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Effects of Nozzle Types and Spraying Volume on the Control of *Hypera postica* Gyllenhal by Using An Unmanned Aerial Vehicle

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Abstract: In the current study, an unmanned aerial vehicle (UAV) was selected for agricultural spraying, with two nozzles, two insecticides and three spraying volumes as the spraying variables; this paper explores the impact of spraying volume on the droplet deposition in alfalfa fields. Furthermore, by comparing the control effect of spraying insecticides on alfalfa leaf weevils and the safety of pasture by UAV, the aim is to establish efficient pesticide spraying techniques for pest control in alfalfa fields, providing guidance for the green control of alfalfa leaf weevils. The effective droplet proportion of the fan-shaped nozzle (SX11001VS) was higher than that of the hollow conical nozzle (TX-VK4), and increasing the spraying volume cannot significantly improve that situation. When the spraying volume increased from 22.5 L/ha to 45.0 L/ha, the average droplet coverage, density and deposition of the two types of nozzles increased with the spraying volume. However, when the spraying volume was 30.0 L/ha and 45.0 L/ha, the average deposition of the two types of nozzles was similar. The control effect of chlorantraniliprole on alfalfa leaf weevils sprayed by using a UAV was higher than that of spinosad. There was a positive correlation between the spraying volume and the control effect, and the prevention effect of the hollow conical nozzle was better than that of the fan-shaped nozzle. The residues of chlorantraniliprole in alfalfa plants after spraying increased with the spraying volume, whether a fan-shaped nozzle or a hollow conical nozzle was used.

Keywords: nozzle types; spraying volume; *Hypera postica* (Gyllenhal); UAV; pesticide residue

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1. Introduction

Alfalfa (*Medicago sativa* L.) is one of the most important forage crops in the world; known as "Queen of forage", it is an essential perennial legume, providing inexpensive forage with high nutritional value and digestibility, and the crude protein content of alfalfa hay can exceed 20% [1]. As a high-quality forage with rich nutrients, alfalfa is also enjoyed by phytophagous insects. It is reported that there are at least 1000 arthropods in alfalfa fields in the United States, of which 100~150 are pests [2]. There are more than 110 kinds of alfalfa pests in northern China, among which *Aphis craccivora* Koch, *Bruchophagusgibbus Boheman*, *Lygus pratersis*, *Odonotothrips lati* and alfalfa leaf weevil (*Hypera postica* (Gyllenhal)) are the main pests [3].

Alfalfa leaf weevil belongs to the Coleoptera (Curculionidae) family, which likes to eat alfalfa. It is the most important economic pest of alfalfa and also feeds on leguminous plants such as shamrock and *Melilotus officinalis* (L.) Pall [4]. The alfalfa leaf weevil is mainly distributed in Xinjiang, Inner Mongolia, Gansu, and other places in China, bringing devastating disasters to the alfalfa industry [5,6]. The larvae and adults of alfalfa leaf weevil can cause harm to alfalfa. There is a phenomenon of overlapping generations of alfalfa leaf

weevils, which can cause multiple insect states to harm alfalfa at the same time, resulting in stunted growth, delayed maturation, reduced yield and reduced competitiveness between alfalfa and other weeds [2]. In addition, alfalfa leaf weevils can also reduce the digestibility of alfalfa crude protein and dry matter, affecting the quality of alfalfa [7].

Unmanned aerial vehicles (UAVs) are composed of a flight platform, navigation flight control and pesticide spray equipment and possess GPS, GIS and RTK technology, which has made great strides in agricultural applications. Due to the continuous reduction in the agricultural labor force, as well as the promotion of efficient agriculture and the development of smart agriculture, the mechanization and intelligence level of plant protection work has been further improved. In particular, UAVs with advantages such as high efficiency, good safety, wide applicability and simple daily maintenance have been effectively promoted and applied in modern agricultural development [8]. It can achieve the separation of operators and spraying equipment to minimize the harm of pesticides to personnel [9]. In addition, the research and application of agricultural UAVs in fertilizer spraying, seed sowing, fruit picking, pollination, and other aspects are also increasing, greatly expanding their application fields [10]. In 2021, the spraying area of UAVs for agricultural plant protection in China exceeded 200,000 ha, and the market reached CNY 11.634 billion in China [11].

