Comparison of Spray Deposition, Control Efficacy on Wheat Aphids and Working Efficiency in the Wheat Field of the Unmanned Aerial Vehicle with Boom Sprayer and Two Conventional Knapsack Sprayers

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Abstract: As a new low volume application technology, unmanned aerial vehicle (UAV) application is developing quickly in China. The aim of this study was to compare the droplet deposition, control efficacy and working efficiency of a six-rotor UAV with a self-propelled boom sprayer and two conventional knapsack sprayers on the wheat crop. The total deposition of UAV and other sprayers were not statistically significant, but significantly lower for run-off. The deposition uniformity and droplets penetrability of the UAV were poor. The deposition variation coefficient of the UAV was 87.2%, which was higher than the boom sprayer of 31.2%. The deposition on the third top leaf was only 50.0% compared to the boom sprayer. The area of coverage of the UAV was 2.2% under the spray volume of 10 L/ha. The control efficacy on wheat aphids of UAV was 70.9%, which was comparable to other sprayers. The working efficiency of UAV was 4.11 ha/h, which was roughly 1.7–20.0 times higher than the three other sprayers. Comparable control efficacy results suggest that UAV application could be a viable strategy to control pests with higher efficiency. Further improvement on deposition uniformity and penetrability are needed.

Keywords: unmanned aerial vehicle; pesticide application; deposition uniformity; droplets penetrability; control efficacy; working efficiency

1. Introduction

Wheat is one of the major food crops in China; the planting area and yield account for 21.4% and 20.9%, respectively, in 2017 (Data from National Bureau of Statistics of China). However, there are many kinds of pests and diseases which harm the production of wheat. These pests and diseases are controlled basically by the application of chemical products.

The selection of the equipment to be used is a critical factor for chemical pest control. In China, more than 88% of sprayers are manually operated [1], which include electric or manual air-pressure knapsack sprayer and knapsack mist-blower sprayer. The quality of the application depends mainly on the skill of the operators. These types of equipment are of low cost, easily maintained and adequate to control periodic and localized problems. However, applications with knapsack sprayer generally

lead to high chemical exposure of the operators [2,3] and postural discomfort [4]. The operational farm size is increasing with the growth of agricultural co-operatives, land leasing and contract farming, while the labor force is declining by urbanization and rural–urban migration [1], leading to these low-efficiency and labor-intensive equipment types no longer being suitable for crop protection. As one of the alternative equipment types, self-propelled boom sprayer appeared on the market, equipped with horizontal spray boom. These machines have relatively higher working efficiency, lower chemical exposure and higher deposition [5]. However, the complicated terrain and small farm size with separated plots limit the use of boom sprayer in China. In recent decades, to adapt to this unique operating environment and meet the shortage supply of the crop protection equipment, unmanned aerial vehicles (UAV) for pesticide application have been developed quickly in China. Comparing with the manned agricultural aircraft, UAVs do not require navigation station or airport, and the edge of field can be its landing site [6]. The low rate of no-load flight and less flight crew reduce the expenditure of operations and administration [6]. Meanwhile, UAVs have short turning radius due to hover and turn around flexibly in the air, which are suitable for working in rough terrain and small plots with high efficiency [1,7,8]. Comparing with the conventional ground crop protection machinery, UAVs operate with lower labor intensity, operator exposure and have a higher working efficiency, especially in rough terrain and small plots [1,6,9]. According to the statistics data by the Chinese Ministry of Agriculture, nearly 14,000 crop protection UAVs are used in the country. The spraying area approached 5.5 million hectares in 2017.

Because of the broad prospect of application, UAVs have attracted plenty of scholar's attention. In the aspect of optimizing operational altitudes and speeds, Qin et al. [7] optimized the flying parameters for preventing plant hoppers, showing that a flight height of 1.5 m and a flying velocity of 5 m/s achieved the maximum lower layer deposition and the most uniform distribution for HyB-15L UAV sprayer (Gao Ke Xin Nong Co. Ltd., Shenzhen, Guangdong, China). The optimal parameters change with the type of UAV and the crop. In a spraying test of different shape (open center shape and round head shape) of circus trees, the 3W-LWS-Q60S UAV (Zhuhai Crop Guardian Aerial Plant Protection Co., Zhuhai, Guangdong, China) performs better when the working height is 1.0 m compared with 0.5 and 2 m [10]. In the aspect of deposition uniformity, a multi-spraying swath test is conducted with different UAV sprayers [9]. There is an obviously inconsistent amount of deposition in the longitudinal and lateral direction and this phenomenon has been reported in many studies [7,10,11]. The control efficacy on pests and diseases is one of the most important evaluation indices of chemical application. Quite different from the conventional large volume application, the UAV sprayer belongs to low volume (LV, 4.7–46.7 L/ha) or ultra-low volume (ULV, 0–4.7 L/ha) [12] spraying equipment with the spray volume in the range of 1–40 L/ha [6,11]. Meanwhile, with the same active ingredient applied per acre, the chemical concentration of UAV is particularly high. Qin et al. [7] studied the control efficacy of HyB-15L UAV with spraying Chlorpyrifos·Regent EC against plant hoppers and found that the insecticidal efficacy is 92% and 74% at 3 and 10 days after application, respectively. On the premise of guaranteed control efficacy, the working efficiency is another important evaluation index of application. Currently, UAVs mostly rely on semi-autonomous control with the flight altitude belonging to autonomous control. The control range is 200–300 m in visible distance with manual control [6]. The payload capacity of the aerial application UAVs is generally 5–25 kg [6,13,14]. Considering the limited payload and the flight range, the effective spray work rates of 2–5 ha/h can be achieved in a vineyard with a gasoline-powered helicopter (RMAX, Yamaha motor Co., Cypress, CA, USA) [11]. The working efficiency of different UAVs in the grain-filling stage of wheat was studied by Wang et al. [9], with the daily working area ranging from 13.4 to 18.0 ha in 8 h. Pesticide spray drift is an important environmental problem for aerial application. Compared with the manned agricultural aircraft [6,15,16], the droplet drift of UAV is effectively reduced with the lower flight height [6,7] and the downwash wind [17,18]. According to Xue et al. [19], under the wind speed of 3 m/s, 90% of drift droplets of Z-3 UAV are located within a range of 8 m of the target area. Similar to Xue et al., Wang et al. [17] measured that 90% of drift droplets of a fuel powered single-rotor UAV are within 9.3–14.5 m under

the wind speed of 0.76–5.5 m/s. Compared with the conventional boom sprayer [20,21], the droplets drift distance of UAV sprayer would be further.

