Effect of aerial spray adjuvant applying on the efficiency of small unmanned aerial vehicle for wheat aphids control

Yanhua Meng[1,2,6], Yubin Lan[1,2*], Guiying Mei[3], Yongwang Guo[4], Jianli Song[5*], Zhiguo Wang[6,7]

(1. *College of Engineering, South China Agricultural University, Guangzhou 510642, China*; 2. *National Center for International Collaboration Research on Precision Agricultural Aviation Pesticide Spraying Technology, Guangzhou 510642, China*; 3. *School of Environmental Sciences, University of Guelph, Guelph, ON, N1G 2W1, Canada*; 4. *The National Agro-Tech Extension and Service Center, Beijing 100125, China*; 5. *College of Science, China Agricultural University, Beijing 100193, China*; 6. *Key Laboratory of Aviation Plant Protection, Ministry of Agriculture and Rural Affairs, Beijing 100193, China*; 7. *Anyang Quanfeng Biological Technology Co., Ltd, Anyang 455000, China*)

Abstract: Small unmanned aerial vehicles **(**UAVs) have been widely used in different aspects of modern farming management, including pest and disease control in China in recent years. In this study, the spray performance of a small plant protection UAV at low volume spray was evaluated by adjusting the pesticide dosage and adding aerial spraying adjuvants. Droplet deposition, droplet density, coverage, control effect and pesticide residue from field trials were assessed. In addition, the residue and control effect of UAV spray were compared to manual knapsack at high volume spray. The results showed that, the adjuvant applying improved the efficiency of UAV spray. Also, the adjuvant applying reduced the dosage of imidacloprid by 20%. However, there was no significant difference on initial residue between UAV spray and knapsack spray. Thus, plant protection UAV spraying pesticide by adding appropriate adjuvant showed the ability of improving the pesticide effectiveness by improving the control efficiency, reducing the pesticide dosage and residue.

Keywords: unmanned aerial vehicle (UAV), aerial spraying adjuvant, deposition, control efficiency, pesticide residue, wheat aphid
DOI: 10.25165/j.ijabe.20181105.4298

Citation: Meng Y H, Lan Y B, Mei G Y, Guo Y W, Song J L, Wang Z G. Effect of aerial spray adjuvant applying on the efficiency of small unmanned aerial vehicle for wheat aphids control. Int J Agric & Biol Eng, 2018; 11(5): 46–53.

1 Introduction

Wheat products are considered staple food which accounts for 27% of the total cereal production worldwide[1] and consumed in more than 100 countries[2]. China, as the biggest wheat-producing country, has approximately 24 million hectares of wheat field[3]. More than 30 kinds of pests and diseases occur on wheat every year, of which, wheat aphid, one of the most typical pests, causes more than 10% of wheat production decrease[4]. Therefore, preventing and controlling of pests and diseases on wheat are important in China. Different kinds of plant protection products and spray equipments have been developed to improve the efficiency of pest and disease prevention or control. Currently, the main plant protection machinery in China is manual knapsack, hand-held spray gun or boom sprayers. The use of boom sprayer is limited by the plant pattern and field topography. During the wheat heading and flowering stage, the layers of wheat plants are interlaced, ground machine sprayers are ineffectively used because of its seriously damage to the wheat plant by machine rolling[5]. Manual knapsacks and spray guns are the most common sprayers in China, but they are of low efficiency due to high labor intensity and high occupational exposure to pesticides[6,7]. Furthermore, manual knapsack sprayers and spray guns are applying at a high volume, which leads to low utilization efficiency of pesticides[8], pesticide residue excess[9] and environmental pollution[10].

In recent five years, UAVs have been developed and used in China to prevent or control pests and diseases on wheat. Plant protection UAVs show many advantages, such as high efficiency, high flexibility (suitable for complex terrain)[11], high pesticide utilization[12,13], no damage on crops, and low pesticide poisoning risk (operated by remote control system). The operation and control efficiency of plant protection UAVs in the field have been investigated. Gao et al.[14] reported that droplet density was higher on wheat head than on middle and bottom leaves, and the control effect was 81.6% with 7.7 L/hm^2 spraying volume by UAV spraying. Xue et al.[15] found that there was no significant difference on the efficacy between the recommended pesticide dose (75 g/hm^2) and decreased dose by 20%-30% with the same spraying volume at 10 d after UAV spraying. Qin et al.[16] reported that droplet performed the most uniform distribution (coefficients of variation =23%) and the droplet deposition in lower layer was maximized with a working height of 1.5 m and flight velocity of 5 m/s; the insecticidal efficacy was 92%-74% from 3 d to 10 d after UAV treatment. Qin's study also indicated that UAV spraying could enhance the duration of efficacy due to a low spray volume and highly concentrated spray pattern. The use of tank-mix adjuvants

Received date: 2017-10-08 **Accepted date:** 2018-08-28
Biographies: Yanhua Meng, PhD candidate, research interests: agricultural aviation application, Email: 01mengmeng@126.com; **Guiying Mei**, PhD, research interests: plant protection, Email: meiguiying@gmail.com; **Yongwang Guo**, PhD, research interests: plant protection, Email: guoyongwang@agri.gov.cn; **Zhiguo Wang**, Senior Engineer, research interests: agricultural aviation application.
***Corresponding author: Yubin Lan**, PhD, Professor, research interests: agricultural aviation application. National Center for International Collaboration Research on Precision Agricultural Aviation Pesticide Spraying Technology, South China Agricultural University, Guangzhou 510642, China. Tel: +86-20-85281421, Email: ylan@scau.edu.cn; **Jianli Song**, PhD, Associate Professor, research interests: plant protection machinery engineering. College of Science, China Agriculture University, Beijing 100193, China. Tel: +86-10-62732830, Email: songjianli170@163.com.

that modify the physical properties and behavior of spray droplets of the pesticide formulation at field dilution is one of the main approaches to improve the spray application process[17]. Gaskin et al.[18] reported that the super-spreader organosilicone adjuvant maintained total spray deposits on fruit using 3-5 times less spray volume (500-700 L/hm^2) than current standard practice (2500 L/hm^2) during the spray application on avocados. The using of anti-drift and anti-evaporation tank-mix spraying adjuvant have been studied to improve the efficiency of spraying performance both in wind tunnel and field aerial spray application, and the results indicated that the adjuvant reduced the droplet drift and enhanced the droplet deposition[19,20].