Spraying insecticides is the primary choice for controlling alfalfa pests. However, the traditional manual spraying method is time-consuming and laborious. Although the boom sprayer has high operating efficiency, it has the disadvantage of rolling alfalfa. UAVs have been widely used in crops such as wheat [12], rice [13], corn [14], grapes [15], citrus [16], cotton [17,18] and pepper [19]. However, there are few studies on the application of UAVs to spray pesticides for the control of pests in alfalfa fields. Li et al. studied the differences and similarities between multi-rotor UAV and conventionally piloted large-scale fixed-wing manned airplane spraying methods [20]. Li et al. found that the primary factors affecting the droplet deposition density and uniformity of pesticides sprayed by using UAVs on alfalfa fields are flight speed > flight altitude > rotor speed and flight altitude > flight speed > rotor speed, respectively [21]. Meanwhile, experimental trials had shown the different droplet distribution that can occur as a function of pressure and velocity or even mode of distribution [22]. The alfalfa leaf weevil, as a major pest in Xinjiang's alfalfa fields, has had a serious impact on the yield and quality of alfalfa. In the current study, a UAV was selected as the spraying equipment, with two nozzles, two insecticides and three spraying volumes as the spraying variables, and the impact of the spraying volume on the droplet deposition in alfalfa fields was explored. Furthermore, by comparing the control effect of spraying insecticides on alfalfa leaf weevils and the safety of pasture by using a UAV, the aim is to establish efficient pesticide spraying techniques for pest control in alfalfa fields, providing guidance for the green control of alfalfa leaf weevils.

2. Materials and Methods

2.1. Materials

The 200 g/L chlorantraniliprole suspension concentrate (SC), was purchased from FMC Corporation, Philadelphia, PA, USA. The 10% spinosad SC was acquired from Qilu Pharmaceutical (Inner Mongolia) Co., Ltd. Chlorantraniliprole (98%) and spinosad (98%) standard were acquired from J&K Scientific Co., Ltd., Beijing, China. The 85% Allura Red was sourced from Zhejiang jigaode pigment Technology Co., Ltd., Longgang, China.

The UAV used in this study was a Dajiang T30 UAV provided by the Shenzhen Dajiang Innovation Technology Co., Ltd., Shengzhen, China. The volume of the tank was 40 L, and it had dimensions of 2858 mm × 2685 mm × 790 mm (length × width × height) (arm deployment, paddle deployment), 6 rotors, and 16 SX11001VS nozzles (fan-shaped) or 16 TX-VK04 nozzles (hollow cone). The operation parameters of the T30 UAV were input by using the intelligent handheld terminal, and carrier phase difference technology was used for flight accurate positioning. During the test, the spraying volume of the T30 UAV

was 22.5 L/ha, 30.0 L/ha and 45.0 L/ha, the spraying width was 5.0 m, the flight speed was 5.0 m/s, and the flight altitude was 2.5 m (from the ground).

2.2. Field Plots

The experiment was carried out in the Shihutan town of Xinjiang Production and Construction Crops, Shihezi, Xinjiang, China, in 2022 (N44°36′16″, E86°7′2″). The experimental field was fertilized at a moderate level. *Medicago sativa* (Zhongmu NO. 1) was sown on 13 April 2019 and irrigated by using drip irrigation. The insecticide was sprayed on 3 May 2022, and the average plant height of alfalfa was 38.89 cm. At that time, the average speed of the wind was 1.03 m/s, the relative humidity was 32.70%, and the temperature was 27.1 °C (Kestrel 5500, Nielsen-Kellerman, Boothwyn, PA, USA). There were 13 treatments (3 spraying volumes with 2 nozzle types and 2 insecticides), each treatment area was 2668 m^2 (40 × 66.7 m), the control was 100 m^2 (Table 1), and there was a 10 m gap between each test field as a buffer zone.

Table 1. Design of experiments.

