Minnesota Mining and Manufacturing Co., Ltd, Minnesota, America, respectively.

Primary Alcohol Ethoxylate, BYK-405, BYK-051N, and Isomeric alcohol ethoxylates were supplied by Shandong Yousuo Chemical Technology Co., Ltd., Linyi, China, BYK Additives (Shanghai) Co., Ltd, Shanghai, China, and Badische Anilin-und-Soda-Fabrik Co., Ltd, Ludwigshafen, Germany, respectively. Neem Crude Oil (45.97% Oleic acid, 17.66% Octadecanoic acid, 17.61% Palmitic acid, 15.81% Linoleic acid), obtained by cold pressing Neem seeds, was supplied by Chengdu Lvjin Biotechnology Co., Ltd, Chengdu, China. The tested

Table 1: The spray droplet distribution (S) of different types of adjuvants.

Adjuvants	S ± SD	$\Phi\text{Vol}_{<150\mu\text{m}} \pm \text{SD}$	D ₅₀ ± SD
Blank control	1.046 ± 0.012 ^{dc}	48.993 ± 0.506 ^{aA}	125.233 ± 0.454 ^{fF}
Feiyan	1.110 ± 0.000 ^{cb}	50.157 ± 1.062 ^{aA}	147.347 ± 1.848 ^{eE}
Maifei	1.459 ± 0.066 ^{aA}	27.410 ± 2.293 ^{fE}	199.637 ± 6.861 ^{aA}
Beidatong	1.158 ± 0.023 ^{bb}	36.110 ± 0.585 ^{cC}	175.067 ± 1.559 ^{cC}
Transmicelle	1.153 ± 0.003 ^{bb}	44.480 ± 0.620 ^{bB}	157.823 ± 0.473 ^{deD}
Kongsayihao	1.163 ± 0.000 ^{bb}	43.433 ± 0.598 ^{bB}	159.927 ± 1.160 ^{deD}
Neem oil	0.926 ± 0.007 ^{ed}	29.500 ± 0.345 ^{deD}	182.917 ± 0.372 ^{bb}
F _{6,14} values	115.687	232.255	139.601
P values	0	0	0

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, P <0.01, respectively).

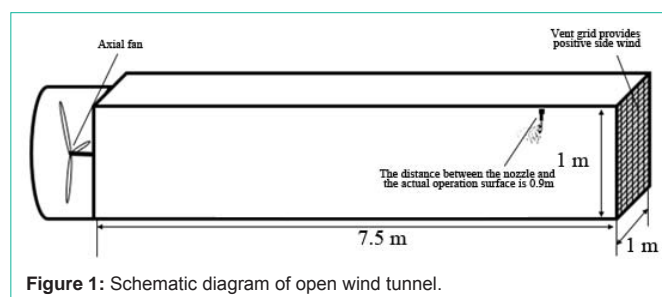


Figure 1: Schematic diagram of open wind tunnel.

nozzles were purchased from the market (Table 1).

Spraying platform and spraying systems

The atomization performance of droplets was analyzed by the droplet test platform of Anyang Quanfeng Aviation Plant Protection Technology Co., Ltd, Anyang, China. The test platform included a particle size measurement system and a spray system that could be used under 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 of the Key Laboratory of Aviation Plant Protection of the Ministry of Agriculture and Rural Affairs; this wind tunnel was created by Anyang Quanfeng Biotechnology Co., Ltd., and has dimensions of length × width × height=7.5×1×1 m (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 diameter of 0.9m. The fan can form a stable one-way 0~8 m/s steeples adjustable wind speed in the working space. After the wind speed was measured by an anemometer, the wind speed value was shown on the screen of the microcomputer.

Comparison of atomization performance of different adjuvants

The nozzle (F110-015) was installed vertically above the laser beam in the test area. There was a 2m distance between the nozzle and test area under the 0.3MPa of spray pressure. Using pure water as the blank control, 5mL of each adjuvant was diluted with 1L of water to create the test solution, and the distribution of droplet particles in different treatments was measured, with triplicates tested for each treatment. The distribution of droplet size was represented by tables or graphs, and the droplet size values were recorded at 10%, 50% and

90% of the total volume. D_{10} stands 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 formula: $S = (D_{90} - D_{10}) / D_{50}$; another index, $\Phi Vol_{<150\mu m}$, is the percentage of droplet size less than $150\mu m$ for the total droplet volume [22].

