Performances evaluation of four typical unmanned aerial vehicles used for pesticide application in China

Wang Shilin, Song Jianli, He Xiongkui*, Song Le, Wang Xiaonan,
Wang Changling, Wang Zhichong, Ling Yun

(*College of science, China Agriculture University, Beijing* 100193, *China*)

Abstract: In recent years, unmanned aerial vehicles (UAVs) for plant protection have achieved rapid development in China. In order to test and evaluate the performances of pesticides application and development status of UAVs in China, four typical UAV models were selected to test the spraying coverage, penetrability, droplets density and the work efficiency. The results showed that the deposition and spraying liquid coverage were inconsistent both in lateral and longitudinal direction. Under the condition of the similar amount of spray volume and operation parameters, the volume median diameter (VMD) of the droplet was negatively correlated with the coverage density. The failure of the UAVs for plant protection mainly took up on the blockage of nozzle, transfusion tube and the liquid pump. The failure rate of UAVs took up 3.73%-4.36% of the total working time. The operation of UAVs during ground service took up 50% of the total working time, the preparation work took up 10%, and the route planning took up around 10%, while net operation time only took up around 30%. On the whole, the high efficiency of UAV was not fully achieved; the daily operated area was not in a satisfactory level now. The spraying performances of UAVs still need further improvement.

Keywords: unmanned aerial vehicle, work efficiency, pesticide application, deposition, distribution
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1 Introduction

Plant protection is an important segment that guarantees fertility and good harvest in agriculture. The equipment is an indispensable tool to realize the target[1]. At present, the plant protection machinery is primarily manual and half mechanized in China, which caused high labor intensity, low efficiency and high probability of poisoning incidents[2,3]. With the popularization of boom sprayer, the labor intensity has been reduced greatly and operating efficiency has been improved dramatically. In the mountainous areas, boom sprayers have encountered a lot of difficulties in field work. Agricultural aviation in these areas is thus dominated by small unmanned aerial vehicles (UAVs)[4]. Compared to conventional agricultural aircraft, UAVs do not require a special airport and can be operated by remote control[5], which is very suitable for complex terrain that common ground machinery cannot enter. In addition, UAVs possess high work efficiency, and strong ability to deal with sudden disasters with low risk[6]. Also, UAVs can help effectively reduce the harm of pesticides to human

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Biographies: Wang Shilin, PhD candidate, research interest: crop protection machinery and pesticide application, Email: shilinag@163.com; **Song Jianli**, PhD, Associate Professor, research interest: crop protection machinery and pesticide application, Email: songjianli170@163.com; **Song Le**, PhD candidate, research interest: pesticide residue analysis, Email: 435823956@qq.com; **Wang Xiaonan**, PhD candidate, research interest: pesticide application drift, Email: 404694775@qq.com; **Wang Changling**, PhD candidate, research interest: aerial pesticide application, Email: wcl1991@cau.edu.cn; **Wang Zhichong**, PhD candidate, research interest: crop protection machinery and pesticide application, Email: 549422839@qq.com; **Ling Yun**, PhD, Professor, research interest: synthesis of agrochemicals, Email: lyun@cau.edu.cn.
*** Corresponding author: He Xiongkui**, PhD, Professor, research interest: crop protection machinery and pesticide application. Centre for Chemicals Application Technology (CCAT), China Agricultural University, No. 2, Yuanmingyuan West Road, Beijing 100193, China. Email: xiongkui@cau.edu.cn.

and environmental pollution during the process of pesticides application[7,8]. Therefore, researchers started to pay more attention to popularize UAVs in pesticide application in the past few years[9].

In recent years, a lot of researches were conducted on UAVs, which mainly focused on the effect of operating parameters on the deposition of droplets and the biological efficiency, which provided a very useful foundation for agricultural aviation applications. Zhang et al.[10] used the infrared thermal imager to study the distribution of spray droplets through temperature gradient of single rotor UAV, and the study indicated that the infrared thermal imaging technology can reflect the distribution regularities of droplets on rice accurately. Ru et al.[11] studied on the aerial electrostatic spray and measured deposition with carbon paper and determined drift by eosin staining. It was found that electrostatic spray can improve the uniformity of droplets deposition, reduce pesticide drift, and increase the pesticide utilization and control efficiency. Qiu et al.[12] studied the spraying performance of CD-10 UAV under the influence of flight height and velocity. A relevant model was established to clarify the relationship between deposition concentration, deposition uniformity, flight height and velocity. As a result, the study found that flight altitude, flight velocity and the interaction between two factors significantly affect the density of droplets and uniformity of droplet deposition. Gao et al.[13] studied the control efficiency of bifenthrin on wheat midge sprayed by single rotor electric UAV in low-altitude and it was proven that centrifugal nozzle is better than hydraulic nozzle. Qin et al.[14] studied the influence of spraying parameters of N-3 UAV on droplets deposition of maize canopy and control effect of insecticides sprayed by UAV against plant hoppers, respectively. The results showed that both the insecticidal efficacy and the persistence period were greater than those achieved with a hand lance operated from a stretcher-mounted sprayer[4,14]. Moreover, there are also some studies related to atomization characteristics of UAV nozzles. Wen et al.[15] studied the atomization characteristics of ultra-low-volume swirl nozzle for UAVs. Ru et al.[16] analyzed droplet size distribution of aerial nozzle for plant protection in wind tunnel and flight conditions.