Treatment	Spray Volume (L/ha)	Nozzle Types	Insecticides	Dosage of Insecticide (mL/ha)
1	22.5	Fan-shaped	200 g·L^{-1} chlorantraniliprole SC	150
2	30.0			
3	45.0			
4	22.5		10% spinosad SC	450
5	30.0			
6	45.0			
7	22.5	Hollow cone	200 g·L^{-1} chlorantraniliprole SC	150
8	30.0			
9	45.0			
10	22.5		10% spinosad SC	450
11	30.0			
12	45.0			
13	CK	-	-	-

2.3. Droplet Deposition Measurement

Allura Red was used as the indicator, with a fixed dosage of 450 g/ha. It was added to the liquid of the insecticide and was mixed thoroughly. The universal clamp was fixed 40 cm from the bottom of the two polyethylene hoses and then fixed on both ends of the filter paper with the universal clamp. One of the universal clamps fixes an additional water-sensitive paper (WSP, 26 × 30 mm, Chongqing Liuliu Shanxia Plant Protection Technology Co., Ltd., Chongqing, China). The two collection methods were one sampling group. Eleven sampling groups, U1-U11, were set up under the UAV flight route, with an interval of 0.8 m for each sampling group and a total length of 8 m (Figure 1) [19]. Three experimental plots were used for each treatment, and the sampling was repeated three times. After spraying, when the droplets on the water-sensitive paper and filter paper were dry, the filter paper and WSP at different positions of each cloth sample point were collected carefully in a Ziplock bag and taken back to the laboratory for unified analysis.

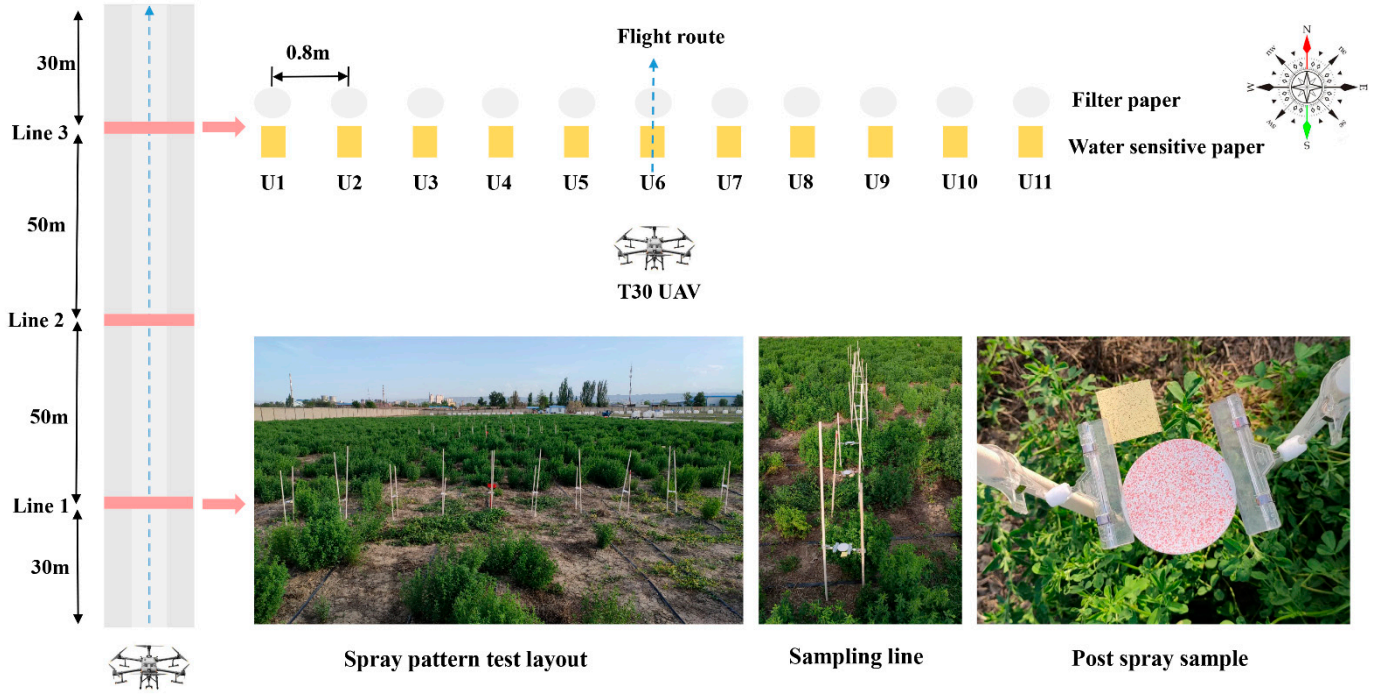


Figure 1. Test layout for spraying pattern analysis from a single UAV flight pass.