Effect of different adjuvants and nozzles on drift

First, 5000mg/L allura red and 6.5mg/L Mansui were added to make mother liquors, and then 5mg/L of the different adjuvants or equal volumes of water were added to create solution A (Maifei), solution B (neem oil), solution C (Transmicelle) and solution D (blank control). The ambient temperature of the spray test was from 28°C to 30°C, and the relative humidity was 70~80%. At 1m, 2m and 3m from the downwind direction of the nozzle, droplet collectors were arranged in the plane perpendicular to the airflow direction, which was made of Mylar (5cm × 8cm) and photo paper with a 0.3m horizontal spacing. Before testing, the spray parameters were adjusted according to the ISO22369-2-2010 test procedures and basis.

In the wind tunnel, different nozzles (F100-015, F100-03, HCC80-02, IDK120-015) were used to spray test solutions A, B, C and D at a 2m/s wind speed and a 0.3MPa pressure, and then the ground drift deposition amount and atomization performance were measured for different treatments. Each treatment was performed in triplicate. When the droplets on the Mylar and photo paper were dried, the Mylar and photo paper were placed into disposable gloves and put into black bags to store in a cool environment.

Determination of atomization performance and estimated drift deposition of ground deposition droplets

Each photo paper was scanned with a scanner (Epson, V600), and the particle size and density of drift deposited droplets were analyzed with the software DepositScan (ARS Headquarters Co., Ltd, Washington, United States) [23].

Determination of ground drift deposition

A total of 0.200g of allura red was accurately weighed and dissolved in 100ml of demonized water and then further diluted to the standard solution with concentrations of 133.33, 88.88, 59.26, 39.51, 26.34, and 17.56 mg/L. Then, the absorbance values were detected with a microplate reader (Migu Molecular Instruments (Shanghai) Co., Ltd., CMax Plus) at 514nm; finally, the standard curve was obtained according to the concentrations responding to the absorbance values ($Y = 39.906X - 2.7352$, $R^2 = 0.9996$).

The allura red on the Mylar was eluted with 5mL demonized water in an ultrasonic eluent, and its absorbance was measured at 514nm with a microplate reader. The deposition amount of the allura red could be calculated according to the standard curve for assessing the accurate deposition of medicinal liquid on a unit area.

The deposition percentage per Mylar 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 formula:

$$\text{Drift deposition percentage per Mylar } pv = (\rho_1 \times V_1) / (t \times V_2 \times \rho_2) \times 100$$

Anti-drift effect RT (%) =

$$\frac{\sum(pvC \times \text{drift distance}) - \sum(pvT \times \text{drift distance})}{\sum(pvC \times \text{drift distance})} \times 100$$

ρ_1 , the concentration of allura red of the drift deposition; ρ_2 , the concentration of the allura red of the test solution and control solution; V_1 , the volume of deionized water dissolved on the Mylar; V_2 , the nozzle flow; t , the spray time; pvC , the drift deposition percentage of nozzle F110-015 at different drift distances; pvT : the drift deposition percentage of the test nozzle at different drift distances.

Determination of the surface tension of liquids

The surface tension of various liquids under unbalanced conditions was detected with a ZL-2 automatic surface tension meter (Shandong Sanpu Kesen Instrument Co., Ltd.) using the ring method. The monitoring time range was from 0 to 180 s under the condition of $30 \pm 0.1^\circ C$. Each test was repeated at least 3 times, and the difference in surface tension was within 1mN/m [24]. 1 μ L of solution was added on a fresh rice leaf with a pipette, and the degree of contact between the droplet and the rice leaf was observed, in order to estimate the spreading ability.

Data analysis

The value of S , $\Phi Vol_{<150\mu m}$, D_{50} , the anti-drift effect and the surface tension of droplets deposited by different adjuvants were compared by using analysis of variance (ANOVA) followed by Duncan'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 value of S , $\Phi Vol_{<150\mu m}$, 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 Duncan's test for multiple comparisons ($P < 0.05$) with the SPSS version 17.0 software package (IBM).