Despite these preceding studies, almost all of the researches focused on the effect of working parameters on droplet deposition and biological efficacy[17]. High efficiency, especially the strong ability to deal with sudden disasters including plant diseases and insect pests with low risk, is one of the most important reasons for the greatly developed UAVs. However, there is no report on the evaluation of the working efficiency of UAVs for plant protection as a very important evaluation index. As an emerging technology, there are still a series of practical issues for UAV spraying for pest protection[9], such as uniformity of droplet distribution, droplet coverage ratio, penetrability of pesticide into the crop canopy, and working efficiency of UAV. In order to identify the pesticides application performances and development status of UAVs in China, four typical UAVs for plant protection, sold in domestic market and tested by the National Plant Protection Machinery Testing Center, were tested in this research.

The aims of this research were to explore the uniformity and coverage of droplet deposition in a multi-spraying swath; study the penetrability of pesticide into the canopy; evaluate the working efficiency of UAVs and to provide technical reference and guidance for a proper and safe aerial spraying in agricultural production of China.

2 Materials and methods

2.1 Selection of four typical UAVs

The four investigated UAVs included: a gas engine motive 3WQF120-12 single rotor UAV (Anyang Quanfeng Aviation Plant Protection Technology Co., Ltd.), a gas engine motive 3CD-15 single rotor UAV (Wuxi Hanhe Aviation Technology Co., Ltd.), a battery motive WSZ-0610 six rotors UAV (Shandong Wish Plant Protection Machinery Co., Ltd.), and a battery motive HY-B-15L single rotor UAV (Shenzhen high-tech new agricultural technology Co. Ltd.). The main technical parameters of UAVs are shown in Table 1.

Table1 Primary technical parameters of selected UAVs

Type	3WQF120-12	3CD-15	WSZ-0610	HY-B-15L
Cost per vehicle/Yuan RMB	228 000	250 000	90 000	188 500
Rotor length/mm	2410	2240	2220	2460
Tank capacity/L	12	15	10	15
Number of nozzle	2	4	2	5
Type of nozzle	LU120-02	Flat-fan 01	Centrifugal atomizer	Four flat-fan and one cone
Type of pump	Diaphragm pump	Diaphragm pump	Gear pump and diaphragm pump	Diaphragm pump
Full load flight time/min	30	20	20	15
Unload flight time/min	50	30	40	35

2.2 Experiment design

The experiment was carried out in early May, 2016 in Anyang City, Henan Province (geographical longitude 114°35'-114°59'E, latitude 35°39'-36°09'N) with the meteorological conditions of field temperature 28.5°C-30.9°C, wind speed 1.63-1.73 m/s and relative humidity 41.4%-54.7%. Spraying uniformity, penetrability and work efficiency on wheat of these four typical UAVs were measured, respectively. The wheat was in grain-filling stage with a plant height of 60 cm and a row spacing of 20 cm. The tests were divided into two parts. Firstly, the uniformity of deposition and coverage of droplets were determined in a specific field (100 m × 100 m). Then, the tests of droplets penetrability in canopy and working efficiency were conducted under the large-scale pest prevention.

2.2.1 Spray liquid and flight parameters

During the whole period of tests, the flight parameters of the four UAVs were set up according to their daily actual filed practice, and the spray volume of each UAV was set as 12 L/hm^2. The dosage and pesticides used in the tests are set as follows: 60% imidacloprid SC (90 g/hm^2), 20% fenvalerate·malathion EC (750 g/hm^2), 30% tebuconazole SC (375 g/hm^2) and 10% amino acids water soluble fertilizer (375 g/hm^2). In order to guarantee the comparability of spraying quantity of each model in the tests, the flow rate of nozzles were calibrated according to the flight parameters of the four models of UAVs. Specific flight parameters are shown in Table 2.