In the laboratory, the WSP was scanned at a resolution of 600 dpi with a scanner. ImageJ software (ImageJ 1.3 8, National Institutes of Health, Bethesda, MD, USA) was used to extract droplet deposits in the digital image for analysis of the droplet size, the number of spray deposits and the area of coverage. Each filter paper was washed with 10 mL of distilled water and kept in separate bags. Each bag was shaken for 5 min. Afterwards, the washing solution was removed from the bag, and the colorant concentration was measured at 514 nm using Tecan Infinite 200 PRO ELIASA. The solution obtained from washing the unsprayed strips of filter paper was used as the baseline solution. The droplet distribution was determined in accordance with the standard curve of Allura Red. The Allura Red (100 mg) was dissolved in 10 mL distilled water and transferred to a 100 mL volumetric flask. The volume was kept constant with distilled water to obtain 1000 mg/L of Allura Red mother liquor. Dilutions of 0.1, 0.2, 0.5, 1.0 and 2.0 mg/L of Allura Red standard solution were prepared with distilled water. The absorbance value was measured at 514 nm by using Tecan Infinite 200 PRO ELIASA (Tecan company, Switzerland), and the Allura Red concentration–absorbance standard curve was obtained. The measured linear equation was y = 0.0495x + 0.0431, and the correlation coefficient was $R^2 = 0.997$. Equation (1) was used to calculate the deposition of droplets on the filter papers [18].

$$\beta_{dep} = \frac{\left(\rho_{smpl} - \rho_{blk}\right) \times F_{cal} \times V_{dil}}{A_{col}} \quad (1)$$

where β_{dep} is the amount of droplet deposition (μL/cm), ρ_{smpl} is the concentration of the sample (mg/L), ρ_{blk} is the concentration of blank control (mg/L), F_{cal} is the correction factor (slope of standard curve), V_{dil} is the volume of the diluent collected for the eluent filter paper (mL), and A_{col} is the area of the filter paper (cm^2).

2.4. Control Effect

Three sampling points were randomly selected for each plot, and the alfalfa at each sampling point was cut (0.5 × 0.5 m) and taken back to the laboratory to count the *H. postica* (Gyllenhal) of all ages. The insect population base was investigated before spraying,

and the number of residual insects was investigated on the 3rd, 7th and 14th days after spraying. The control effect was calculated according to Formulas (2) and (3).

$$\text{Reduction rate of insect population } (\%) = \frac{\text{insect population before spraying} - \text{insect population after spraying}}{\text{insect population before spraying}} \times 100 \quad (2)$$

$$\text{Control effect } (\%) = \frac{\text{reduction rate of insect population in the treatment} - \text{reduction rate of insect population in the CK}}{100 - \text{reduction rate of insect population in CK}} \times 100 \quad (3)$$

2.5. Pesticide Residue

The alfalfa samples were collected before spraying and 3 d, 7 d and 14 d after spraying. A method was developed to determine pesticide residues in alfalfa samples using the QuEChERS-pretreatment method and HPLC. Measures of 2.0 g of alfalfa samples were accurately weighed, frozen in liquid nitrogen and ground into powder. The powder was transferred to a 50 mL centrifuge tube. Subsequently, 10 mL of distilled water was added to the centrifuge tube, and the mixture was soaked for 2 min. Then, 10 mL of acetonitrile was added and vortexed for 60 s. After that, the QuEChERS extraction salt package (50 mL, containing 6 g anhydrous magnesium sulfate and 1.5 g anhydrous sodium acetate, Agela Technologies, Tianjin, China) was added to the sample, which was violently shaken for 1 min and centrifuged for 10 min at 8000 rpm. A measure of 5 mL of supernatant was transferred to a 15 mL QuEChERS purification tube (Agela Technologies, Tianjin, China), vortexed for 60 s and centrifuged for 5 min at 8000 rpm. Then, 0.5 mL of supernatant and 0.5 mL of distilled water were added to a 1.5 mL centrifuge tube, vortexed and mixed evenly, and filtered by using filter membrane (0.22 μM, Agilent) for liquid HPLC. Blank samples were used for validation studies and matrix-matched standard calibration. An untreated group was set up as a control group, and all samples were stored in a −20 °C freezer.