Despite these preceding studies, research is focused mainly on parameter optimization, droplet deposition and biological efficacy of one equipment. Few studies compare different kinds of crop protection equipment, especially including UAV sprayer. Under the same working condition, the comparison of different crop protection equipment on deposition, control efficacy and working efficiency is very important for equipment selection and application quality analysis. The main objective of this research was to compare the application quality of a battery motive 3WTXC8-5 six-rotor UAV with a 3WX-280H self-propelled boom sprayer and two conventional knapsack sprayers (3WBS-16A2 electric air-pressure knapsack sprayer and WFB-18 knapsack mist-blower sprayer). The comparison items included the spray deposition on the plants and run-off, uniformity and penetrability of the deposition, deposition characterization (including droplet size, number of spray deposits and the area of coverage), pesticide efficacy on wheat aphid and working efficiency. The experimental results show that the control efficacy of the UAV on wheat aphid was comparable to other spraying equipment with the working efficiency significantly higher than others. Unfortunately, UAV still have many problems on deposition uniformity and droplets penetrability.

2. Materials and Methods

To compare the advantage and shortcoming of the UAV with other spraying equipment, we selected three typical types of crop protection equipment including a self-propelled boom sprayer and two conventional knapsack sprayers for field spray deposition, control efficacy on wheat aphid and working efficiency tests. The spray deposition was compared from four aspects: the total amount of deposition and losses to the ground, deposition uniformity, droplets penetration in the canopy and characterization of the deposition (including droplet size, number of spray deposits and the area of coverage).

2.1. Spray Equipment

A battery motive 3WTXC8-5 six-rotor UAV (Henan Tianxiucai Aviation protection machinery Co., Ltd., Kaifeng, China) (Figure 1A) was used in this study. The UAV was powered by two 12,000 mAh Li-Po batteries (Shenzhen Grepow battery Co., Ltd., Shenzhen, China). The flying time was 15–20 min with full tank. The flight speed was 12.6–14.4 km/h with two rotary cup atomizer arranged on both sides. The interval of nozzles was 0.85 m and the installation angle was vertically downward. The rotate speed of the disk was 10,000 rotations per minute. The chemicals were transferred from the tank to the nozzles by a HXB600 micro liquid pump (Shanghai Hallya Electric Co., Ltd., Shanghai, China) and the flow rate was 1.24 L/min. The accuracy of the flight height and flight velocity were controlled by the well-trained operator. The flight height was 1.0 m and the effective spraying width was 4.0 m. The spray volume of one sortie was close to 10 L/ha, which was equal to two times the tank capacity.

One of the comparison systems was the 3WX-280H self-propelled boom (SPB) sprayer produced by Sino-Agri Fengmao Plant Protection Machinery Company (Beijing, China) with the tank capacity of 280 L (Figure 1B). There are 12 ISO 04 nozzles (Spraying system Co.) installed vertically on the spray boom with the same interval of 0.5 m on the 6-m boom. The spraying height of the boom was 0.5 m from the top of the canopy. The spray pressure was 4 bar and the flow rate was 18.2 L/min. The operation speed was 6.0–6.5 km/h. Under these application conditions, the spray volume was close to 300 L/ha.

Figure 1. Four test sprayers: (**A**) 3WTXC8-5 six-rotor unmanned aerial vehicle (UAV) sprayer; (**B**) 3WX-280H self-propelled boom (SPB) sprayer; (**C**) WFB-18 knapsack mist-blower (KMB) sprayer; and (**D**) 3WBS-16A2 electric air-pressure knapsack (EAP) sprayer.

The two other conventional sprayers were WFB-18 knapsack mist-blower (KMB) sprayer (Sino-agri Fengmao, China) (Figure 1C) and 3WBS-16A2 electric air-pressure knapsack (EAP) sprayer (Chuangxing sprayer factory, Xinxiang, China) (Figure 1D). EAP sprayer was equipped with twin hollow cone nozzles and a pressure pump provided a maximum pressure of 4 bar and a flow rate of 1.6 L/min. The tank capacity was 16 L and the length of the lance of the EAP sprayer was 81 cm. The spray swath width was close to 2.5 m. The traveling speed in the test was approximately 1.1–1.3 km/h and the spray volume under these application conditions was close to 300 L/ha. The KMB sprayer was developed to improve the spraying efficiency of air-pressure knapsack sprayer, which was equipped with a tank, a spray pipe, a nozzle and a gasoline engine. The droplets were sprayed from the nozzle, which were further atomized by the high speed air flow. The high speed air flow was produced by high speed whirling impeller driven by the gasoline engine. The flow rate in this test was 2.0 L/min with the tank capacity of 18 L. The spraying swath width was close to 6.0 m. The traveling speed was approximately 2.7–3.0 km/h and the spray volume was close to 75 L/ha. The working height of the nozzle of two conventional sprayers was 0.5 m from the top of the canopy. The spraying patterns of two knapsack were both swinging spraying.

All working parameters and spray volumes for each sprayer were established taking into account local farmers practices. Before tests, all spray equipment performed a preliminary test to calibrate the equipment to ascertain the flow rate of the nozzles. After the flow rate was ascertained, the traveling speed was also calculated to obtain the stated application rate. To achieve the velocity, the operator needed to repeat several times before undertaking each trial until the desired traveling speed was reached. Each spraying treatment was done by a well-trained applicator.