2.2.2 Deposition and coverage of pesticide

The spraying deposition, distribution and coverage of droplets were tested in a 100 m×100 m area. Filter paper and water sensitive paper (WSP) were used to analyze the deposition of liquid and the distribution of droplets in multi-spraying swath. Three lines of filter papers and WSPs were manipulated perpendicular to flight direction (lateral direction) in the center of testing region, and the length of each line was 15 m. The interval of filter papers in line was 0.25 m, and the interval of WSPs was 1.0 m. The filter papers were placed horizontally, while the WPSs were placed in both horizontal and vertical direction. In order to test the effect of flight speed on the distribution uniformity, three longitudinal test zones were arranged along the route direction (longitudinal direction). Filter papers were placed horizontally in the distance of 1 m, 2 m, 5 m, 9 m, 24 m, 34 m, 44 m and 50 m from the border. The height of filter papers and WSPs equals to wheat plants. The layout diagram of experimental field is shown in Figure 1, and the specific ways of filter papers and WSPs are shown in Figure 2.

Table 2 Flight parameters of UAV in field test

Type of UAV	3WQF120-12	3CD-15	WSZ-0610	HY-B-15L
Flight velocity/m·s^{-1}	5.0	6.0	4.0	4.5
Flight height/m	2.0	2.0	2.0	1.5
Swath/m	4.5	5.0	5.0	6.0
Flow of single nozzle /L·min^{-1}	0.80	0.54	0.72	0.38

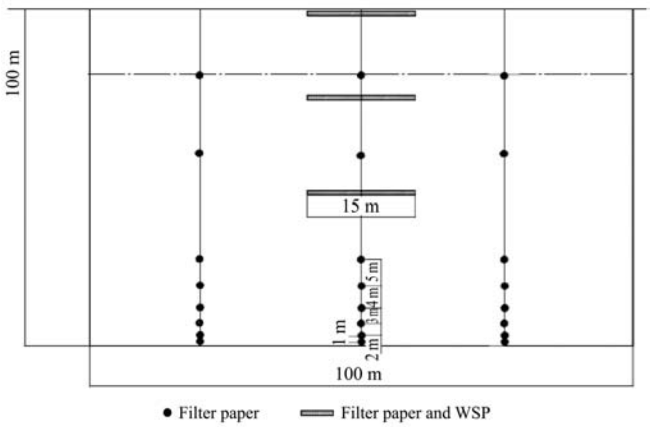


Figure 1 Layout of experimental field

a. Crosswise filters b. Longitudinal filter c. Horizontal WSP d. Vertical WSP

Figure 2 Diagram of filter papers and WSPs

2.2.3 Penetrability of spraying liquids

Testing plot was set in the real pest and disease control area of wheat field. Five sampling points were diagonally arranged in the control area of the four UAVs. Two hours after pesticide application, no less than 1 kg wheat plants of over ground part were collected in each sampling point, and equally divided into upper, middle and lower parts, then stored at –20°C until analysis (storage time was not more than one week before analysis).

2.2.4 Working efficiency

Each operation team consists of two UAVs and three labors. One of the UAVs was used for pesticide application, and the other was a standby. Two labors controlled the UAVs in turns, and the other one was in charge of ground service. The working time of each operation team was from 6:00 to 10:00 and 15:00 to 19:00 every day. The experiment was carried out in the form of large-scale pest prevention. The farmland was assigned randomly to each operation team participated in this test. The following operation items of UAVs for each team were monitored three days in details. The operation items included the time of preparation, route planning, failure maintenance, ground service, net operation and the area operated.

2.3 Sample collection and data processing

2.3.1 Filter paper sampling

The fancy red with mass fraction of 1.5% was used as a tracer added into spraying liquid to quantify the amount of spray liquids deposited on the filter papers. After pesticide application, each filter paper was removed and then placed in separate sealed bags, and then stored in a cool and dark place before analysis. The collected filter papers were washed by 10 mL deionized water in the laboratory. After vibration and elution, 200 μL of eluent was transferred into the ELISA plate, and scanned at 492 nm by Multiskan MK3 enzyme micro-plate reader (Thermo scientific, USA) to estimate the concentration of fancy red and figure out the deposition of spraying liquids on unit area.

2.3.2 WSP sampling

After pesticide application, the WSPs were allowed to dry and placed into the labeled envelopes, then sealed in dry place. Rubber gloves are indispensable during the process of collecting WSPs. A 600 dpi digital image of each WPS was acquired with a handheld scanner in the lab. After that, an imagery software DepositScan[18] (USDA, USA) was utilized to extract droplet deposits in the digital image and analyze the coverage, density, size of droplets on WSPs.