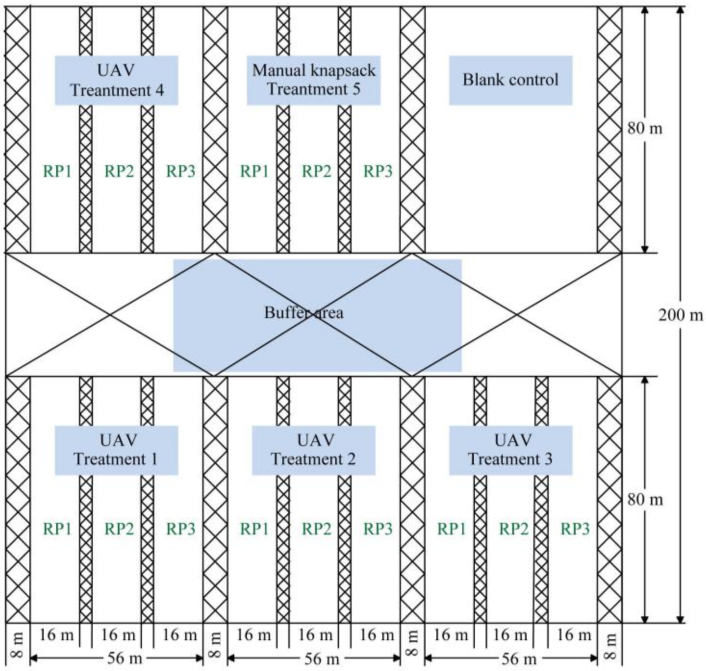
Currently, tank-mix spray adjuvants are usually added into pesticide liquid to improve droplet deposition through anti-drift, anti-evaporation and facilitate droplet expansion and deposition. Zhou[21] reported that the use of UAV and the adjuvant with low spray volume clearly improved the droplet density in rice canopy and control efficiency. Furthermore, the concentration of pesticide sprayed by UAV is much higher than that of by ground machinery, because UAV spray in low volume (LV) or ultra-low volume (ULW) while ground machinery spray in large volume[22]. There is concern about the droplet distribution uniformity, penetrability, deposition and pesticide residue while using UAV spraying pesticides due to its LV or ULV spraying.

In this study, the control efficiency of UAV spray with adjuvants was investigated through different field experiments. The density, coverage of the pesticide droplets, penetrability of droplet deposition in wheat canopy, pesticide residue and insecticidal control effect were evaluated by adjusting the dosage of pesticide and/or adding tank-mix adjuvants.

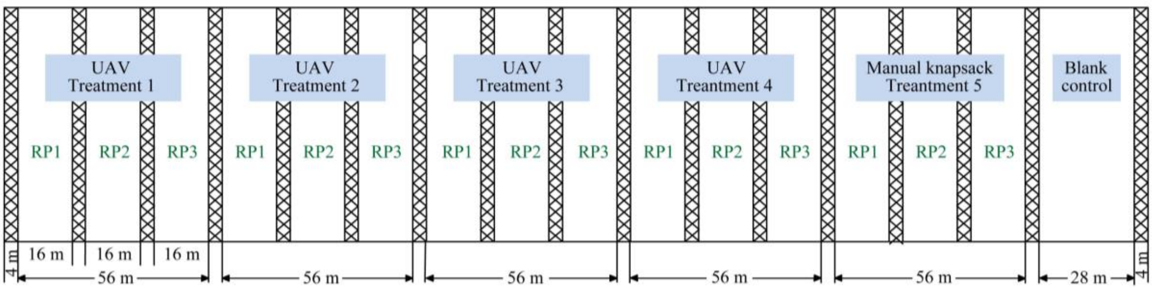
2 Materials and methods

2.1 Experimental condition

The experiments were conducted in the experimental field of Institute of Plant Protection, Chinese Academy of Agricultural Sciences, Xinxiang, China (35°18′N, 113°54′E) (Xinxiang site) and Yonghe Town, Anyang County, China (30°51′N, 114°45′E) (Anyang site) from late April to early May, 2017 and early May to Middle May, 2017, respectively. In Xinxiang, during the spraying test, the field temperature, wind speed and relative humidity were 25.2℃-29.5℃, 1.15-2.17 m/s, and 43.1%-49.6%, respectively. The tested wheat in Xinxiang, Aikang 58, was in heading-flowering stage with a plant height of 75 cm and a row spacing of 20 cm. In Anyang, the meteorological condition was as follows: field temperature at 27.2℃-30.5℃; relative humidity of 42.3%-48.6%; wind speed at 0.8-1.65 m/s. The tested wheat in Anyang was in flowering-grain filling stage, which was the critical period for aphid control. The cultivated varieties and plant pattern were the same as Xinxiang. The average length and width of wheat head was about 8 cm × 1 cm (except beard of wheat head). The square wheat field (200 m × 200 m) in Xinxiang and rectangle wheat field (300 m × 80 m) in Anyang were divided into 6 zones respectively, of which five were for treatments and one was for blank control (Figure 1).



a. Xinxiang site



b. Anyang site

RP: repeat; Buffer area: xx.

Figure 1 Layout of experimental treatments in Xinxiang site and Anyang site

2.2 UAV and electric knapsack

The small UAV used in this study was equipped with single-rotor gas engine motive plant protection aircraft system (3WQF120-12, Quanfeng, China). The system contains a 12 L tank, three pressure nozzles, and a 4-6 m spray swath. The working flight height was 0.5-3 m and flight velocity was 1-7 m/s. The manual sprayer (WS-18D, Weishi, China) used in this study was designed to be worn as a knapsack and had an electric sprayer wand with a 18 L tank capacity, and was 0.38 m × 0.26 m × 0.575 m in size. The UAV and manual sprayer were operated by a well-trained pilot and well-trained pesticide applicator, respectively.