Results

Effect of different adjuvants on atomization

When the F110-015 nozzle with a spray pressure of 0.3MPa was tested, the S value considering the neem oil (0.926) was significantly less than that of the blank treatment (no adjuvants); in contrast, the S values considering other adjuvants were significantly increased, with the maximum S value of the treatment due to the addition of Maifei (1.459) (Table 1).

Compared with the blank control treatment, for the Feiyan treatment, the value of $\Phi Vol_{<150\mu m}$ was higher, even though there was no significant difference between the two treatments. In contrast, the values of $\Phi Vol_{<150\mu m}$ were significantly lower in the other adjuvant treatments, with the largest reductions of 29.5% and 27.4% for neem oil and Maifei, respectively (Table 2).

Compared with the blank control D_{50} results, D_{50} was significantly promoted in the treatments with any adjuvants; the D_{50} results of the neem oil and Maifei increased to 182.9 μ m and 199.6 μ m, respectively (Table 3).

Drift deposition of different adjuvants and nozzles at different distances

The deposited droplet particles of different adjuvants and nozzles at different distances were analyzed by scanning the photo paper (Figure 2), and the results are shown in Tables 4. The results

Table 2: Multiple comparison of D_{50} of deposited droplets.

Adjutants	Mean of D_{50} (μm) \pm SD	Nozzles	Mean of D_{50} (μm) \pm SD	Drift distance	Mean of D_{50} (μm) \pm SD
Transmicelle	567.5 \pm 613.5 ^{aA}	F110-015	446.7 \pm 220.8 ^{bB}	1m	808.0 \pm 577.2 ^{aA}
Maifei	438.3 \pm 280.1 ^{bA}	IDK120-015	313.1 \pm 126.1 ^{cB}	2m	438.7 \pm 246.0 ^{bB}
Neem oil	471.4 \pm 225.2 ^{bA}	F110-03	405.5 \pm 216.8 ^{bcB}	3m	238.2 \pm 74.9 ^{cC}
		HCC80-02	847.5 \pm 722.5 ^{aA}		

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 ($P < 0.05$, $P < 0.01$, respectively).

Table 3: Multiple comparison of span distribution (S) of deposited droplets.

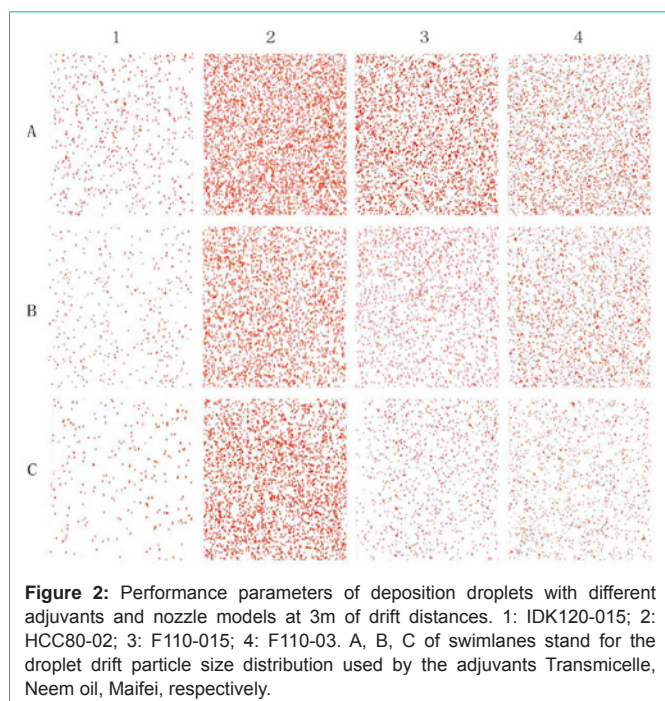
Adjutants	Mean of S \pm SD	Nozzles	Mean of S \pm SD	Drift distance	Mean of S \pm SD
Transmicelle	1.068 \pm 0.369 ^{aA}	F110-015	1.099 \pm 0.245 ^{abA}	1m	1.217 \pm 0.215 ^{aA}
Maifei	0.975 \pm 0.197 ^{aA}	IDK120-015	0.728 \pm 0.225 ^{bB}	2m	1.050 \pm 0.371 ^{bB}
Neem oil	1.039 \pm 0.379 ^{aA}	F110-03	1.063 \pm 0.305 ^{bA}	3m	0.797 \pm 0.202 ^{cC}
		HCC80-02	1.213 \pm 0.318 ^{aA}		

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 ($P < 0.05$, $P < 0.01$, respectively).