2.2. Experiment Design

2.2.1. Field Plots

The tests were conducted at the agricultural experiment station of the Chinese Academy of Agricultural Science located at Xinxiang, Henan Province, China (latitude $35°8'8''$, longitude $113°46'58''$) (Figure 2). The experimental farm is a trapezoidal field nearly 50 ha in area and it consists of many square fields approximately 200 m on a side (Figure 2). The tested material was "Bainong AK58" wheat in the booting-filling stage on 27 April, which was sown on 10 October, 2014. The plant spacing, plant height, leaf area of the flag leaf, and planting density were 12 cm, 84.8 ± 4.1 cm, 1927.1 cm^2 and 4.1×10^6 plant/ha, respectively. The wheat in the whole test area grew well and consistently.
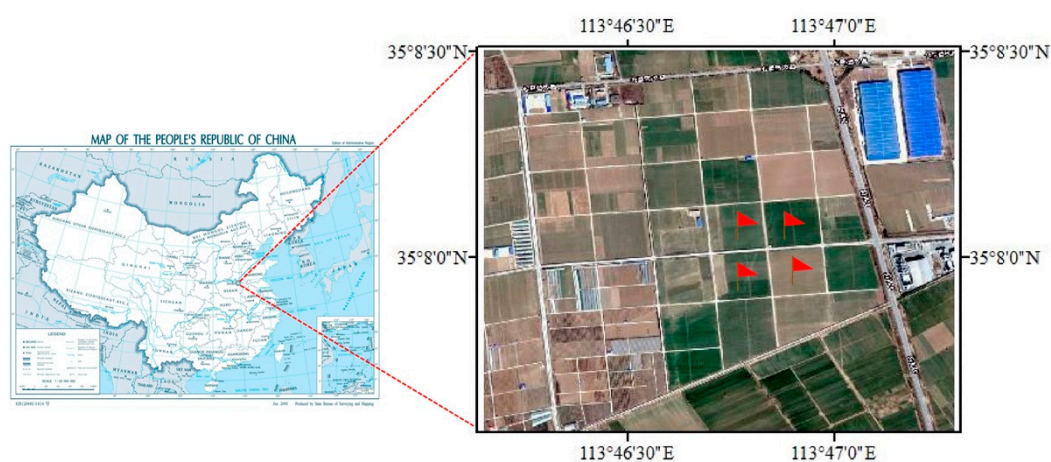

Figure 2. The test location and the brief overview of the studied wheat field. The experimental fields are marked with red flags.

2.2.2. Spray-Deposition Measurements

The experiment consists of five treatments: four kinds of spray equipment treatment and a blank control. The spray deposition, the control efficacy on wheat aphids and working efficiency were tested. The spray deposition and the control efficacy were tested in a 170 m $\times$ 190 m area (Figure 3A). In the test field, treatments were arranged within the location as a randomized complete block design with three replications, resulting in three blocks each with five plots corresponding to different treatments. Each plot was a 30 m $\times$ 50 m area. Ten-meter buffer zones [17,19] between plots were set to avoid the drift pollution (Figure 3A).

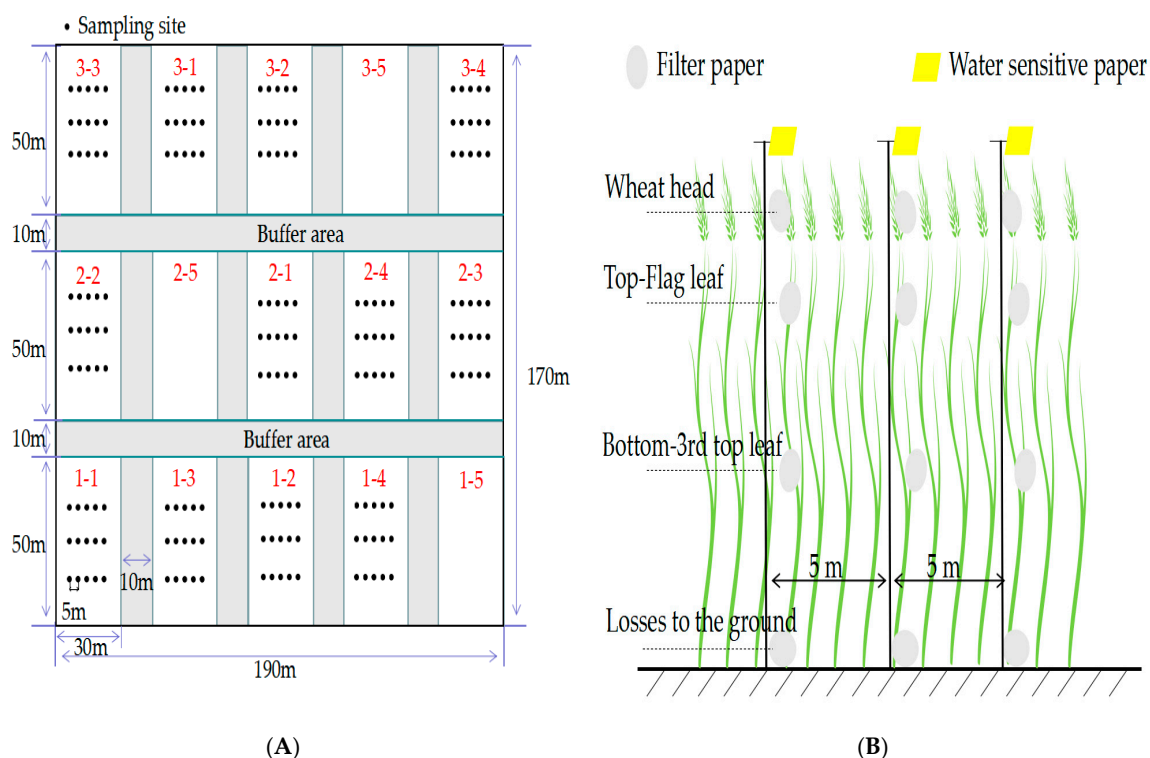**Figure 3.** (**A**) Experimental layout of each treatment; and (**B**) placement of filter papers and water-sensitive paper at each sampling position within the wheat canopy.

Prior to the application in each treatment, sample collectors were placed at each plot in five equally-spaced sample sites. Each sample site was 5 m apart and spanned a total of 20 m. The sample sites were repeated three times with an interval of 15 m between each repetition. To avoid cross contamination between plots, sampling was arranged at the center of the plots, as shown in Figure 3A.