2.3 Experimental design

To evaluate the efficiency of the UAV, the experiment was carried out in two districts in Henan province, China, as described above. The experiment in Xinxiang was set for evaluation of the droplet density, coverage, deposition, pesticide residue and insecticidal effect, while the experiment in Anyang was arranged for measurement of the control efficacy. To improve the efficiency, the organosilicone adjuvant QF-LY (Quanfeng, China) and the methylated vegetable oil adjuvant FFD (Mingshun, China) were used in this study. To facilitate the monitoring of spraying effect, 1.5% mass concentration of Allura Red (Shanghai Dyestuffs, China) was mixed with spraying liquid. 4 UAV spray (T1, T2, T3 and T4) and 1 manual sprayer (T5) with different pesticide dosage and with or without adjuvant were conducted in this study (Table 1) in two experimental sites respectively. Three replications of each treatment were completed in the similar weather condition in one day. The applied spray rate for 4 UAV treatments was 12.6 L/hm^2 while the spray rate for manual spray was 270 L/hm^2. The UAV spray treatments were operated at the flight velocity of 5 m/s with a spray swath of 4 m and a working height of 2 m above the crop canopy. The pesticide used in this study was 60% imidacloprid SC (Quanfeng, China). The experimental sampling deployments included droplet deposition sampling points, density and coverage points in a test (Figure 2), among which, droplet density and coverage comprised horizontal and vertical collectors (Figure 3) and droplet deposition sampling positions of wheat plant contained four parts (Figure 4). In every tested zone, five parallel longitude direction sampling lines and five lateral direction sampling lines were deployed in four spraying swaths. The intervals between neighboring collectors in lateral direction and longitudinal direction were 3 m and 10 m, respectively. At the crossing points of the two sampling lines, collecting papers were manipulated horizontally and wrapped around the foam round strip with a 15 mm diameter (EPE high elastic, simulated wheat head) in vertical direction. The foam round strips were placed into hollow PVC tubes with 90 cm length and 18 mm diameter which were inserted into the soil in the collecting sites. An untreated plot (blank control) was set up as a control group.

Table 1 Experimental treatments

Treatment	Sprayer	Pesticide and adjuvant	Dosage /g·hm^{-2}	Spray rate/L·hm^{-2}
T1	UAV	60% imidacloprid SC	90	12.6
T2	UAV	60% imidacloprid SC	72	12.6
T3	UAV	60% imidacloprid SC	72	12.6
		Adjuvant QF-LY	18.9	
T4	UAV	60% imidacloprid SC	72	12.6
		Adjuvant FFD	126	
T5	knapsack	60% imidacloprid SC	90	270

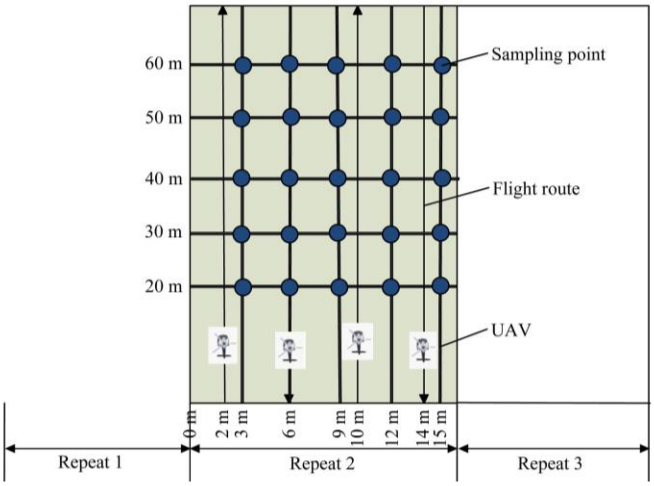


Figure 2 Sampling deployments in every replication (tested zone) in every UAV treatment

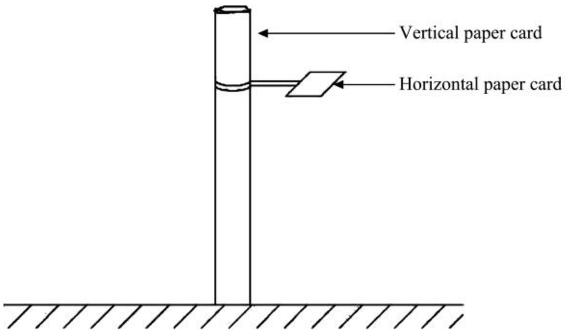


Figure 3 Placements of vertical and horizontal collectors for droplet density and coverage measurements

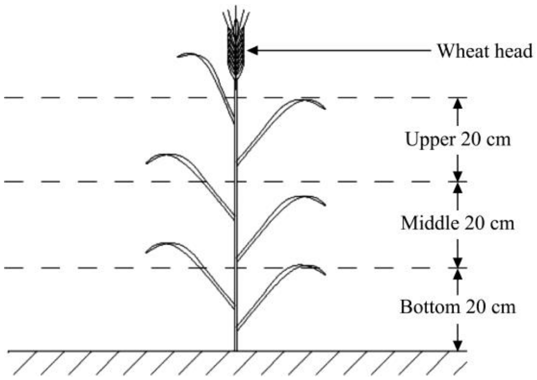


Figure 4 Sketch map of sampling pesticide deposition position

2.4 Sampling and measurement

2.4.1 Measurement of droplet deposition, coverage and density

The spray deposition, coverage and density of pesticide droplets were sampled in every treatment except knapsack treatment. For droplet density and coverage measurement, Kromekote® cards (60 mm × 40 mm) were used as sampling collectors in multi-spraying swath[23]. After spraying, the paper cards were placed in labeled zip-lock plastic bags (140 mm × 100 mm × 0.05 mm) individually. All sample bags were labeled with the information that included treatment, replication number, sample directions and serial number of location in the field. At sampling counting, the droplets on the paper card side facing the sprayed droplets coming direction were counted for performance evaluation. Sampling papers, for analyzing the key parameters of droplet deposition distribution, such as coverage and density of spray droplets, were scanned by a photograph scanner (HP Scanjet G4050) and were analyzed by the DepositScan program (USDA, USA). For the pesticide droplet deposition sampling, one column, which comprises five sampling points, was treated as one sampling set, wherein two wheat plants were collected per sampling point (within 1 m^2). Every wheat plant was sectional cut into four parts (Figure 4): wheat head; upper layer including flag leaf and the second top leaf; middle layer including the third and fourth top leaves; bottom layer including the fifth and sixth top leaves. These sectional parts of wheat plants were packaged individually into labeled zip-lock plastic bags (140 mm × 200 mm × 0.05 mm) and stored in cool box, and laboratory evaluation was done within 12 h. The sectional parts of wheat plant samples were washed in deionized water (wheat head: 60 mL; upper, middle and bottom: 40 mL) in the same zip-lock bags. The elution was filtered through a 0.22 μm membrane after vibration for 5 min. 200 μL of filtered elution was transferred into ELISA plate and the concentration of Allura Red was determined using BioTek Synergy 4-enzyme microplate reader (BioTek Instrument, USA) at 514 nm wavelength. A standard curve was created by calibrating the absorbance of the solutions to the standard solutions. The linear regression equation was as follow: $Y = 0.0219x + 0.0312$ ($R^2 = 0.99$), where Y is the value of absorbance and x is the concentration (mg/kg) of the standard solutions. The absorbance of the eluting liquid of leaves and wheat heads was used as the input of the equation to evaluate the content of Allura Red in the elution where the content of Allura Red was further used for evaluating the pesticide deposition on unit area of leaf or wheat head.