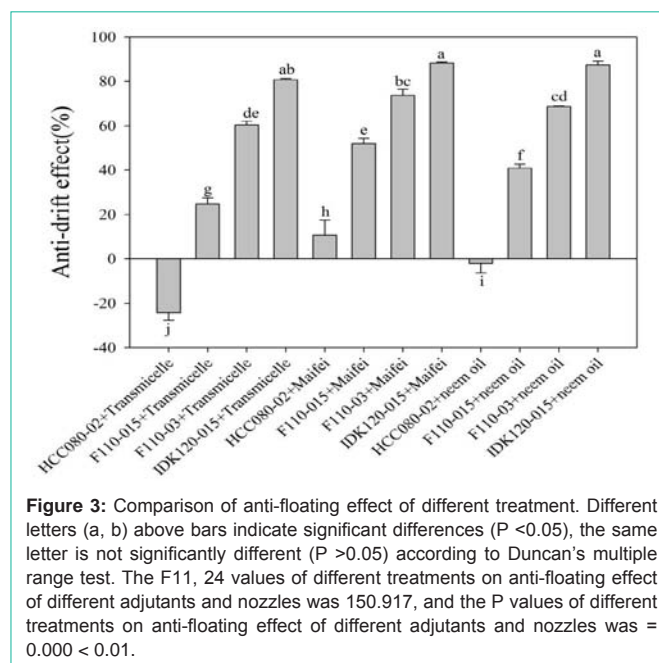
Table 4: Multiple comparison of estimated drift deposition.

Adjutants	Drift deposition \pm SD ($\mu\text{L}/\text{cm}^2$)	Nozzles	Drift deposition \pm SD ($\mu\text{L}/\text{cm}^2$)	Drift distance	Drift deposition \pm SD ($\mu\text{L}/\text{cm}^2$)
Transmicelle	2.424 \pm 3.412 ^{aA}	F110-015	2.063 \pm 1.432 ^{bB}	1m	3.868 \pm 3.19 ^{aA}
Maifei	1.870 \pm 1.748 ^{aA}	IDK120-015	0.595 \pm 0.492 ^{cC}	2m	1.905 \pm 1.731 ^{bB}
Neem oil	2.126 \pm 1.588 ^{aA}	F110-03	1.810 \pm 1.475 ^{bB}	3m	0.643 \pm 0.529 ^{cC}
		HCC80-02	4.271 \pm 3.853 ^{aA}		

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 ($P < 0.05$, $P < 0.01$, respectively).



indicated that there was an extremely significant difference among the tested adjutants (factor A) in the droplet volume D_{50} ($F = 5.606$, $df = 2$, $P = 0.007 < 0.01$); meanwhile, the droplet volumes of Maifei (438.3 μm) and neem oil (471.4 μm) were significantly lower than that of Transmicelle (567.5 μm). The droplet volume D_{50} of the tested nozzles (factor B) also showed an extremely significant difference



($F = 55.353$, $df = 3$, $P = 0.000 < 0.01$), and the D_{50} value of nozzle IDK120-015 (313.1 μm) was the lowest, followed by those of F110-03 (405.5 μm) and F110-015 (446.7 μm), whereas that of HCC80-02 (847.5 μm) was the highest. The D_{50} values of different drift distances (factor C) were extremely different ($F = 93.305$, $df = 2$, $P = 0.000 < 0.01$), among which those of 3m (238.2 μm) and 2m (438.7 μm) were significantly lower than that of 1m (808.0 μm), and the difference

Table 5: Multiple comparison of drift deposition percentage per Mylar (pv).