Sample collectors at each sample site consisted of one water-sensitive paper (WSP) (25 mm × 75 mm) and four filter papers (90 mm in diameter) (Figure 3B). The WSP was used to evaluate the characteristic of deposition such as an area of coverage, number of spray deposits and droplet size. The filter papers were used to measure the deposition distribution in the canopy. The WSPs were fixed horizontally on plastic rods through double-headed clamps. The heights of these clamps were adjusted to assist in positioning at a height equivalent to the head of the wheat canopy. The filter papers were used to simulate leaves to collect foliar deposition at different heights and losses to the ground. On each sampling site, three filter papers were attached on the wheat head, flag leaf and third top leaf of one wheat plant. To evaluate the losses to ground, a filter paper was placed on the ground.

In all tests, 70% Imidacloprid·Regent Water dispersible granule (WDG) at 85.7 g a.i./ha (active ingredient) (Zhejiang Sega Science and Technology Co., Ltd.) and allure red (80% purity, purchased from Beijing Oriental Care Trading Ltd.) were added into the tank. The pesticides were prepared according to the recommended dose. Allure red was used as the tracer according to the spraying area at 450 g/ha. Allure red, a water-soluble colorant, is frequently used in these types of studies [3,9,15]. It presents high recovery rate, high photostability and low acute toxicity in different species of animals according to the Joint FAO/WHO Expert Committee on Food Additives as well as the European Union's Scientific Committee for Food.

Nearly 30 s after spraying, five randomly selected wheat plants of over ground part, WSPs and filter papers of different canopy positions at each sampling site were collected and placed in labeled plastic zip-lock bags. Five random wheat plants were combined and bagged as one sample. The sample of wheat plants was used to measure the total deposition per plant. For each plot, there were 15 wheat plant samples, 60 filter papers (4 from each sampling site) and 15 WSPs. All samples were placed

in zip-lock bags along with a label describing the treatment, replication, and location information. Samples were placed into light-proof seal box immediately after collection and transported to the laboratory for analysis.

Each filter paper and the wheat sample were washed in 0.02 L and 0.2 L of distilled water in the collection bags, respectively. Samples were agitated and vibrated for 10 min to allow the dye to dissolve into the water solution. Previous tests have shown that this methodology results in near total recovery of dye deposited on samples [22]. After vibration and elution, a sample portion of the wash effluent was filtered through a 0.22 μm membrane and the filtered wash effluent was poured into a cuvette to measure the absorbance value by a UV2100 ultraviolet and visible spectrophotometer (LabTech, Co. Ltd., Beijing, China) at an absorption wavelength of 514 nm. Spray deposits were quantified by comparison with similarly determined dye concentrations from spray tank samples and the area of the respective samples. The data were expressed as a quantity of dye (μg) deposited per unit area of the sample (cm^2) or quantity of dye (μg) deposited per plant. Note that throughout the text whenever the term "deposition" is used, it refers to the mass of dye (which would correspond to amount of active ingredient), not the mass of total spray mix, deposited on specified sampling surface. The distribution uniformity of the spray deposition in the canopy was analyzed using the value corresponding to the coefficient of variation (CV), calculated as the quotient between the standard deviation and the average of the spray deposits on the crop. In addition, for each application, the recovery rate was calculated using Equation (1):

$$R = (D \times P/A) \times 10^6 \tag{1}$$

where R is the recovery rate (%), D is the average deposited tracer solution per plant (μg/plant), P is the plant density (4.1×10^6 plant/ha), A is the additive amount of allure red (450 g/ha), and 10^6 is the unit conversion factor.

In the laboratory, the WSPs were scanned at a resolution of 600 dpi with a scanner. After that, imagery software DepositScan [23] (USDA, USA) was utilized to extract droplet deposits in the digital image and analyzed the droplet size, number of spray deposits and the area of coverage. The Volume Median Diameter (VMD) is a key index for reflecting the droplet size, which was used in this study.

The climatic conditions were recorded using a Kestrel 5500 digital meteorograph (Loftopia, LLC, USA), which recorded temperatures of 18.3–22.4 °C, a relative humidity of 46.3–53.7% and wind velocities of 3.6–10.8 km/h.

2.2.3. Investigation of Control Efficacy

To analyze the field efficacy of different spraying equipment with different spray deposition characteristics, we selected wheat aphid as the field test target according to the occurrence of diseases and pests. The wheat aphid was investigated and recorded four times according to pesticide field efficacy test criteria. Before the pesticide application on 27 April, the base number of the wheat aphids per hundred plants was more than 500, which meet the control criteria. The assessment was made by sampling five locations per plot on wheat aphid. The aphid number of 10 strains of wheat per location was investigated before spraying and the wheats were marked with a red string. After application on Days 1, 3, and 7, the number of aphid in the same location and plant was investigated again. The overall control effect against wheat aphid was calculated without regard to the types or instars of the wheat aphid. The mortality and control effects were obtained based on the population numbers of live insects in each zone before and after spraying. The control effect was calculated according to Equations (2) and (3):

$$\text{Mortality (\%)} = (\text{The number of pests before application} - \text{The number of pests after application})/\text{The number of pests before application} \times 100 \tag{2}$$

$$\text{Control effect (\%)} = [\text{Observed mortality (\%)} - \text{Control mortality (\%)}]/[100 - \text{Control mortality (\%)}] \times 100 \tag{3}$$

2.2.4. Working Efficiency Test

To better reflect the work efficiency (ha/h) of different equipment, the spraying area and the total spraying time of five filled tanks of chemical for each sprayer were recorded. The spray equipment was operated by experienced operators. The preparation time of mixing chemicals and other preparations, such as replacing the batteries or adding chemicals, did not count in the spraying time because they are greatly influenced by the cooperation and organization of the large-scale application. The spraying parameters are described in Section 2.2.1.

2.2.5. Statistical Analysis

Before the significant difference analysis, the percentage of the area of coverage on WSPs and the mortality of wheat aphids were transformed using $y = \arcsin\sqrt{X/100}$. The total deposition and losses to the ground, deposition on different canopies, number of spray deposits and droplet size were $\log(x + 1)$ transformed to stabilize wide variances and meet normality assumptions. After transformation, the data were analyzed for normality using the Kolmogorov–Smirnov test and for equal variances across the treatments and repeats using Levene's test ($p < 0.05$). The significant difference for the transformed data was conducted using analysis of variance (ANOVA) by Duncan's test at a significance level of 95% with SPSS v22.0 (SPSS Inc, an IBM Company, Chicago, IL, USA).