2.4.2 Pesticide dissipation measurement

After pesticide spraying, the leaves and wheat heads were collected respectively at sampling points at times of 0.083 (2 h), 1 d, 3 d, 7 d and 14 d to measure the dissipation of imidacloprid according to the standard operating procedures on pesticide registration residue in field trial[24]. In each zone tested, 2 kg of wheat plant were randomly picked at the head, upper, middle, bottom parts of the wheat plants at every sampling point, respectively. The samples were placed into labeled zip-lock plastic bags (240 mm × 340 mm × 0.05 mm). Afterwards, all samples were stored in a –20℃ freezer. Blank samples were collected for recovery studies and standard curve verification. The leaf and wheat head samples for pesticide dissipation measurement were chopped into small pieces, and then powdered by an herbal plant disintegrator. 2.5 g sample was put into a 50 mL Teflon tube, and 10 mL acetonitrile was added. After 1 min shaking, the mixture was vortexed at 4000 r/min for 1 min, and then vortexed and then shaken for another 2 min after adding 1.5 g NaCl. The sample was then centrifuged at 4000 r/min for 5 min. Approximately 1 mL supernatant was transferred into a 2 mL centrifuge tube containing 50 mg PSA and 150 mg $MgSO_4$. The tube with mixture was vortexed at 4000 r/min for 2 min and then centrifuged at 10 000 r/min for 5 min. The sample was filtered through a 0.22 μm nylon filter and transferred into a sample vial for LC-MS/MS analysis. The target pesticide imidacloprid was analyzed using the Waters Xevo TQD ACQUITY UPLC system (H-CLASS/XEVO TQD), which was connected to a triple-quadrupole mass spectrometer (Waters, USA) equipped with an electro spray ionization (ESI) source and surveyor liquid chromatography system. The mobile phase was 60% acetonitrile as phrase A and 40% pure water as phrase B at a flow rate of 0.2 mL/min. The injection volume was 10 μL and the temperature was 30°C. The compound was detected in multiple reaction monitoring (MRM) mode and positive ESI mode. The source parameters were: gas flow: 16 L/min; gas temperature: 500°C, nebulizer gas: 30 psi; and capillary voltage: 2600 V. The quantitative and qualitative ion pairs were 255.1/209.17 with collision energy of 14 eV and 255.1/175.04 with 12 eV, respectively. The retention time of imidacloprid was 0.76 min.

2.4.3 Observation of control effect

At the Xinxiang experimental site, the control effect study was based on the preventive pest control, wherein the experiment was carried out 3-5 d before the wheat aphid occurrence. Regardless of the types or instars of wheat aphid, the number of wheat aphid was surveyed on 7 d and 14 d after spraying. The insecticidal effect was calculated using the formula below:

$$IE = \frac{CK - TR}{CK} \times 100\% \qquad (1)$$

where, IE is insecticidal effect, %; CK is the number of surviving insects in blank control treatment; TR is the number of surviving insects in spraying treatments.

At Anyang experimental site, the study was carried out in the critical time for wheat aphid control. Similar as in Xinxiang site, the number of live wheat aphids were calculated before spraying and on 1 d, 3 d and 7 d after spraying in all tested zones and blank control zone, ignoring the types or instars. The insecticidal dropping rate and correction control efficiency were calculated according to the two following equations[25]:

$$DR = \frac{BS - AS}{BS} \times 100\% \qquad (2)$$

where, DR is the insecticidal dropping rate; BS is the number of live insects before spraying and AS is the number of live insects after spraying in control treatment zone.

$$CE = \left(1 - \frac{CK_b \times TR_a}{CK_a \times TR_b}\right) \times 100\% \qquad (3)$$

where, CE is the correction control effect; CK_b and CK_a are the numbers of live insects in blank control zone before and after spraying respectively, and TR_b and TR_a are the numbers of live insects in treatment zone before and after spraying respectively.

2.4 Statistical analysis

The data was analyzed using software SPSS v.20.0 (SPSS Inc., Chicago, IL). The significant differences were evaluated by Duncan’s test for a significance level of 95%. The pesticide dose of T2, T3 and T4 are 80% of that of T1. To make the pesticide deposition of four UAV treatments comparable, the entire results of the absorbance of Allura Red in elution of T2, T3 and T4 were multiplied by 80%.

3 Results and discussion

3.1 Droplet deposition analysis

The pesticide depositions of three layers of leaves were measured per cm^2, while the wheat head deposition was measured per wheat head. Hence, the results were divided into leaf group and head group, and the deposition comparison was among the treatments of the two groups respectively. For the leaf group, the droplet depositions of three layers in four UAV treatments were shown in Table 2. In the upper and middle canopy, the descending order of droplet depositions was as follow: T1, T3, T4 and T2, while in bottom canopy, the descending order was T1, T4, T3 and T2. For upper and middle layer, T2 was significantly lower than other treatments, while no significant differences were observed amongT1, T3 and T4. For the bottom layer, no significant differences were observed among all treatments. For the wheat head group (Table 3), there was significant difference between T1 and T2, and the deposition of T1 (164.59 ng per wheat head) was the highest among four treatments while that of T2 (109.08 ng per wheat head) was the lowest among these four. Considered that the pesticide dose of T2, T3 and T4 was 80% of that of T1, there was significant difference between T3 and T2, T4 and T2 respectively, while there was no significant difference among T1, T3 and T4 after applying the adjuvants. It could be the tank-mix adjuvant QF-LY used in T3 and FFD used in T4 increased the deposition of droplets while spraying.

The main target areas are wheat head, flag leaf and the top second leaf for the prevention and control of wheat aphid. By comparing T1 and T2 (Table 2 and Table 3), it was found that the pesticide droplet deposition in wheat head and different layers of canopy was decreased by reducing the pesticide dosage. When comparing T2, T3 and T4 (Table 2 and Table 3), it could be concluded that the two adjuvants increased the droplet deposition in wheat head and the upper canopy, and the performance of the adjuvant QF-LY in increased droplet deposition was better than that of FFD. The droplet deposition of T3 in upper canopy and wheat head showed no significant difference from that of T1. Thus, it is suspected that the control efficacy of T1 was similar to that of T3 by reducing 20% of the pesticide dosage and adding spraying adjuvant.