Adjutants	pv ± SD (%)	Nozzles	pv ± SD (%)	Drift distance	pv ± SD (%)
Transmicelle	0.080 ± 0.067 ^{aA}	F110-015	0.075 ± 0.033 ^{bB}	1m	0.105 ± 0.070 ^{aA}
Maifei	0.056 ± 0.051 ^{cC}	IDK120-015	0.017 ± 0.012 ^{dD}	2m	0.066 ± 0.047 ^{bB}
Neem oil	0.064 ± 0.056 ^{bB}	F110-03	0.043 ± 0.023 ^{cC}	3m	0.030 ± 0.024 ^{cC}
		HCC80-02	0.134 ± 0.066 ^{aA}		

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 ($P < 0.05$, $P < 0.01$, respectively).

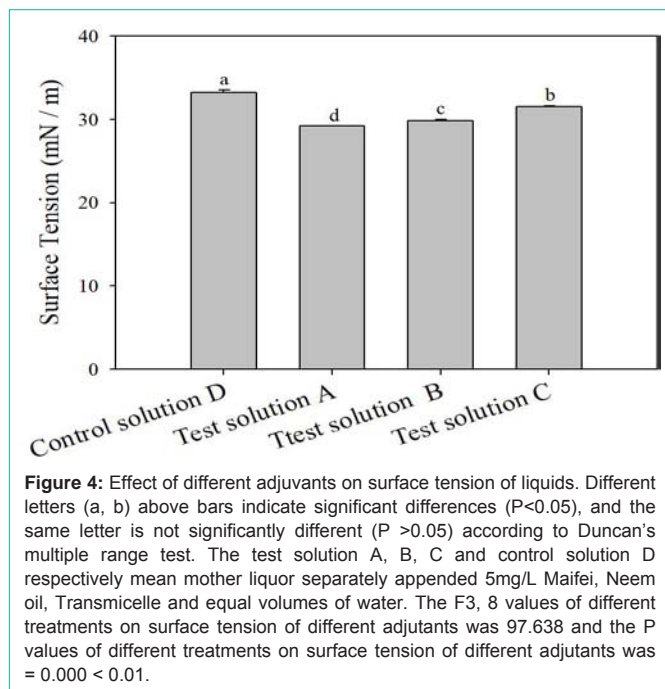


Figure 4: Effect of different adjuvants on surface tension of liquids. Different letters (a, b) above bars indicate significant differences ($P < 0.05$), and the same letter is not significantly different ($P > 0.05$) according to Duncan's multiple range test. The test solution A, B, C and control solution D respectively mean mother liquor separately appended 5mg/L Maifei, Neem oil, Transmicelle and equal volumes of water. The $F_{3, 8}$ values of different treatments on surface tension of different adjuvants was 97.638 and the P values of different treatments on surface tension of different adjuvants was $= 0.000 < 0.01$.

between 3m and 2m was also significant. Among multiple factors, the interaction between factors A and B was extremely significant ($A \times B \times F = 5.592$, $df = 5$, $P = 0.001 < 0.01$); the interaction between factors A and C was significant ($A \times C \times F = 3.375$, $df = 4$, $P = 0.018 < 0.05$); the interaction between factors B and C ($B \times C \times F = 15.491$, $df = 6$, $P = 0.000 < 0.01$) and factors A, B, and C ($A \times B \times C \times F = 3.046$, $df = 10$, $P = 0.006 < 0.01$) also reached extremely significant levels.

The S of droplets deposited by different adjuvants and nozzles drifted at different distances was tested by scanning the photo paper, and the results are shown in Tables 5. The results showed that there was no significant difference in the S among the tested adjuvants (factor A) ($F = 1.886$, $df = 2$, $P = 0.165 > 0.05$). In contrast, an extremely significant difference in S was observed among the different nozzles (factor B) ($F = 23.190$, $df = 3$, $P = 0.000 < 0.01$), of which the S value of nozzle IDK120-015 (0.728) was significantly lower than those of HCC80-02 (1.213), F110-015 (1.099), and F110-03 (1.063). Meanwhile, extremely significant differences in S were observed for the drift distances (factor C) ($F = 30.408$, $df = 2$, $P = 0.000 < 0.01$); the S at 3m (0.797) was significantly lower than those at 1m (1.217) and 2m (1.05). Among the multiple factors, the interactions between factors A and B ($A \times B \times F = 2.502$, $df = 5$, $P = 0.046 < 0.05$) and A and C ($A \times C \times F = 3.298$, $df = 4$, $P = 0.02 < 0.05$) were significant, whereas the interactions between factors B and C ($B \times C \times F = 2.171$, $df = 6$, $P =$