2.3.3 Wheat sampling

In order to analyze wheat samples, three layers of wheat plant were grinded into small pieces or powder by a vegetation disintegrator, respectively. Five grams of the sample was weighted into a 50 mL Teflon tube, while 5 mL of deionized water and 10 mL of acetonitrile were added as well. Five minutes later, samples were shaken in a reciprocating shaker for 10 min. Then 4 g of $MgSO_4$ and 1 g of NaCl were added with quick shake and swirled for 1 min. Samples were centrifuged at 4000 r/min for 5 min, and the supernatant was transferred into a 1.5 mL centrifuge tube with 30 mg GCB and 50 mg PSA. The tube was swirled for 1 min, then centrifuged at 20 000 r/min for 1 min. Transfer the supernatant solution into a sample vial for the LC-MS/MS analysis after filtration through a 0.22 μm nylon filter. Tebuconazole was applied as the target pesticide to analyze the penetrability of spraying liquids by UAVs.

The LC-MS/MS analysis was carried out by using the Thermo TSQ Quantum triple-quadrupole mass spectrometer (Thermo Fisher, USA), which was equipped with an electro spray ionization (ESI) source and Surveyor Liquid Chromatography System. The separations were performed by using a 100 × 2.1 mm × 1.7 μm Hypersil GOLD C18 analytical column from Thermo (USA). Elution was performed with 70% acetonitrile as mobile phase A and 30 % ultrapure water contained 0.1% formic acid as mobile phase B. Separation of the analyzed from the C18 column was performed at a flow rate of 0.3 mL/min. The column was kept at 30°C. The injected sample volume was 5 μL. Analysis of the compound was carried out by using the multiple reaction monitoring (MRM) mode and positive ESI mode. The conditions for MS detection as follows: electrospray voltage was 3500 V; ionization and capillary temperature was 350°C; atomization gas and curtain gas for high-purity nitrogen; the collision gas was argon with the pressure of 0.2 Pa; sheath gas flow rate was 6.5 L/min; and auxiliary gas flow rate was 5.0 L/min. The other MRM conditions are shown in Table 3.

Table 3 MRM parameters of tebuconazole

Compound	Formula	MRM transitions /(*m/z*)	Collision energy E/eV	Tube lens U/V	Retention time *t* /min
Tebuconazole	$C_{16}H_{22}ClN_3O$	307.9/70.1, 307.9/151.0	18/25	129/129	1.86