Table 2 Depositions of pesticide in each layer of wheat canopy and depositing percentages of each upper layers in UAV treatments

Treatment	Upper/ng cm^2 (%)	Middle/ng cm^2 (%)	Bottom/ng cm^2 (%)
T1	66.47±13.94(100) ^{a}	54.72±12.92(82.3) ^{a}	46.58±9.32(70.1) ^{c}
T2	50.25±13.87(100) ^{b}	38.10±12.87(75.8) ^{b}	35.84±8.72(71.3) ^{c}
T3	61.48±17.29(100) ^{a}	49.38±10.83(80.3) ^{a}	36.66±12.66(59.6) ^{c}
T4	54.52±14.10(100) ^{a}	44.62±12.57(81.8) ^{a}	39.26±14.80(72.0) ^{c}

Note: the data in the table were average ±SD; the data in the parenthesis was the percentage of deposition of each upper layer (except wheat head); the different small letters (in columns) mean significant differences at p<0.05 level by Duncan's range test in the same canopy position.

Table 3 Average droplet deposition per wheat head

Treatment	Adjuvant	Average deposition/ng wheat head
T1	--	164.59 ±14.57 ab
T2	--	109.08 ±12.37 b
T3	QF-LY	152.50 ±17.90 a
T4	FFD	149.82 ±22.37 a

Note: the data in the table were average ±SD; the different small letters indicate significant differences at p<0.05 level by Duncan's ANOVA range test.

3.2 Droplet penetration in wheat canopy

To analyze the penetration of droplets in wheat canopy, the droplet deposition on the upper layer were determined as a reference (i.e. 100%) due to the reason there is no barrier for accepting droplets on the upper layer, and the deposition in the middle and bottom canopy were counted separately to calculate the percentage by referring to the upper according to the following equation:

$$P_{layer\ i}=\frac{n_{layer\ i}}{N_{upper}}\times 100\% \tag{4}$$

where, $P_{layer\ i}$ is the penetration ratio of the layer; $n_{layer\ i}$ is the value of droplet deposition in the i layer, and N_{upper} is the value of droplet deposition in upper layer.

The results of droplet penetrability of different treatments are shown in Table 2. The percentages of deposition in middle canopy of T1, T3 and T4 are 80.3%-82.3% of the upper canopy, while that of T2 was the lowest value, which was 75.8% of the upper canopy. The deposition at bottom canopy of T1, T2 and T4 had the highest proportion, which were in between 70.1%-72.0%, while T3 had the smallest proportion, which was only 59.6%. T2 with 75.8% in the middle and T3 with 59.6% in the bottom layer of the upper canopy showed the lowest penetrability. Droplets penetrability performance of T2, T3 and T4 were changed by reducing 20% of the pesticide dosage and adding spraying adjuvant. Comparison of T1 and T2 revealed that the amount of pesticide deposition in middle canopy decreased after reducing 20% of the pesticide dosage. Therefore, it is assumed that high concentration with low volume spraying improved the movement characteristics of pesticide droplets which further changed the droplet distribution in the canopy. When applying pesticide using ground machine with low concentration and high volume spraying, minor changes of the pesticide concentration will not affect the physical and chemical properties, such as the surface tension and viscosity of the droplets. While using UAV for pesticide spraying with high concentration and low volume spraying, slightly change of pesticide concentration will have huge impact on the characteristics of droplets, such as the atomization, evaporation and distribution. In the same way, adding adjuvant into spraying liquid can improve the distribution of droplet distribution in the canopy. Different adjuvants have different influence on the depositing characteristic of pesticide droplets among T2, T3 and T4. Both the adjuvant QF-LY and FFD increased the penetration in the middle canopy by reducing the pesticide dosage and adding spraying adjuvant into T3 and T4, the penetration ratio of T3 and T4 are similar to that of T1. Adjuvant QF-LY reduced the penetration of the droplets in bottom canopy while FFD increased the penetration of the droplets in bottom canopy.

3.3 Droplet distribution in the upper canopy

At the same fly velocity and spraying flow rate, the adjuvant QF-LY and FFD were added into the pesticide liquid in T3 and T4 respectively to evaluate the impact of the two adjuvants on the droplet density and coverage in both horizontal and vertical directions. As shown in Table 4, on both the horizontal and vertical direction, the average droplet density showed the same descending order: T3, T4, T2 and T1. Two adjuvants had the effect of increasing droplet density and coverage on the upper canopy. In vertical direction, both T3 and T4 were significantly higher than T2 and T1. In addition, both the droplet density and coverage of T3 were significantly higher than that of T4, T2 and T1. Similarly, in horizontal direction, both the average droplet density and coverage of T3 were significantly higher than that of the other treatments, while no significant difference were observed among T4, T2 and T1. It is assumed that the adjuvant QF-LY and FFD reduced the volatilization of pesticides and the surface tension of droplets, which reduced the contact angle and increased the coverage of the droplet. For the wheat aphid control, wheat head and flag leaf are the main control areas. The droplet density and coverage on vertical direction are represented as the main factor to evaluate wheat aphid control efficacy. The droplet coverage is better when there are more droplets in the main areas. For the pesticide that is effective by contact action, better droplet coverage brought better control effect. At the same pesticide dosage, the droplet coverage of T3 was the best. So technically, the control efficiency of wheat aphid on the first day after spraying was the highest among T2, T3 and T4.

Table 4 Average and coefficients of variation (CV) of droplet density and coverage in upper canopy in both horizontal and vertical direction

Treatment	Adjuvant	Average droplet density/cm^2 (CV, %)	Average droplet Coverage/% (CV, %)
Horizontal direction			
T1	--	45.26(32.31) b	3.85(39.01) b
T2	--	51.39(43.42) b	4.51(48.47) b
T3	QF-LY	75.53(27.05) a	6.55(45.87) a
T4	FFD	54.91(26.15) b	4.65(33.87) b
Vertical direction			
T1	--	71.59(46.82) C	4.90(44.49) C
T2	--	82.33(36.80) C	5.94(51.45) BC
T3	QF-LY	136.80(34.74) A	11.77(58.42) A
T4	FFD	108.64(30.50) B	8.00(44.38) B

Note: Different letters (in the same columns) represent significant difference at p<0.05 level by Duncan's ANOVA analysis.