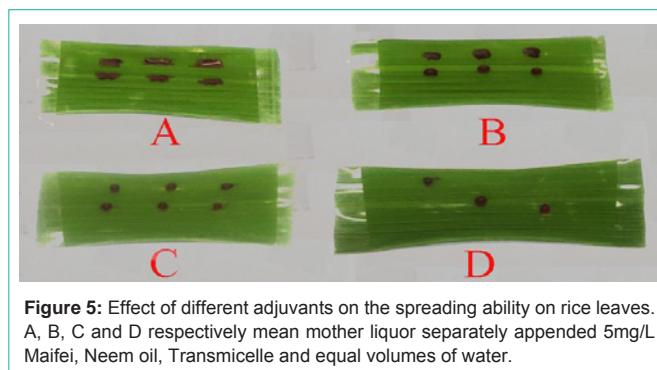


Figure 5: Effect of different adjuvants on the spreading ability on rice leaves. A, B, C and D respectively mean mother liquor separately appended 5mg/L Maifei, Neem oil, Transmicelle and equal volumes of water.

$= 0.066 > 0.05$) and factors A, B and C ($A \times B \times C \times F = 0.765$, $df = 10$, $P = 0.661 > 0.05$) were not significant.

The drift deposition amounts for different adjuvants and nozzles at different distances were also estimated by scanning the photo paper. The results showed that the estimated drift deposition amounts were significantly different among the tested adjuvants (factor A) ($F = 4.981$, $df = 2$, $P = 0.012 < 0.05$). Additionally, the estimated drift deposition amounts for the different nozzles (factor B) were extremely significantly different ($F = 67.899$, $df = 3$, $P = 0.000 < 0.01$); the estimated drift deposition amount of nozzle IDK120-015 ($0.595 \mu\text{L}/\text{cm}^2$) was the least, followed by those of F110-03 ($1.81 \mu\text{L}/\text{cm}^2$) and F110-015 ($2.063 \mu\text{L}/\text{cm}^2$), and the highest estimated drift deposition amount was for HCC80-02 ($4.271 \mu\text{L}/\text{cm}^2$). The influence of the estimated drift deposition amount on the drift distance (treatment C) was extremely significant ($F = 89.704$, $df = 2$, $P = 0.000 < 0.01$); the estimated drift deposition amount of the 3m ($0.643 \mu\text{L}/\text{cm}^2$) treatment was extremely significantly lower than those of the 2m ($1.905 \mu\text{L}/\text{cm}^2$) and 1m ($3.868 \mu\text{L}/\text{cm}^2$) treatments. The interactions between factors A and C ($A \times C \times F = 3.570$, $df = 4$, $P = 0.014 < 0.05$) and factors A, B and C ($A \times B \times C \times F = 2.660$, $df = 10$, $P = 0.014 < 0.05$) also reached a significant level. Additionally, the interactions between factors A and B ($A \times B \times F = 5.171$, $df = 5$, $P = 0.001 < 0.01$) and factors B and C ($B \times C \times F = 14.406$, $df = 6$, $P = 0.000 < 0.01$) were extremely significant.