3. Results and Discussion

3.1. Spray Deposition

3.1.1. Total Deposition on the Crops and Losses to the Ground

The samples of the wheat plant were used to measure the total spray deposition per plant. The filter papers were used to measure the spray deposition in different wheat canopy and losses to the ground, and the recovery rate was calculated from the amount of the total deposition and additive. The total deposition of the UAV was not significantly different from the other sprayers (Table 1). Among the four sprayers, the EAP sprayer achieved the highest total deposition and the KMB sprayer achieved the lowest (Table 1). Compared with the SPB and KMB sprayer, the UAV and EAP sprayer had significantly higher recovery rates. The dose transfer process studied showed the transfer of pesticide from the spray tank to the target organism and in this process, losses of drift and run-off had great influence on deposition [24]. In this study, the SPB and KMB sprayer had relatively lower depositions and, correspondingly, those two sprayers had the higher run-offs, which were 0.39 and 0.50 μg/cm^2 (Table 1). Similar to other studies [25,26], it could be that high-volume spraying easily leads to run-off. In Table 1, Columns 4 and 5, compared with other sprayers, UAV had the lowest losses to the ground.

Table 1. The average (Avg.) and coefficient of variation (CV) of the total deposition on the plants, losses to the ground and the recovery rate of four sprayers.

Spray Equipment	Total Deposition		Losses to the Ground		Recovery Rate
	Avg. (μg/Plant)	CV (%)	Avg. (μg/cm^2)	CV (%)	Avg. (%)
UAV sprayer	76.8 a	87.2	0.13 b	78.2	70.0 a
SPB sprayer	68.7 a	32.1	0.39 a	39.0	62.7 a
EAP Sprayer	84.8 a	84.4	0.14 b	118.2	77.3 a
KMB Sprayer	61.9 a	81.2	0.50 a	97.1	56.5 a

Note: Values followed by the same letter in the column do not differ statistically ($p < 0.05$; Duncan's Test).

3.1.2. The Uniformity of the Deposition

In addition to the total deposition, the uniformity of the deposition is also very important for controlling pests and diseases. The uniformity of the SPB sprayer was better than the others. The CV

of the deposition was only 32.1%, which was significantly lower than the others (Table 1). This means it had a better deposition uniformity. However, the CVs of the deposition in this study was much greater than the value of Chinese National Standard requirement (10%) [27]. This may be due to the different measuring methods. In the study by Yang et al. [28], the CV of the deposition distribution ranged from 5% to 10% with different spray pressures and nozzle heights, which are far lower than the result of our study. This is because the Teejet pattern check was used by Yang et al., which is not influenced by the environment and the crop canopy. By comparison, the results in our study were a reflection of the actual uniformity of the deposition distribution on the crops.

Compared with the SPB sprayer, the UAV sprayer had a significant lower uniformity of the deposition distribution with the CV of 87.2% (Table 1). This result was larger than the Civil Aviation of China General Aviation Operation Quality and Technology Standard for ultra-low volume spraying, which is 60% [8]. The uniformity of the deposition distribution of the UAV was influenced by many factors, such as the types [9], the flight accuracy, the flight parameters [7], the spraying system, the biased downwash wind [18] and the meteorological condition. Precise flight route control and auto navigation are essential for chemicals application with improving the deposition distribution uniformity [14]. Xue et al. [8] developed an automatic navigation unmanned spraying system for the N-3 unmanned helicopter, which can significantly improve the deposition uniformity. The flight parameters also have a great influence on the deposition distribution uniformity. Various UAV sprayers under different flight parameters have been tested to find optimal spraying heights and speeds [7,10,18]. Qin et al. [7] found that the flight parameters affect not only the distribution uniformity on rice canopy but also the control efficacy on wheat hoppers. Bae and Koo [29] pointed out that most agricultural helicopters exhibit biased downwash, resulting in an uneven spray pattern. To address this problem, a roll-balanced agricultural helicopters with an elevated-pylon tail rotor system was developed. In their study, the uniformity of the spray patterns and area of coverage was improved.

The CVs of depositions of the EAP and KMB sprayer were 84.4% and 81.2%, respectively, which indicate a nonuniform deposition (Table 1), mainly due to the manual operation of the sprayer. The deposition uniformity was worse because it depended on the stability of the traveling speed along the spraying route and on the regularity of the arm movement of the operators.

3.1.3. Droplets Penetrability

In the test, filter papers were used to measure the tracer deposition on the different canopies of wheat. An analysis of the deposition on the wheat heads showed that the deposition of the low volume sprayer of the UAV and KMB sprayer were significantly higher than the SPB and EAP sprayer (Figure 4). The greatest deposition was achieved with the conventional KMB sprayer with 1.46 $\mu g/cm^2$, which was 18.7%, 80.2% and 111.6% more than the UAV, EAP and SPB sprayer, respectively (Figure 4). From the droplet size test results presented in Section 3.1.4, the VMD of droplets of KMB and UAV sprayer were lower than the other two sprayers. The main reason for higher wheat head deposition of UAV and KMB sprayer may be that fine droplets were better retained in the upper canopy [30].

The deposition of four sprayers on the flag leaf (top canopy) ranged from 0.57 to 1.02 $\mu g/cm^2$ (Figure 4). The UAV sprayer had the highest deposition on the flag leaf, which was 41.7–78.9% higher than the other sprayers. However, influenced by the great variability, the depositions on the flag leaf were not significantly different. In the study by Zhu et al. [31], the spray deposits decreased dramatically from the top to the bottom of the canopies and also tended to linearly decrease as the leaf area index increase. Due to the overlap and the block of the blades at the later growth stage of the wheat, the depositions on the lower parts were far less than top parts. The depositions of different sprayers were influenced by many factors, such as spraying pressure, spraying height and spraying pattern. The deposition of the UAV sprayer on the third top leaf (bottom canopy) was only 0.26 $\mu g/cm^2$, which was not significantly different from the other two conventional sprayers. However, it was 50.0% compared to the SPB sprayer and the deposition of SPB sprayer on the bottom was 0.52 $\mu g/cm^2$.