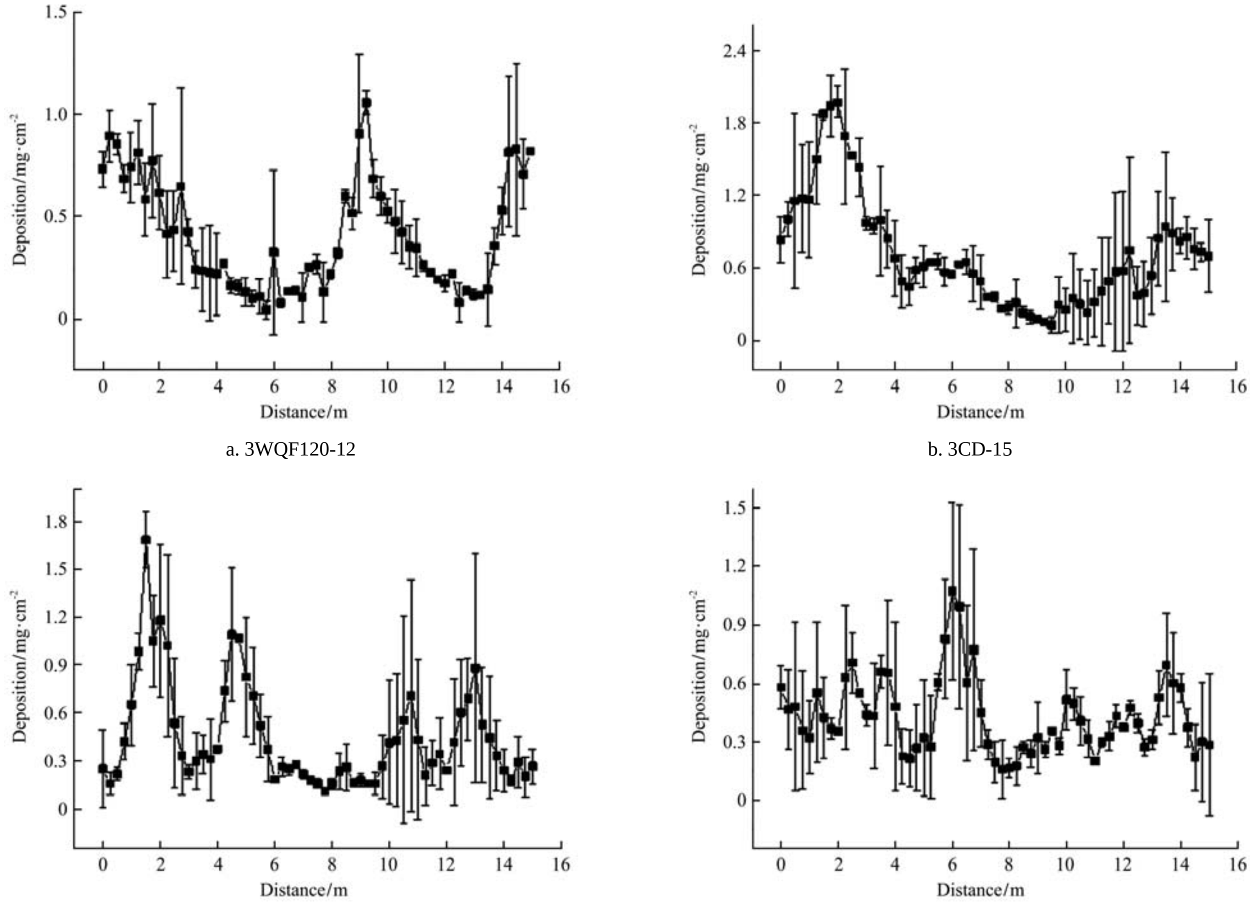
3 Results and discussion

3.1 Deposition and coverage of pesticide

In order to calculate the spraying deposition, a standard curve was built by measuring the absorbance of a series of fancy red solutions of known concentrations. The mass fractions of standard solutions used in this test as follows: 0, 5.0 mg/kg, 10.0 mg/kg, 15.0 mg/kg, 20.0 mg/kg, 25.0 mg/kg, 50.0 mg/kg and 100.0 mg/kg. The deposition of spraying liquids was quantified using the following linear Equations: Y=0.0253x+0.0317 (R^2=0.9982). In this Equation, Y represents the absorbance obtained from ELISA plate; x represents the concentration (mg/kg) of standard solutions. The absorbance of filter paper eluate was taken into the linear regression Equation to determine the content of fancy red in that eluate, and then the deposition of spraying liquids on unit area can be calculated by the fancy red concentration.

The deposition results in lateral direction of each UAV are shown in Figure 3. In the length of multi-spraying swath (15 m), there were obviously inconsistent amount of deposition among the four UAVs in different locations, and the maximum amount of deposition was several times of minimum on each UAV. Uniformity of pesticide distribution is an important factor in evaluating the effect from agricultural airplane[19]. In this case, the coefficient of variation (CV) is used to evaluate the uniformity of spraying liquid deposition. The smaller the CV is, the better the uniformity of the spray deposition is[20]. The CVs of the deposition in lateral direction of the four UAVs respectively were 65.45%, 62.58%, 70.81% and 43.04%, which were much greater than the CV (20%) of boom sprayer specified in the Chinese National Standard[21]. The result obtained in this study was consistent with the conclusion of Qin et al.[4] in paddy and Zhang et al.[22] in citrus, which indicated that there was a great uneven pesticide deposition sprayed by UAVs in China. Uneven spraying liquid distribution was determined by the operating parameters of UAVs and properties of spraying liquids. The spraying height of small UAVs can influence the distribution of droplets[22]. The flight height of four UAVs ranged from 1.5 m to 2.0 m, which was much higher than that of ground plant protection machinery. Hence, the settling time and distance of droplets increased. Bird et al.[23] indicated that the droplet size significantly affects the performance of aerial applications. The droplet size of four UAVs was smaller than ground pesticide application, which increased the specific surface area of spraying liquid and led to a more susceptible liquid to meteorological conditions. Therefore, drift and evaporation of droplets were further intensified in the process of settlement. In addition, the airflow created by UAVs can also affect the distribution uniformity of liquids in the process of droplets settlement.

The deposition results in longitudinal direction of four UAVs are shown in Figure 4. As can be seen from the figure, the deposition at the boundary of operation area was significantly higher than that of the central area. The acceleration and deceleration of the four UAVs near the boundary had a great influence on the uniformity of spraying liquids in longitudinal direction. The length of regulating velocity is about 10 m. When the distance to boundary was greater than 10 m, the amount of deposition is relative uniform in three longitudinal test lines due to the constant-speed movement of the UAVs. The pesticide application of UAVs is mainly in a low volume (LV) and ultra-low volume (ULV) spraying, thus the concentration of pesticide is particularly high. The excess deposition of spraying liquids near the boundary is likely to cause crop injury or excessive pesticide residues.