3.4 Pesticide residue in wheat leaves and wheat heads

The pesticide residue on leaves and heads were calculated by referring to the measurements of adding the imidacloprid standard solution into the blank sample. There were five concentration settings of the standard solutions: 0.05 mg/kg, 0.1 mg/kg, 0.2 mg/kg, 0.4 mg/kg, and 0.8 mg/kg. The linear regression equations determined by the base objects for leaves and wheat heads were Y =30659.8x+94.992 (R^2=0.9990) and Y=30456.9x−801.577 (R^2 = 0.9996), respectively, wherein Y stands for the response peak volume observed from the measurement system and x indicates the amount (mg/kg) of imidacloprid. The recovery measurements were performed respectively by adding appropriate volume of three fortification concentrations (0.1 mg/kg, 0.2 mg/kg and 0.4 mg/kg) into blank samples. Every fortified concentration was measured triplicates (Table 5). Recoveries and relative standard deviations (RSDs) of leaf and wheat head were 88.6%-108.6% with RSDs 2.71%-7.88%, and 89.4%-112.2% with RSDs 4.73%-7.38%, respectively. These values met the requirements proposed by US EPA and EU Commission for verification criteria (Recovery: 70%-120%, RSDs≤20%). The dissipation rate constant and half-life of imidacloprid sprayed by UAV treatments and manual knapsack treatment were calculated according to the following regression equation[23]:

$$C=C_0e^{-kt} \tag{5}$$

where, C is the residues, mg/kg; C_0 is the initial pesticide deposition, mg/kg; k is the constant of dissipation rate; and t is the time after spraying, d.

Table 5 Average recoveries (%) and relative stand deviations (RSDs) of imidacloprid

Replication	Recoveries of fortification concentrations/mg·kg^{-1}					
	leaf			Wheat head		
	0.1	0.2	0.4	0.1	0.2	0.4
1	88.6	103	106.1	89.4	106.6	109
2	91	97.7	93.5	103.4	102.1	94.6
3	101.1	99.4	108.6	99.2	112.2	105
Average recoveries	93.6	100	102.8	97.3	107	102.9
RSDs, %	7.09	2.71	7.88	7.38	4.73	7.23

As it can be seen from Table 6, among the four UAV treatments, the descending order of initial imidacloprid residues (2 h after spraying) in leaves were T3 (14.48 mg/kg), T1 (13.56 mg/kg), T4 (9.92 mg/kg) and T2 (8.8 mg/kg). Although it was not consistent with the descending orders of the droplet deposition of leaves in Table 2, the droplet deposition in leaves among T1, T3 and T4 had no considerable difference. In addition,

Table 6 Residues, half-life and other statistical parameters for imidacloprid in leaf and head

Days	Leaf/mg·kg^{-1}	Wheat head/mg·kg^{-1}
T1: UAV spraying		
0.083	13.56	3.296
1	10.552	3.360
3	4.288	2.848
7	2.336	0.788
14	0.374	0.572
Regression equation	$C = 12.375e^{-0.251t}$	$C = 3.4683e^{-0.142t}$
Determination coefficient (R^2)	0.9851	0.8851
Dissipation rate constant/d^{-1}	0.251	0.412
Half-life/d	2.8	4.9
T2: UAV spraying with 80% dose		
0.083	8.8	3.129
1	8.736	2.712
3	7.456	1.472
7	2.216	1.144
14	0.567	0.452
Regression equation	$C = 10.641e^{-0.209t}$	$C= 2.8412e^{-0.134t}$
Determination coefficient (R^2)	0.98	0.9638
Dissipation rate constant/d^{-1}	0.209	0.134
Half-life/d	3.3	5.2
T3: UAV spraying with 80% dose + QF-LY		
0.083	14.48	3.84
1	16.882	3.384
3	17.632	2.688
7	6.256	0.696
14	0.4468	0.376
Regression equation	$C = 24.456e^{-0.263t}$	$C = 3.808e^{-0.178t}$
Determination coefficient (R^2)	0.9169	0.9371
Dissipation rate constant/d^{-1}	0.263	0.178
Half-life/d	2.6	3.9
T4: UAV spraying with 80% dose + FFD		
0.083	9.92	3.36
1	9.408	2.388
3	5.28	1.664
7	5.696	0.396
14	0.9812	0.54
Regression equation	$C = 10.766e^{-0.158t}$	$C= 2.4695e^{-0.138t}$
Determination coefficient (R^2)	0.9107	0.706
Dissipation rate constant/d^{-1}	0.158	0.138
Half-life/d	4.4	5.1
T5: manual knapsack spraying		
0.083	10.664	3.32
1	12.762	3.461
3	14.486	2.256
7	2.06	0.882
14	0.66	0.454
Regression equation	$C = 15.304e^{-0.229t}$	$C= 3.4571e^{-0.154t}$
Determination coefficient (R^2)	0.9083	0.9608
Dissipation rate constant/d^{-1}	0.229	0.154
Half-life/d	3.0	4.5

the applied pesticide dosage of T3, T4 and T2 was 20% less than that of T1, and the initial pesticide residue of T3 was the highest. It is suspected that the adjuvant used in T3 (QF-LY) highly improved the deposition of pesticide in leaves. The initial residue of manual knapsack spraying was 10.664 mg/kg which was higher than that of T4 and T2 and less than that of T3 and T1. For UAV spray treatments, the descending order of initial imidacloprid residue in wheat heads were T3 (3.840 mg/kg), T4 (3.360 mg/kg), T1 (3.296 mg/kg) and T2 (3.129 mg/kg). The initial residue of manual knapsack spraying of wheat heads was 3.320 mg/kg, no significant difference from UAV spraying. The half-life of imidacloprid on leaves and wheat heads in UAV treatments were 2.6-4.4 d and 3.9-5.2 d, while in the manual knapsack treatment was 3.0 d and 4.5 d, respectively.

3.5 Control effect of wheat aphid

In the UAV spraying treatments of Xinxiang experimental site, 7 d and 14 d after spraying, the insecticidal effects of T5 were 89.84% and 86.86 %, respectively, which were higher than the UAV treatments (Table 7). There was no significantly difference between the insecticidal effects of T5 and T1 after 14 d of spray. However, T2 was significantly lower than the other three UAV treatments both on 7 d and 14 d after spraying. Although the pesticide dosage of T2, T3 and T4 were the same, the tank-mix adjuvants used in T3 and T4 enhanced the deposition performance. The reason underlying remains unknown and need to be further investigated. The insecticidal effect of T3 and T4 were lower than T1. However, the control effects were still acceptable and the benefit from further enhancement becomes minor. In the UAV spraying treatments of Anyang experimental site, the control efficiency of knapsack spraying (T5) on 1st day after spraying was 69.64%, which was higher than that of the four UAV treatments (Table 8). On the 3rd day, the control efficiency of T5 and T1 was 82.06% and 79.38%, respectively, which was higher than that of T4 (77.13%) and T2 (75.01%); and there were no significant differences between T3 (78.17%) and T4, T3 and T1, respectively. On the 7th day, T1 (91.28%), T3 (90.45%), T4 (89.36%) and T5 (92.22%) showed a better efficiency than that of T2 (87.28%).