Standard Curve and Added Recovery. The chlorantraniliprole (98%) standard (50 mg) was dissolved in 50 mL acetonitrile (HPLC grade) and diluted to 100 mL, then diluted to 0.1, 0.5, 1.0, 2.0, 4.0 and 10.0 mg/L by using acetonitrile (HPLC grade) to obtain a series of standard solutions. The standard solution was analyzed with a Shimadzu LC-2050 CN equipped with a reverse-phase column (ShimNex CS C18 4.6 × 250 mm 5μm, Shimadzu Japan) at 35 °C. The detection wavelength was 265 nm. The mobile phase was acetonitrile/0.1% formic acid solution (80/20, v/v) at a flow rate of 0.4 mL/min, and the injection volume was 5 μL. The standard curve was obtained by drawing the area as an ordinate and drawing the concentration of the chlorantraniliprole standard solution as abscissa. The standard curve equation of chlorantraniliprole was y = 20,484.4x − 357.102, R^2 = 0.9997. The peak area and concentration of chlorantraniliprole exhibited a good linear relationship (0.1–10 mg/L) (Supplementary Materials).

2.6. Data Statistics and Processing

Data were compared across different application rates using analysis of variance (ANOVA). The confidence interval was set to 95% and $p < 0.05$, with 99% and $p < 0.01$ chosen to indicate a significant difference between the two groups. SPSS 18.0 was used for data processing and analysis, and the figures were made using SigmaPlot 12.5 and Origin 2021.

3. Results

3.1. The Effect of Spraying Volume and Nozzle Types of UAV on the Droplet Size

After UAV spraying, the droplet size treated with different spraying volumes showed an approximately normal positive distribution, with most of the droplet sizes concentrated between 50 and 150 μm (Figure 2). When using a fan-shaped nozzle (SX11001VS), the proportion of effective droplets with a particle size of 100~300 μm was 76.8%. When replaced with a hollow conical nozzle (TX-KV4), the proportion of droplets with a particle size less than 100 μm was 60.6%, and the proportion of effective droplets with a particle size

of 100~300 μm was only 28.3%. At a spraying volume of 45.0 L/ha, 90.9% of the droplets sprayed by the hollow conical nozzle (TX-KV4) were concentrated in 50~150 μm, while 87.9% of the droplets sprayed by the fan-shaped nozzle (SX11001VS) were concentrated in 50–150 μm. It is worth noting that 84.8% of the droplet size was concentrated above 100 μm after spraying with a fan-shaped nozzle (SX11001VS), while 60.6% was concentrated above 100 μm after spraying with a hollow conical nozzle (TX-KV4). Increasing the spraying volume did not significantly improve this situation.

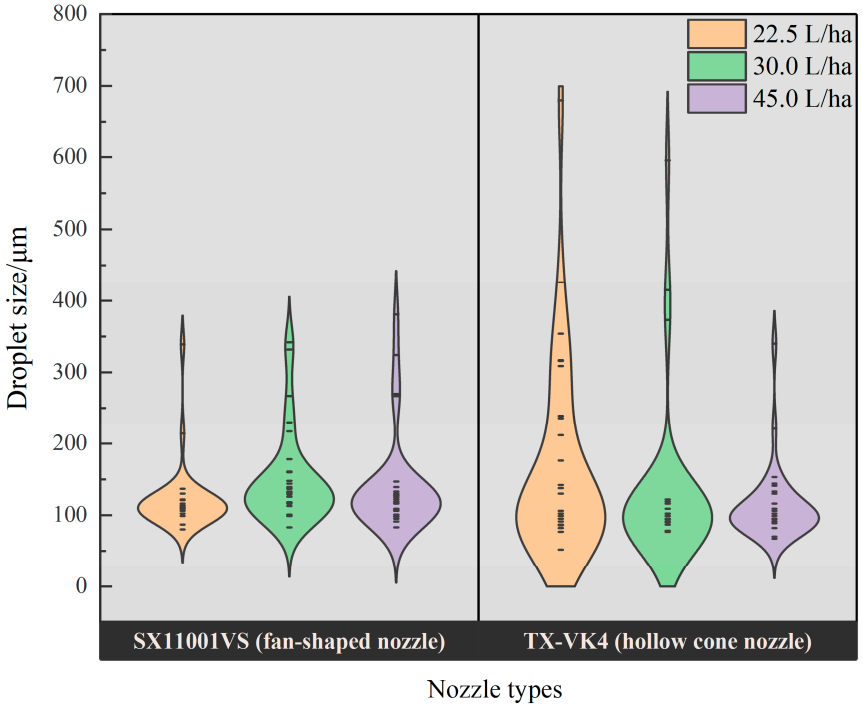


Figure 2. The effect of spraying volume and nozzle types of UAV on droplet size.