To improve the adhesive rate of solution and control efficacy, it is crucial to enhance the droplets penetrability and obtain a homogeneous deposition distribution [31], especially since many pests and diseases occur on the bottom of plants. Although many studies [18,19] have proven that the downwash airstream generated by the UAV is conducive to the disturbance of leaves and droplets penetration, the results from our study proved that the penetration of the droplets of UAV is still worse than boom sprayer. This result is similar to the results of Wang et al. [9] and Qin et al. [7]. There are many factors accounting for the poor droplet penetrability. One of the most important reasons is that the droplets were sprayed by the rotary cup atomizers, which lack the downward kinetic energy in comparison with hydraulic nozzles. Wang et al. [9] compared four kinds of UAV sprayer and found the flight height and the flight speed had a pronounced impact on droplet penetrability. In their study, the penetrability of the droplets was inversely proportional to the flight speed and the flight height. The flight parameter had an effect on the downwash flow, which further affected the droplets penetrability. Chen et al. [18] testified that the vertically downward wind had a significant effect on the penetrability. To improve the droplet penetrability of the UAV sprayer, the fly height and speed should be lower, thus ensuring operating efficiency, and suitable nozzles should be chosen to improve the droplets penetrability.

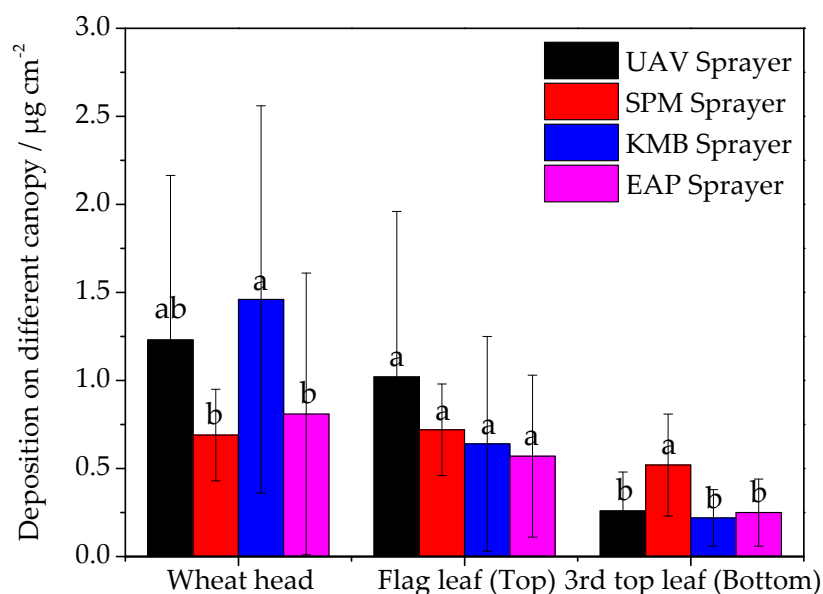The deposition uniformity on different parts of the canopy was consistent with the total deposition. The SPB sprayer had the best deposition uniformity (CVs < 56%) on different canopies and other sprayers had lower uniformity (CVs > 70%).

Figure 4. Deposition of four sprayers on the different canopies of wheat. Bars with different letters are significant different, Duncan's test, *p* < 0.05.

3.1.4. Characterization of Deposition

In the test, the WSPs were used to evaluate the characteristics of the deposition, which included droplet size, number of spray deposits and the area of coverage. Influenced by the spray volume and spraying system, the deposition characteristics of different sprayers were quite different (Figure 5). The spray volume of SPB sprayer approached 300 L/ha, which was identical to EAP sprayer belonging to the large volume application. Furthermore, the nozzles of SPB sprayer are similar to EAP sprayer, which are hydraulic nozzles. From the test results of WSPs, the VMD of the droplets of the SPB and EAP sprayer were 272.3 and 254.1 μm, respectively. They were not significantly different from each other (Figure 5). Although the VMD of droplets and the spray volume of SPB sprayer were similar to EAP sprayer, the area of coverage and the number of spray deposits of SPB sprayer were 75.9% and 73.9% greater than the EAP sprayer with no significant difference (Figure 5). From the CVs results of the total deposition, the greater area of coverage and number of spray deposits of SPB sprayer may be

due to the better deposition uniformity. As a conventional knapsack sprayer, the spray volume of KMB sprayer was quite lower than the EAP sprayer of 75 L/ha. With the air assistance, the VMD of droplets of KMB sprayer was significantly lower than the EAP sprayer, which was only 154.7 μm. Results from previous studies had proved that the area of coverage is proportional to the spray volume [32]. The area of coverage of KMB sprayer was lower than the EAP sprayer with no significant difference (Figure 5). However, with finer droplets, the number of spray deposits of the KMB sprayer was quite similar to the EAP sprayer (Figure 5).
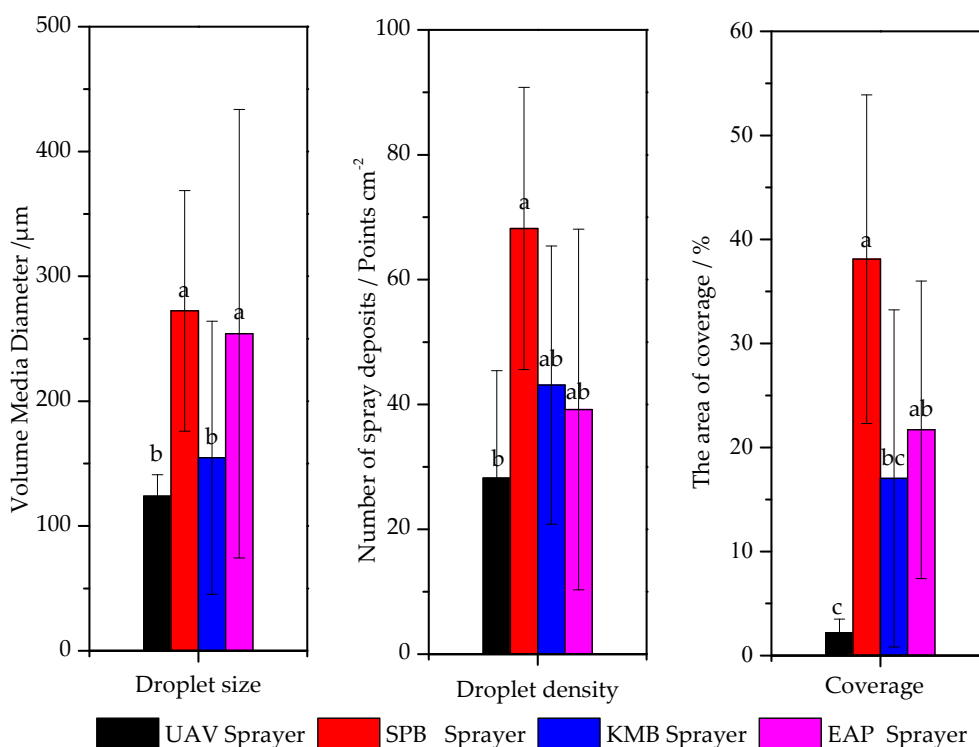