Effect of different adjuvants and nozzles on the percentage of drift deposition per mylar

The drift amounts of different nozzles at different distances were measured by eluting the microcards, and the drift deposition percentages per Mylar pv of each treatment were calculated according to the formula above. The results indicated that pv was extremely significant among the tested adjuvants (factor A) ($F = 43.212$, $df = 2$, $P = 0.000 < 0.01$), the pv result of the Transmicelle treatment (0.080%) was significantly higher than those of the Maifei and neem oil treatment (0.056% and 0.064%, respectively); the pv of different

nozzles (factor B) was extremely significant ($F = 569.530$, $df = 3$, $P = 0.000 < 0.001$), while that of nozzle IDK120-015 (0.017%) was the least significant among the treatments, followed by F110-03 (0.043%), F110-015 (0.075%), and the pv of HCC80-02 (0.134%) was the highest (most significant) among the other treatments; the pv of the drift distance (factor C) was extremely significant ($F = 409.076$, $df = 2$, $P = 0.000 < 0.01$), the highest of which was for the 1m (0.105%) treatment, followed by the 2m (0.066%) and 3m (0.030%) treatments. Among the multiple factors, the interactions between factors A and B ($A \times B \times F = 4.652$, $df = 6$, $P = 0.000 < 0.01$), factors A and C ($A \times C \times F = 2.112$, $df = 4$, $P = 0.0088 < 0.01$) and factors B and C ($B \times C \times F = 50.191$, $df = 6$, $P = 0.000 < 0.01$) all indicated extremely significant interactions; nevertheless, the interactions between factors A, B and C were not significant ($A \times B \times C \times F = 0.657$, $df = 12$, $P = 0.786 > 0.05$).

Anti-drift effect of different adjuvants and nozzles

The anti-drift effect of each treatment is shown in Figure 2. For the same adjuvants, HCC080-02 (-24.168%~10.798%) increased the drift, while F110-03 (60.355%~73.624%) and IDK120-015 (80.711%~88.302%) reduced the drift compared with the results of F110-15 (24.765%~51.855%). For the same nozzle, the anti-drift effects of Maifei (10.798%~88.302%) and neem oil (-2.177%~87.291%) were significantly higher than those of Transmicelle (-24.168%~80.711%); the IDK120-015 nozzle with Maifei and neem oil had significantly higher anti-drift effects than those with other adjuvants, reaching 87.291%~88.302% (Figure 3).

Effect of different adjuvants on the surface tension of liquids

The surface tension of the blank control solution D (33.2mN/m) was significantly higher than those of the other tested solutions ($P < 0.05$), for example, those of C (31.5mN/m) and B (29.9mN/m). The surface tension of solution A (29.2mN/m) was the lowest among the treatments ($P < 0.05$) (Figure 4). Additionally, the use of adjuvants could significantly increase the spreading ability, opposite to the surface tension, and the greatest influence was observed for the adjuvant Maifei.

Discussion

Effect of different adjuvants on spray atomization performance

The complex process of spraying the chemical liquid on the organism surface and generating biological effects included atomization, spray delivery, impact, wetting, retention, drug diffusion and biological effects; the atomization performance, which directly affected the loss of pesticides and deposition behavior [9,25-27]. The addition of adjuvants to crop protection agents has become increasingly important to enhance the efficacy of crop protection products, due to factors such as droplet drift reduction, evaporation, and improved droplet spreading on leaf surfaces of plants [28,29]. Our results suggested that neem oil could significantly decrease the S value compared with that of the blank control, whereas the S and D_{50} values significantly increased due to the addition of other adjuvants, even though the $\Phi Vol_{<150\mu m}$ values were significantly reduced; in contrast, the D_{50} values of neem oil and Maifei were the largest among all the results. Under the high deformation processes in a spray nozzle, the addition of the adjuvant SDS could shift the droplet size distribution

to larger droplet sizes [30]. However, Santos et al. [31] found that the addition of mineral oil resulted in a higher D_{50} and uniformity coefficient of droplets. The spray adjuvants can change the properties of the solution, which was beneficial to the wetting and spreading of the droplets on the target and avoided the loss of control agents [32].