3.2. The Effect of Spraying Volume and Nozzle Types of UAV on the Droplet Coverage and Droplet Density

The effects of the spraying volume and nozzle types on the droplet coverage rate and droplet density sprayed on plants by using a UAV are shown in Figure 3. When the spraying volume of the UAV was 22.5 L/ha and 30.0 L/ha, the droplet coverage and droplet density of the two nozzles after spraying were similar, and the hollow conical nozzle (TX-KV4) was higher than the fan-shaped nozzle (SX11001VS). The droplet coverage and droplet density were increased with the increase in spraying volume, which was more evident on the fan-shaped nozzle (SX11001VS). When the spray volume was 45.0 L/ha, the droplet coverage and droplet density of the fan-shaped nozzle (SX11001VS) were 8.9% and 390.1/cm^2, respectively, and for the hollow conical nozzle (TX-KV4), they were 9.1% and 465.4/cm^2, respectively. It should be noted that due to the influence of crosswind (1.03 m/s), the peak values of droplet coverage and droplet density after spraying via UVA were not directly below the route (U6), which was at sampling points U7 and U8 at a distance of 0.8~1.6 m from U6. When the spray volume was 22.5 and 30.0 L/ha, the average droplet coverage and average droplet density of the fan-shaped nozzle (SX11001VS) were similar: 2.5% and 2.3%, and 132.4 droplets/cm^2 and 104.1 droplets/cm^2, respectively. Compared to the fan-shaped nozzle (SX11001VS), the hollow conical nozzle (TX-KV4) had higher average droplet coverage and density, which was 4.1% and 5.0%, and 222.4 droplets/cm^2 and 267.9 droplets/cm^2, respectively. When the spraying volume increased to 45.0 L/ha, the average coverage and average density of droplets in both nozzles were increased. The average coverage and average density of droplets in the hollow conical nozzle (TX-KV4)

were 6.1% and 359.7 droplets/cm^2, respectively, which were better than the 4.4% and 216.0 droplets/cm^2 of the fan-shaped nozzle (SX11001VS).