Figure 5. Characterization of the deposition including droplet size, number of spray deposits and the area of coverage.

The spray volume of UAV sprayer was 5 L/ha, which was lower than the other three sprayers. With the unique atomization method, the droplets were smashed by the high rotational speed of the rotary cup (10,000 rpm). The VMD of the droplets was 124.0 μm, which was finer than the three other sprayers (Figure 5). Another characteristic of this nozzle, which differed from hydraulic nozzle, is that the width of the droplet spectrum of this nozzle was narrower and the droplet size was more uniform with high rotational speed [33]. The result in this study verified that the CV of the VMD of the droplets was only 17.1%, which was far less than the other sprayers (CV > 35%) (Figure 5). Because of the lower spray volume, the area of coverage of the UAV was 2.2%, which were quite lower than the other sprayers and was only 5.8% to 12.8% of the other three sprayers. The number of spray deposits of the UAV was 28.2 points/cm^2, which was also significantly lower than others (Figure 5). This may go against the control of pests or diseases, especially when the contact pesticides were applied. Therefore, the focus of further studies will be improving the spreading coefficient of the droplets and increasing the area of the coverage, such as adding adjuvant in the tank [34,35], or changing into electrostatic-charged sprays [36,37].

Spraying systems had a great effect on the characteristics of deposition, including the area of coverage, number of spray deposits and droplet size. It is difficult to judge the application quality by a single index. Although the lower spray volume of UAV could lead to lower area of coverage and fewer deposits, the dose applied per area was not significant lower than other sprayers, because of the higher concentration of each droplets. Syngenta Crop Protection AG (Basel, Switzerland) recommends

that the satisfactory results can be obtained by a number of spray deposits of at least 20–30 points/cm^2 for insecticide or pre-emergence herbicide applications, 30–40 points/cm^2 for contact post-emergence herbicide applications and 50–70 points/cm^2 for fungicide applications [23]. The number of spray deposits only needs to reach a certain threshold to achieve a good control efficacy [38].

3.2. Control of Wheat Aphids

The control efficacy of the four sprayers applying 70% Imidacloprid·Regent WDG on wheat aphids are indicated in Figure 6. Although the spray deposition characteristics of the four sprayers were significantly different from each other, the differences of control efficacy were not remarkable. The control efficacies on Day 7 after application were all beyond 70%. From the comparison of four sprayers, it was found that the SPB and KMB sprayers achieved the best control efficacy, while the efficacies were intermediate for EAP and UAV sprayer. Deposit structure plays a major role in toxin efficacy [24,38]. According to the results of the deposition, the SPB sprayer had the best deposition uniformity and penetrability, which benefit the control of wheat aphids, especially since wheat aphids tend to favor the lower portions of plants. The larger area of coverage and a larger number of spray deposits increased the odds of interaction between active ingredients and pests.
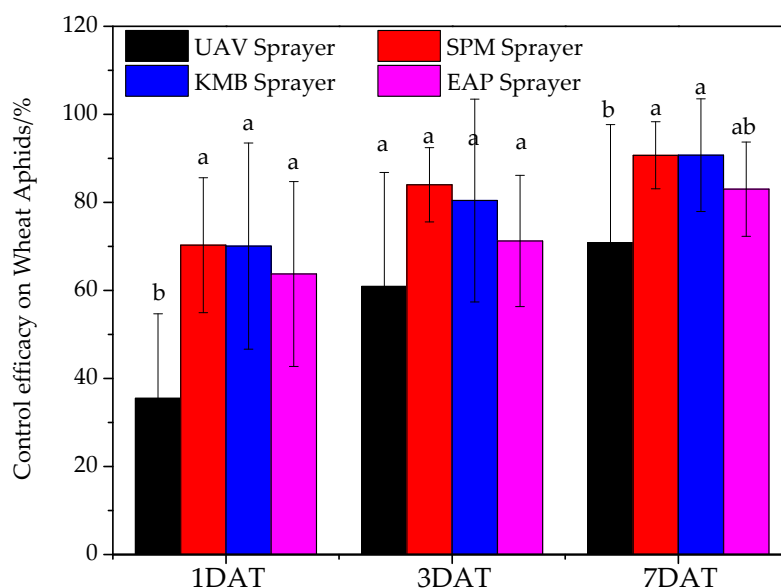

Figure 6. Control efficacy (%) of four sprayers against wheat aphids in the field tests at Days 1, 3, 7 after treatment. DAT, days after treatment.