The performances of control efficiency among all treatments were related to the acting mechanism of pesticide and spraying methods. Imidacloprid belongs to neonicotinoids which acts on the central nervous system of insects, with low toxicity to mammals and high toxicity to insects[26], it is effective on contact and via stomach digestion[27]. On the 1st day, the efficacy was mainly contributed by contact toxicity, which means, with the same pesticide dosage, the higher droplet density and coverage results in the higher control efficiency. In knapsack spray treatment, the entire upper canopy was contacted by pesticide with high volume of "shower" spraying. On the 3rd and 7th day, stomach digestion of imidacloprid plays the main role in the control efficiency. Although the control efficiency among all treatments showed significant difference, the performance met the requirements of pest control. Tank-mix spraying adjuvant could improve the penetrability and coverage of droplet in wheat canopy. By reducing 20% of pesticide dosage and adding adjuvant in spraying liquid, the control efficiency was very similar to the treatment using the recommended pesticide dosage. With the same pesticide dosage, the control efficiency of UAV treatment is similar to that of the knapsack spraying treatment. Thus, it can be concluded that plant protection UAV is beneficial for controlling wheat aphid during the flowering-grain filling period. In addition, when using appropriate tank-mix adjuvant, the pesticide dosage could be reduced by 20% without reducing the control efficiency. The adjuvant significantly enhanced the control efficiency. The dosage of pesticide was reduced without degradation of insecticidal control effect. This study showed that the adjuvant is of great potential for UAV spray.

Table 7 The control efficiency of wheat aphid at the wheat heading and flowering stage (Xinxiang)

Treatments	Surviving insects (ind.) (mean ± SD)		Insecticidal effect/% (mean ± SD)	
Days-after treatments	7 d	14 d	7 d	14 d
T1	10.5±1.6	25.3±0.9	83.72±2.8 b	85.36±0.9 a
T2	22.4±1.8	53.5±3.6	65.44±2.7 c	69.05±3.6 c
T3	13.1±1.7	31.5±6.6	79.7±2.9 b	81.68±4.5 ab
T4	13.0±1.7	37.5±1.9	79.93±2.7 b	78.32±1.9 b
T5	6.4±0.7	13.3±2.2	89.84±3.0 a	86.86±3.6 a
CK	64.8±1.2	173.5±10.9	0.0±0.0d	0.0±0.0d

Note: The data in table are mean ± SD. Surviving insects was counted from 300 wheat heads and flag leaves distributed at 15 points in one treatment (5 points in very replication zone); Different letters in the same column represent significant differences among all treatments on the same day by Duncan's range test (p<0.05).

Table 8 The control efficiency of wheat aphid at wheat flowering and grain filling stage (Anyang)

Treatment	Base num. (ind.)	Surviving Insect (ind.)	Insecticidal dropping rate/%	Correction control efficiency/%
1 d after spraying				
T1	106.8±4.9	46.7±5.0	56.34±3.6 b	63.54±0.8 b
T2	109.67±7.5	52.1±2.9	52.55±4.0 b	60.37±0.7 cd
T3	118.7±8.2	52.9±4.1	55.35±4.1 b	62.69±1.2bc
T4	101.7±11.4	46.5±1.4	53.9±4.4 b	61.53±0.3d
T5	110.6±6.9	40.1±1.9	63.68±2.9 a	69.64±1.4 a
CK	120.8±2.6	144.5±10.0	——	——
3 d after spraying				
T1	106.8±4.9	29.7±2.6	72.11±3.7 ab	79.38±0.8 b
T2	109.67±7.5	37.1±0.8	66.31±2.7b	75.01±0.8 d
T3	118.7±8.2	34.9±1.2	70.44±4.2 ab	78.17±1.2 bc
T4	101.7±11.4	31.3±0.6	69.1±3.9 ab	77.13±0.6 c
T5	110.6±6.9	26.8±3.5	75.7±3.2 a	82.06±0.6 a
CK	120.8±2.6	163.1±17.5	——	——
7 d after spraying				
T1	106.8±4.9	16.8±0.4	84.24±0.9 ab	91.28±0.5 ab
T2	109.67±7.5	25.3±4	76.98±3.0 c	87.28±1.5 d
T3	118.7±8.2	20.5±1.8	82.73±1.6 ab	90.45±0.8 ab
T4	101.7±11.4	19.4±2.6	80.8±3.1 bc	89.36±1.8 bd
T5	110.6±6.9	15.6±2.0	85.92±1.2 a	92.22±0.6 a
CK	120.8±2.6	218.4±7.6	——	——

Note: The data in table are mean ± SD. Surviving insects was counted from 300 wheat heads and flag leaves distributed at 15 points in one treatment (5 points in very replication zone). Different letters in the same column represent significant differences among all treatments on the same day by Duncan's range test (p<0.05).

4 Conclusions

In this study, plant protection UAV was used for wheat aphid control during the heading-flowering stage and flowering-grain filling stage by reducing 20% of the pesticide dosage and with or without tank-mix adjuvant. Droplet distribution, pesticide residue and control efficiency were evaluated. Manual sprayer was used as the control. For wheat aphid control, wheat head and the upper layer were the key parts for spraying. The results showed:

1) The pesticide droplet deposition in wheat head and different layers of canopy was decreased by reducing the pesticide dosage. After applying the tank-mix adjuvant QF-LY and FFD, the droplet deposition in wheat head and the upper and middle layer of canopy was significantly increased, and the performance of QF-LY was better than that of FFD.

2) With the same pesticide dosage, the control efficiency of UAV treatment is similar to that of the knapsack spraying treatment. By reducing 20% of pesticide dosage and adding adjuvant in spraying liquid, the control efficiency was very similar to the treatment using the recommended pesticide dosage by UAV or manual sprayer. Thus, the pesticide dosage could be reduced by 20% without reducing the control efficiency by applying appropriate tank-mix adjuvant.

3) The half-life of Imidacloprid on leaves and wheat heads in UAV treatments were 2.6-4.4 d and 3.9-5.2 d, while in the manual knapsack treatment was 3.0 d and 4.5 d. No considerable differences of initial residue with UAV spraying and manual knapsack spraying were observed in both wheat heads and leaves.