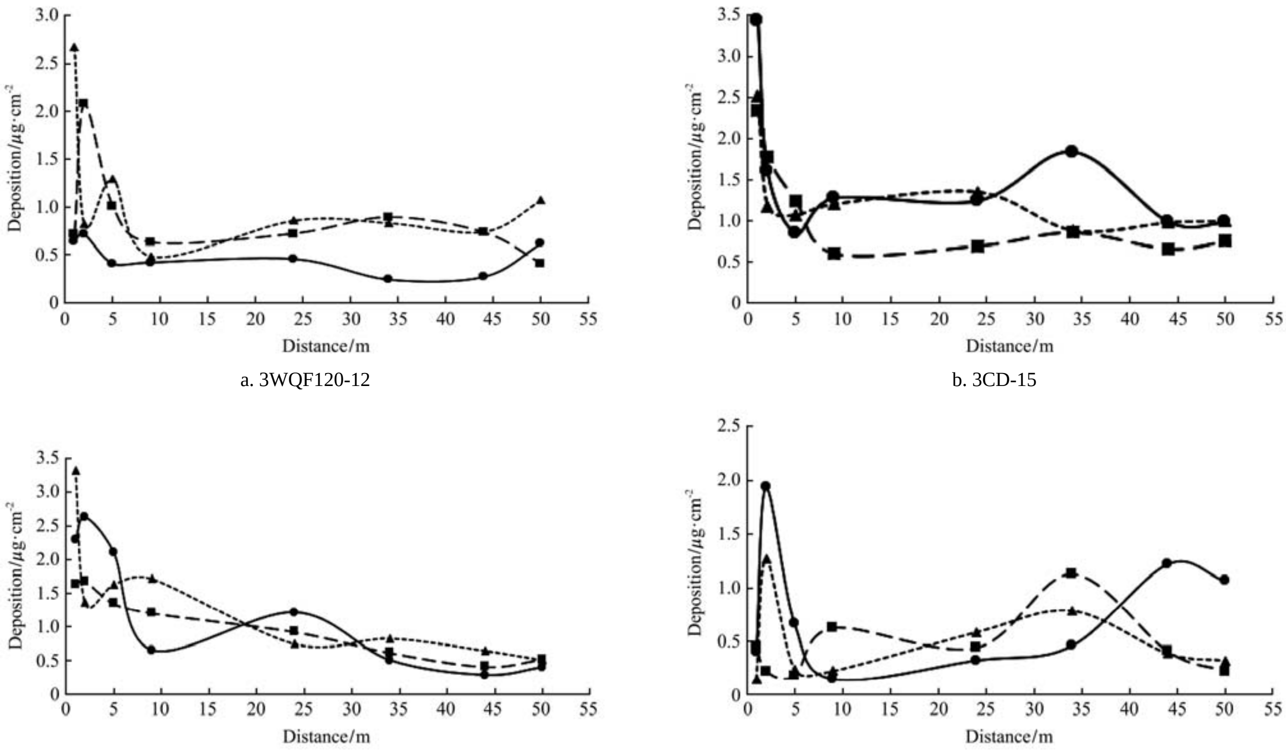
a. 3WQF120-12

b. 3CD-15

c. WSZ-0610

d. HY-B-15L

Figure 3 Deposit characters in crosswise of four UAVs



a. 3WQF120-12

b. 3CD-15

c. WSZ-0610

d. HY-B-15L

Figure 4 Deposit characters in longitudinal of four UAVs

The comprehensive effects of flight parameters, properties of spraying liquids and meteorological conditions resulted in the un-uniformity of deposition applied by UAVs both in lateral and longitudinal direction. Thus, the uniformity of deposition can be enhanced by improving flight parameters, optimizing flight stability and operability. Moreover, changing the properties of spraying liquids, such as developing specialized formulations of aerial pesticide application or adding anti-drift and anti-evaporation adjuvants into the spraying liquids, can also help[24].