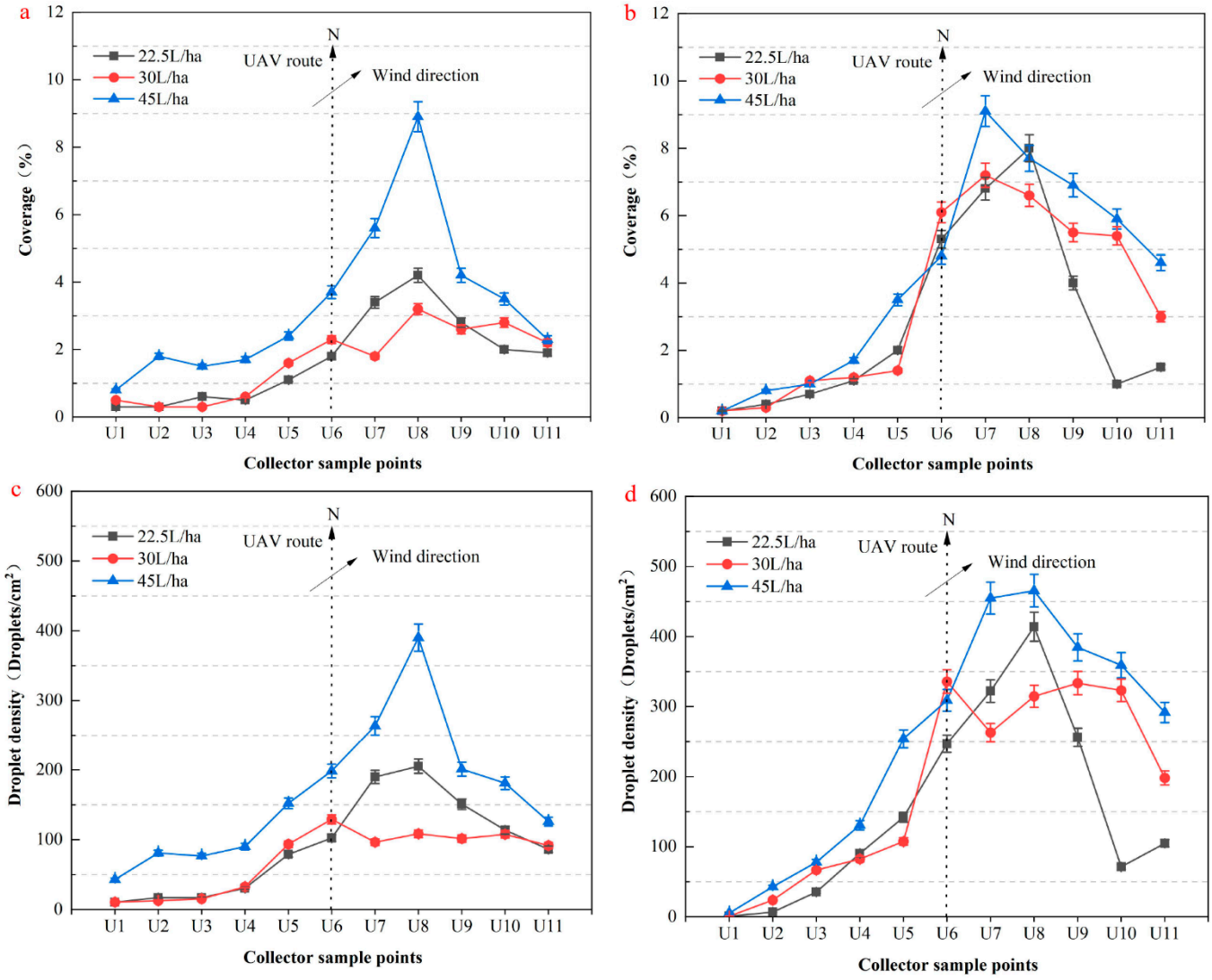


Figure 3. The effect of spraying volume on the droplet coverage of fan-shaped nozzle (SX11001VS, (**a**)), hollow conical nozzle (TX-VK4, (**b**)), droplet density of fan-shaped nozzle (SX11001VS, (**c**)) and hollow conical nozzle (TX-VK4, (**d**)).

3.3. The Effect of Spraying Volume and Nozzle Types of UAV on the Droplet Deposition

The droplet deposition, droplet coverage and droplet density showed similar trends, with peak values at sampling points U7 and U8 (Figure 4). When the spraying volume of the UAV was 45.0 L/ha, the droplet deposition in the fan-shaped nozzle (SX11001VS) and hollow conical nozzle (TX-VK4) was 0.86 μL/cm^2 and 1.13 μL/cm^2, respectively, which shows that the hollow conical nozzle was superior to the fan-shaped nozzle. When the spraying volume was 22.5 L/ha and 30.0 L/ha, the droplet deposition of the two spray nozzles was similar. Due to the influence of crosswind, the average deposition of sampling points U5~U11 increased with the increase in the spraying volume, which was more obvious when using hollow conical nozzles. When the spraying volume increased from 22.5 L/ha to 45.0 L/ha, the average deposition of the hollow conical nozzle (TX-VK4) was increased from 0.52 μL/cm^2 to 0.61 μL/cm^2, and for fan-shaped nozzles, increased from 0.46 μL/cm^2 to 0.54 μL/cm^2. It is worth noting that when the spray volume was 30.0 L/ha and 45.0 L/ha, the average deposition of the two types of nozzles did not change

significantly, with 0.55 μL/cm^2 and 0.54 μL/cm^2 (fan-shaped nozzle) and 0.59 μL/cm^2 and 0.61 μL/cm^2 (hollow conical nozzle), respectively.