The feasibility of tank-mix adjuvants in UAV spraying was investigated based on two field trials. It is found that the control efficiency of UAV spraying was improved by adding adjuvant even with reduced pesticide dosage. Therefore, the cost for the pesticide also reduced. However, no considerable differences of initial residue with UAV spraying and manual knapsack spraying were observed. Therefore, further studies for UAV spraying are worth to be conducted in the future. Based on the observations in this study, further work on the relationships among pesticide dosage, control efficiency, and residue should be considered.

Acknowledgement

This research was supported by the National Key Research and Development Program of China (Grant No: 2016YFD0200700) and Educational Commission of Guangdong Province of China for Platform Construction: International Cooperation on R&D of Key Technology of Precision Agricultural Aviation (Grant No. 2015KGJHZ007). We also would like to thank the staff Liang Zijing from Anyang Quanfeng Biological Technology Co., Ltd and PhD candidate Li Yanjie and Wang Shiling from China Agricultural University for their contribution in this research.

[References]

[1] Curtis B C, Rajaram S, Gómez Macpherson H. Bread wheat: improvement and production. Food and Agriculture Organization of the United Nations, 2002; 103–117.

[2] Shewry P R. Wheat. Journal of Experimental Botany, 2009; 60(6): 1537–1553.

[3] National Bureau of statistics of China. http://data.stats.gov.cn/easyquery.htm?cn=C01&zb=A0D0F&sj=2016

[4] Chen J L. The control of wheat aphids. Beijing Jindun Publisher, 2014; pp.1–12. (in Chinese)

[5] Qin W C, Xue X Y, Zhang S M, Gu W, Wang B K. Droplet deposition and efficiency of fungicides sprayed with small UAV against wheat powdery mildew. Int J of Agric & Biol Eng, 2018; 11(2): 27–32.

[6] Chen S D, Lan Y B, Li J Y, Zhou Z Y, Liu A M, Mao Y D. Effect of wind field below unmanned helicopter on droplet deposition distribution of aerial spraying. Int J of Agric & Biol Eng, 2017; 10(3): 67–77.

[7] He X K. Improving severe draggling actuality of plant protection machinery and its application techniques. Trans of the CSAE, 2004; 20(1): 13–15. (in Chinese)

[8] Garcerá C, Moltóo E, Chueca P. Effect of spray volume of two organophosphate pesticides on coverage and on mortality of California red scale Aonidiella auranii (Maskell). Crop Protection, 2011; 30: 693–687.

[9] Poulsen M E, Wenneker M, Withagen J, Christensen H B. Pesticide residues in individual versus composite samples of apples after fine or coarse spray quality application. Crop Protection, 2012; 35: 5–14.

[10] Sánchez-Hermosilla J, Rincón VJ, Páez F, Agüera F, Carvajal F. Field evaluation of a self-propelled sprayer and effects of the application rate on spray deposition and losses to the ground in greenhouse tomato crops. Pest Management Science, 2011; 67: 942–947.

[11] Guo Y W, Yuan H Z, He X K, Shao Z R. Analysis on the development and prospect of aviation plant protection. China Plant Protection, 2014; 34: 78–82. (in Chinese)

[12] Xue X Y, Lan Y B, Agricultural aviation applications in USA. Trans of the CSAE, 2013; 44(5): 194–199. (in Chinese)

[13] Zhou Z Y, Zang Y, Luo X W, Lan Y B, Xue X Y. Technology innovation development strategy on agricultural aviation industry for plant protection in China. Trans of the CSAE, 2013; 29(24): 1–10. (in Chinese)

[14] Gao Y Y, Zhang Y T, Zhang N, Niu L, Zheng W W, Yuan H Z. Primary studies on spray droplets distribution and control effects of aerial spraying using unmanned aerial vehicle (UAV) against Wheat Midge. Crops, 2013; 2: 139–142. (in Chinese)

[15] Xue X Y, Qin W C, Sun Z, Zhang S C, Zhou L X , Wu P. Effects of N-3 UAV spraying methods on the efficiency of insecticides against planthoppers and Cnaphalocrocis medinalis. Acta Phytophyl Acica Sinca, 2013; 40(3): 273–278. (in Chinese)

[16] Qin W C, Qiu B J, Xue X X, Chen C, Xu F Z. Droplet deposition and control effect of insecticides sprayed with an unmanned aerial vehicle against plant hoppers. Crop Protection, 2016; 85: 79–88.

[17] Holloway P J. Physicochemical factors influencing the adjuvant-enhanced spray deposition and coverage of foliage-applied agrochemicals. In: Interactions between adjuvants, agrochemicals and target organisms. Springer Berlin Heidelberg, 1994; pp.83–106.

[18] Gaskin R E, Manktelow D W, Skinner S J, Elliot G S. Use of a superspreader adjuvant to reduce spray application volumes on avocados. New Zealand Avocado Growers' Association Annual Research Report, 2014; 4: 8–12.

[19] Fritz B K, Hoffmann W C, Bretthauer S, Wolf R E, Bagley W E. Wind tunnel and field evaluation of drift from aerial spray applications with multiple spray formulations. Pesticide formulations and delivery systems: innovating legacy products; for new uses, 32ND volume, 2013; 1558: 96–113.

[20] Wang X N, He X K, Song J L, Andreas H. Effect of adjuvant types and concentration on spray drift potential of different nozzles. Trans of the CSAE, 2015; 31(22): 49–55. (in Chinese)

[21] Zhou A. Preparation and performance evaluation of settling agent with low volume spray. MS dissertation. Hunan Agricultural University, Changsha, 2016.

[22] Xue X Y, Tu K, Lan Y B, Qin W C, Zhang L. Effects of pesticides aerial applications on rice quality. Trans of the CSAM, 2013; 44(12): 94–98. (in Chinese)

[23] Zhu H, Salyani M, Fox R D. A portable scanning system for evaluation of spray deposit distribution. Computers and Electronics in Agriculture, 2011; 76(1): 38–43.

[24] Institute for the control of Agrochemicals MoA. Standard operating procedures on pesticide registration residue field trials. Standards Press of China, Beijing, 2007.

[25] GB/T 17980.79—2004. Pesticide--Guidelines for the field efficacy trials (Ⅱ)--Part 79: Insecticides against aphids on wheat. Standards Press of China, Beijing, 2004.

[26] Gervais J A, Luukinen B, Buhl K, Stone D. Imidacloprid technical fact sheet. National Pesticide Information Center, 2012.

Pesticide Information Profiles: Imidacloprid Breaz. Extension Toxicology Network, 2012.