The DepositScan software was used to measure the droplet coverage, droplet density, the variation between droplet size and droplet density on WSPs, and the results are shown in Table 4. Though both droplets density and coverage on vertical WSPs were lower than those on horizontal direction, there still existed certain amount of droplets. A downwards flow was produced when the rotors of UAVs were rotating, which helped the droplets to deposit on vertical targets through dispersing the canopy. The droplets density of WSZ-0610 on horizontal and vertical WSPs ranged at 8.2-127.2 g/cm^2 and 3.9-109.5 g/cm^2, respectively. The droplets' VMD of WSZ-0610 on the WSPs was 128 μm, which was the smallest because of a centrifugal nozzle. However, other droplets' VMDs from UAVs with hydraulic nozzles were much larger than those produced by centrifugal nozzle. The sizes of droplets were decided by nozzles of UAVs. With the same spray volume and similar operating parameters, the size of droplets and droplet density showed a negative correlation, while there was no such correlation between the percentage of coverage and droplet size. Although WSZ-0610 had the highest density of droplets on WSPs, its CV of deposition on crosswise reached 70.81%, which was the highest of all. Smaller droplets were impressionable to the meteorological conditions[25,26], and the air flow produced by six rotors of WSZ-0610 was different from that produced by single rotor UAVs. All these effects are possible to lead to the largest CV. However, further research for the specific reasons of imparity is still needed.

Table 4 Sizes of droplets, density and coverage on WSPs

Type of UAVs	Horizontal		Vertical		Sizes of droplets/μm		
	Density/g·cm^{-2}	Coverage/%	Density/g·cm^{-2}	Coverage/%	DV(10)	DV(50)	DV(90)
3WQF120-12	6.9-68.1	0.48-2.21	1.9-29.0	0.13-1.64	143	253	356
3CD-15	6.6-26.9	0.43-2.62	2.4-16.7	0.09-1.28	157	314	543
WSZ-0610	8.2-127.2	0.18-1.85	3.9-109.5	0.12-1.08	77	128	169
HY-B-15L	14.7-38.5	0.78-2.24	2.9-21.6	0.16-1.16	133	264	340

3.2 Penetrability of spraying liquids

In the process of determining the penetrability of tebuconazole, the external standard method was used for quantitative analysis. The test was conducted by fortifying a certain amount of standard solutions of tebuconazole into the blank substrate. Seven concentrations of standard solutions were set for the test, and they are 0, 5.0 μg/kg, 10.0 μg/kg, 50.0 μg/kg, 100.0 μg/kg, 500.0 μg/kg and 1000 μg/kg. A linear regression equation was obtained through the determination of the base objects. Amount of tebuconazole in each layer was quantified by using the following linear equation: Y=2.0048x–1.334 with R^2 = 0.9998. In this equation, Y represents the response peak area obtained from analytical instrument, and x represents the amount (μg/kg) of tebuconazole. The recoveries of added tebuconazole ranged from 86.67% to 88.73% with acceptable relative standard deviations (RSDs) of 0.90%.

The amount of tebuconazole on upper layer of each UVA was defined as 100%, while the quantity of tebuconazole on middle and lower was expressed in the percentages of upper layer. The results of penetrability of four UAVs are shown in Figure 5. WSZ-0610 and HY-B-15L had better penetrability. The depositions of tebuconazole sprayed by HY-B-15L on middle and lower were 46.8% and 16.4% of the upper layer, and the deposition of WSZ-0610 was 52.1% and 12.0%, respectively. The depositions of tebuconazole sprayed by 3CD-15 on middle and lower were 39.0% and 10.4% of the upper layer. In the same way, the results of

3WQF120-12 were 24.1% and 5.2%, respectively. Leaf area index (LAI), structure of canopy and natural wind exerted a tremendous influence on pesticide deposition and distribution in crop canopy[22,27,28]. However, when the three factors are parallel, the impact of flight parameters on penetrability will become more pronounced[4]. Table 2 shows the flight parameters of UVAs, the speeds of 3WQF120-12 and 3CD-15 were 5 m/s and 6 m/s, respectively, which were faster than the speeds of WSZ-0610 and HY-B-15L. The airflow on wheat canopy created by UAVs will be changed by the flight speed. The flight height of HY-B-15L was 1.5 m, which was lower than the other three, and led a larger airflow on wheat canopy. Small droplets are more sensitive to meteorological conditions[29] so that they are more vulnerable to winds. As can be seen in Table 4, the VMD of WSZ-0610 was the smallest for 128 μm, which was more susceptible to the transfer of downward air stream. Also, the airflow of six rotors UAV WSZ-0610 was different from that of single rotor UAVs. Therefore, the penetrability of WSZ-0610 and HY-B-15L were better than 3WQF120-12 and 3CD-15.