Effect of spray performance parameters on drifting

Since the drift was closely related to spray droplet size [33], the smaller a spray droplet, the longer it remained airborne and the higher the possibility of drifting by crosswind; moreover, spray droplets of a few microns in size could evaporate before deposition [34]. Our results showed that the estimated drift deposition amount and percentage of drift amount at 3m was significantly lower than those at 1m and 2m, which had a smaller D_{50} values. Kirk [35] reported that D_{50} had a profound influence on droplet drift, and França et al. [36] also found that there was an inverse correlation between drift potential and D_{50} , which indicates that D_{50} could be used to predict the behavior of drift risk, and the addition of a mineral oil adjuvant could result in an increase in the velocity of droplets and reduced drift. Our results showed that the D_{50} of the adjuvant Transmicelle with a higher drift deposition percentage was lower than those of Maifei and neem oil. Collin et al. [37] found that 63% drift reduction was achieved by incorporating certain spray adjuvants, and the wind tunnel data for droplet spectra also showed strong agreement with field deposition trends. Stainier et al. [25] evaluated the effects of 4 adjuvants on two formulations of phenmedipham applied with three types of hydraulic nozzles using a wind tunnel, and the results were also consistent with ours. However, Ferguson et al. [38] found that the addition of adjuvant DRT oil was an effective way to reduce the spray solution drift potential across all nozzle types, but the greatest reduction in drift potential could be achieved by changing the nozzle type. Therefore, our results showed that the estimated drift deposition amount and the drift percentage of nozzle IDK120-015 were significantly lower than those of HCC80-02, F110-015 and F110-03. Franca et al. [36] compared the droplet diameter, velocity, and potential drift index of air-induction nozzles with those of conventional nozzles using an open-wind tunnel and found that air-induction nozzles produced larger droplets but did not affect the spray speed, thereby reducing the potential drift index. Air-induction nozzles can promote the formation of larger and less homogeneous droplets, without considerably affecting the velocity of the droplets.

Effect of air-induction nozzle and adjuvants on drift and surface tension

The most common recommendation for reducing drift was to use coarser droplets (a smaller fraction of fine droplets), mainly using air-induction nozzles or anti-drift adjuvants to eliminate some small droplets produced by spray [31,37], because small droplets would deviate from the target due to the wind. Our results showed that the anti-drift effect from plant protection drones with the use of the air-induction nozzle IDK120-015 and adjuvant Maifei was significantly higher than those of other nozzles or adjuvants, similar to the results of Creech et al. [29] Fornasiero et al. [39] also found that low-drift nozzles or normal nozzles with anti-drift adjuvant could decrease potential drift and effectively control pests.

Carvalho et al. [40] found that the emulsifiable concentrate formulation, which resulted in the lowest surface tensions, was

more effective at decreasing the driftable fines than the water dispersible granule and suspension concentrate formulations. Wang et al. [30] found that the addition of associative SDS to a base dilute poly (ethylene oxide) solution 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. Our results also showed that the addition of adjuvant Maifei significantly reduced the surface tension of the liquids. The smaller the surface tension was, the better the droplet spread [41]. Feng et al. [42] found that large droplets have slightly reduced retention in corn but have significantly increased absorption, promoting the translocation of glyphosate to the growing sink tissues. The coarser droplets produced by the low-drift nozzles and anti-drift adjuvant did not reduce the efficacy of the insecticides, unlike the high-drift nozzles under the same operating parameters. In general, both these approaches can provide sufficient and uniform fruit coverage of insecticides [39].

Conclusion

We evaluated the spray atomization performance of different adjuvants by the droplet size measurement system, and found that the addition of adjuvants would modify the distribution span S , $\Phi Vol_{<150\mu m}$ and D_{50} , $\Phi Vol_{<150\mu m}$ and D_{50} of the Maifei treatment decreased and increased the most of all the treatments. In the wind tunnel, we found that there were negative correlations between the drift distance, D_{50} and percentage of drift amount; the adjuvants Maifei and the nozzle IDK120-015 significantly decreased the drift deposition amount. And the anti-drift effect of nozzle IDK120-015 plus Maifei was significantly stronger than that of other nozzles or adjuvants. The surface tension of different adjuvants measured by an automatic surface tension meter showed that the addition of adjuvants could significantly decrease the surface tension, especially for Maifei. These results suggest that the addition of Maifei could be an effective way to reduce the spray solution drift with all nozzle types and decrease the surface tension of liquids.

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Authors Contribution

XW designed the research. CG, YM and XW performed the assays. CG, XZ, RY, YR, LS and XZ analyzed the data. XW and CG wrote the manuscript.

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