Because UAV sprayers are still in the initial development stage in China, there are still many problems on the spraying system and working parameter. These problems lead to unevenness deposition and poor penetrability. The lower area of coverage and fewer spray deposits with the nonuniform deposition reduced the chance of aphids to be exposed to the insecticides. The control efficacy of UAV sprayer on Day 1 after application was significantly lower than other sprayers, which was only equal to 50.5% of the SPB sprayer. However, in time, the control efficacy increased. The reason could be that, with the movement of the aphids and the systemic action of the active ingredients, the chance of wheat aphids being exposed to the active ingredients increased. On Day 3 after application, the control efficacy increased to 60.9% and, on Day 7 after application, the control efficacy increased to 70.9%. Although it was also significantly lower than the SPB and KMB sprayers, it was still an acceptable result for farmers, especially in complex small plots or rice fields, where the SPB sprayer is hard to work and the KMB and EAP sprayer have a low work efficiency. Although the UAV sprayer, especially for the electrical multi-rotor UAV, used in the field, is an innovation, the low volume application is not a new technology. Many studies had been conducted to evaluate the feasibility of low

volume application for pests and diseases control. In the laboratory, Maczuga and Mierzejewski [39] found that several spray deposits of 5–10 points/cm^2 on foliage after spraying were effective (90% mortality) against second and third instars. Washington et al. [40] investigated the effect of fungicide spray number of spray deposits (points/cm^2), droplet size and proximity of the spray deposits to fungal spores on the banana leaf surface. The test results suggest that the inhibition zones of two contact fungicides on the leaf surface extend beyond the visible edge of the spray droplet deposit and a mean droplet deposit density of 30 points/cm^2 can inhibit the germination of the ascospore below 1%. Latheef et al. [36] evaluated the efficacy of aerial electrostatic-charged sprays for season-long control of sweet potato whiteflies, and they concluded that the control efficacy of electrostatic-charged sprays with spray volume of 4.68 L/ha was comparable with those on cotton treated with conventional applications of 46.8 L/ha.

3.3. Working Efficiency

Working efficiency is also an important evaluation index for equipment selection. The UAV sprayer used in the test belongs to semi-autonomous control, which is the most common in China. By recording the spraying time of five sorties with the filled tank, the average spraying time of each sortie of the UAV sprayer was calculated as 0.095 h (Table 2). The average spraying area of each sortie was 0.39 ha with the spray volume of 5 L (Table 2). Calculated from the spraying time and area, the work efficiency of the UAV sprayer was 4.11 ha/h (Table 2). The work efficiency test results were consistent with Wang et al. [9], who reported that the working efficiency of UAV was at 13.4–18.0 hectare per 8 h, i.e., 1.68–2.25 ha/h. In his test, the operation items included the time of preparation, route planning, failure maintenance, and ground service, which accounted for 50% of the whole process. With micro-electronic technology development, the multi-sensor data fusion and real-time kinematic positioning technology and product will be applied in agriculture UAV, with which the UAV can achieve fully autonomous flight, significantly improving the working efficiency [41].

Table 2. Working efficiency (ha/h) of four sprayers.

Sprayer	Tank Capacity (L)	Spray Area (Means ± Standard Error, ha)	Spray Time (Means ± Standard Error, h)	Working Efficiency (ha/h)
UAV sprayer	5	0.39 ± 0.04	0.095 ± 0.01	4.11
SPB sprayer	280	0.93 ± 0.06	0.39 ± 0.03	2.38
KMB Sprayer	18	0.22 ± 0.02	0.14 ± 0.01	1.57
EAP Sprayer	16	0.039 ± 0.004	0.19 ± 0.01	0.21

Note: Spray area in the table means the area per spray with full tank. Spray time in the table means the time per spray with full tank.

Compared with the UAV sprayer, the SPB sprayer had a relatively lower working efficiency. The average spraying time was 0.39 h and the spraying area was 0.93 ha with the tank capacity of 280 L (Table 2). Although there are many other kinds of boom sprayers with a much longer boom, the complexity of the terrain and the farm size limit the usage of larger boom sprayers in China. The average farm size in China is amongst the smallest in the world of 0.67 ha and more than half (57.5%) of farms are small (<2 ha) [1]. Thus, this kind of small boom sprayer is widespread with the working efficacy of 2.38 ha/h (Table 2).

From the test results, the working efficiency of two conventional knapsack sprayers were 1.57 and 0.21 ha/h, respectively (Table 2). Conventional knapsack sprayers need to be carried on the back, which easily leads to exhausting and lower work efficiency. Especially for the EAP sprayer, the working efficacy was only 5.1% of the UAV sprayer. Although these knapsack sprayers also hold very large market share (88%, from China Agriculture Yearbook Editorial Committee 2016) in China, with the development of technology and the growth of farming size, these lower working efficiency sprayers will be tapered and the studies on high efficiency sprayers will be necessary.

4. Conclusions

In this study, four typical sprayers were used for pesticide application in the wheat field. The total deposition on the plants and losses to the ground, the uniformity of the deposition, droplets penetrability, characteristics of the deposition, control efficacy on wheat aphids and working efficiency were compared in this research. The conclusions are shown as follows:

1) The total deposition of the UAV sprayer was not significantly different from the other three sprayers, but the losses to the ground were the lowest.

2) The UAV sprayer had a poor deposition uniformity (CV = 87.2%) and droplets penetrability (0.26 μg/cm^2 on the third top leaf), which need to further improve in the future. By comparison, the SPB sprayer has the best deposition uniformity (CV = 32.1%) and droplets penetrability (0.52 μg/cm^2 on the third top leaf).

3) The area of coverage, number of spray deposits and droplet size varied with spray volume and the nozzle type of the different sprayers. Compared with other sprayers, the deposition characterizations of the UAV sprayer were a lower area of coverage (2.2%), a lfewer spray deposits (28.2 points/cm^2), finer droplet size (VMD = 124.0 μm), higher concentration and lower spray volume.

4) Although the spray deposition characterizations of the UAV sprayer were different from the three other sprayers, the control efficacy of applying 70% Imidacloprid·Regent WDG on wheat aphids was comparable with other sprayers. The control efficacy of UAV sprayer on Day 7 after the application was 70.9%.

5) The working efficiency of the UAV sprayer was 4.11 ha/h, which was 1.7, 2.6, and 20.0 times those of SPB, KMB and EAP sprayer, respectively. This is the greatest advantage of the UAV sprayer.

The experiment demonstrated the feasibility and high efficiency of the UAV sprayer. The deposition uniformity and the droplets penetrability of the UAV also need to be improved. Due to the lower coverage and poor deposition uniformity, the effective measures, such as optimizing the spraying system or adding adjuvant in the tank to improve deposition uniformity and penetrability would be needed in the future.

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