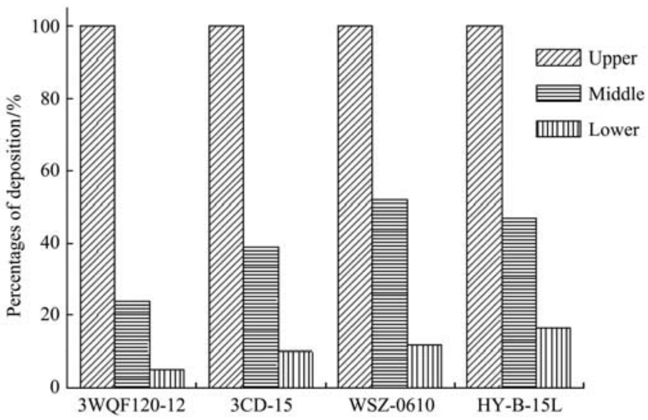


Figure 5 Deposition of four UAVs in different layers

3.3 Working efficiency of UAV

As a high efficiency plant protection machinery, the statistics of working efficiency and the time scale of every operation item make a great deal of sense. However, working efficiency of UAV was simply evaluated by area completed per sortie in previous. The impact of failure maintenance, preparation and ground service were neglected. In this study, preparation included the assemble of UAVs and preparation of spraying liquid, and ground service included the replacement of spraying liquid and fuel oil or battery. Failure rate is the ratio that the time of the failure took up during the whole working process. The failure included not only the damage and replacement of parts, but also the stability of control system, the blocking of pump, tube, nozzle, and all other factors which will influence the normal work stability. Net operation is the process of UAVs spraying in wheat field.

The percentages of operation items and daily operated area of UAVs are shown in Table 5. The proportion of preparation time was relatively balanced, ranging from 7.60% (3CD-15) to 9.56% (3WQF120-12), and is mainly at the beginning of the work. Since there was no crash or other major failures occurred in this test, the failures of the UAVs mainly occurred in the blocking of nozzles, transfusion tube and pump, and it took up 3.73%-4.36% of the total time during the process of crop protection. Those failures can be avoided via changing components and washing them with clean water. On the other hand, it indicated that the formulations of pesticide used were not suitable for the spray system of UAVs. The stability of the spray system can be improved by reducing the viscosity of the spraying liquids and increasing the fluidity or developing specialized formulations of aerial pesticide application. The observation of terrain (route planning) was around 10%, which can be shortened through autonomous route planning and sortie. For example, a route planning algorithm with the minimum return number was proposed by Xu et al.[30], which can reduce the ineffective energy consumption in non-operate situation and improve operational efficiency in the same time.

The percentages of ground service, net operation and daily operated area of HY-B-15L were not given because the motor of HY-B-15L generated a lot of heat during working. So HY-B-15L took a mode of two UAVs spraying alternately. When an UAV completed a sortie, it should be cooled for a while, and the ground staff can add pesticide in and change the batteries at the same time. Meanwhile, the other operator can control the other UAV to spray as well. Also, the takeoff and landing time of UAVs was saved and the time for ground staff to leave the operating area can be saved as well. However, this spraying mode greatly increased operating cost.

On the whole, the proportion of ground time accounted 50% of the whole process, while the net operation was only about 30%. The ground service of 3CD-15 was the highest, reaching 52.14%. This was because the power system and spray system of 3CD-15 was independent, so that the spraying system was supplied with additional power from the battery. Hence, batteries should be changed besides adding pesticide and fuel in ground service for 3CD-15. In this test, the daily working area ranged from 13.4 hm^2 (WSZ-0610) to 18.0 hm^2 (3WQF120-12), which was not a satisfactory result. Obviously, it is necessary to further strengthen the efficiency of UAVs.

Table 5 Percentages of operation items and daily operated area

UAV	Preparation /%	Failure rates /%	Rout planning /%	Ground service /%	Net operation /%	Area /$hm^2 \cdot d^{-1}$
3WQF120-12	9.56	3.73	9.75	47.03	29.93	18.0
3CD-15	7.60	3.42	9.84	52.14	27.00	16.7
WSZ-0610	8.37	4.36	10.37	48.96	27.94	13.4
HY-B-15L	8.81	4.17	10.26	--	--	--

4 Conclusions

In this study, four typical UAVs were used for pesticide application in wheat field. The uniformity of deposition, spraying coverage, droplets density, penetrability and work efficiency of UAVs were tested in this research. The results are showed as follows:

1) Pesticide application of UAVs is on a low precision level, and the spraying liquid distribution was un-uniformity; the deposition performances need to be further improved in China. With the same spray volume and similar operating parameters, the VMD and droplet density showed a negative correlation, while there was no such correlation between the percentages of coverage and VMD.

2) The downward air flow produced by rotors of UAV can promote the spraying liquid deposit into bottom of canopy and increase penetrability.

3) During the whole working time, failure rate was lower than 5%. The time of preparation, rout planning, ground service took up the most of the whole working time. The rate of net operation was lower than 30%.

4) On the whole, the advantage of high efficiency of UAVs is not fully achieved, and the daily operated area of UAVs is not in a satisfactory level and should be further strengthened.

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