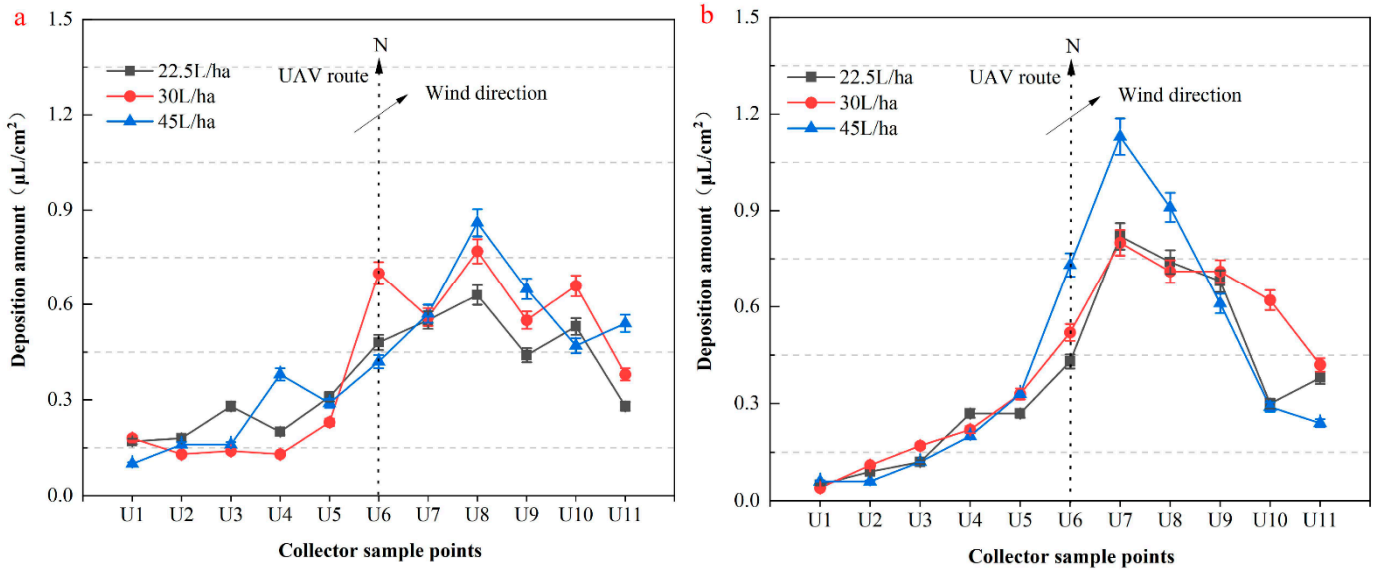


Figure 4. The effect of spraying volume on the droplet deposition of fan-shaped nozzle (SX11001VS, (**a**) and hollow conical nozzle (TX-VK4, (**b**).

3.4. The Effect of Spraying Volume and Nozzle Types of UAV on the Control Effect of Alfalfa Leaf Weevil

As shown in Figure 5, 3 days after spraying, the control effects of 200 g/L chlorantraniliprole SC on alfalfa leaf weevil sprayed by using a UAV were 49.84%~57.59% (fan-shaped nozzle) and 55.16%~57.33% (hollow conical nozzle). The control effects of 10% spinosad SC on alfalfa leaf weevil sprayed by using a UAV were 53.51%~58.93% (fan-shaped nozzle) and 54.47%~56.76% (hollow conical nozzle). There was no significant difference between the treatments. Seven days after spraying, the control effect of each treatment on alfalfa leaf weevil exceeded 60%. Overall, the control effect of chlorantraniliprole treatments was slightly higher than that of spinosad. When using a hollow conical nozzle (TX-VK4) with a spraying volume of 45.0 L/ha, the 200 g/L chlorantraniliprole SC had the highest control effect on alfalfa leaf weevil (77.68%), significantly better than the treatment with a low spraying volume. For a 10% spinosad SC, at a spraying volume of 22.5 L/ha, the use of a hollow conical nozzle (TX-VK4) had the lowest control effect on alfalfa leaf weevil (62.34%). With the increase in spraying volume, the control effect increased, but there was no significant difference between them. After 10 days of spraying, the control effect of each treatment on alfalfa leaf weevil exceeded 70%, showing good persistence. The UAV used a hollow conical nozzle to spray 200 g/L chlorantraniliprole SC, with the highest control effect (86.27%) at a spraying volume of 45.0 L/ha. It is worth noting that the prevention effect of low spraying volume was significantly lower than that of high spraying volume. The results of droplet deposition showed that the hollow conical nozzle (TX-VK4) spraying had smaller droplets, better droplet coverage, droplet density and droplet deposition, also showing a slightly better control effect on alfalfa leaf weevil.

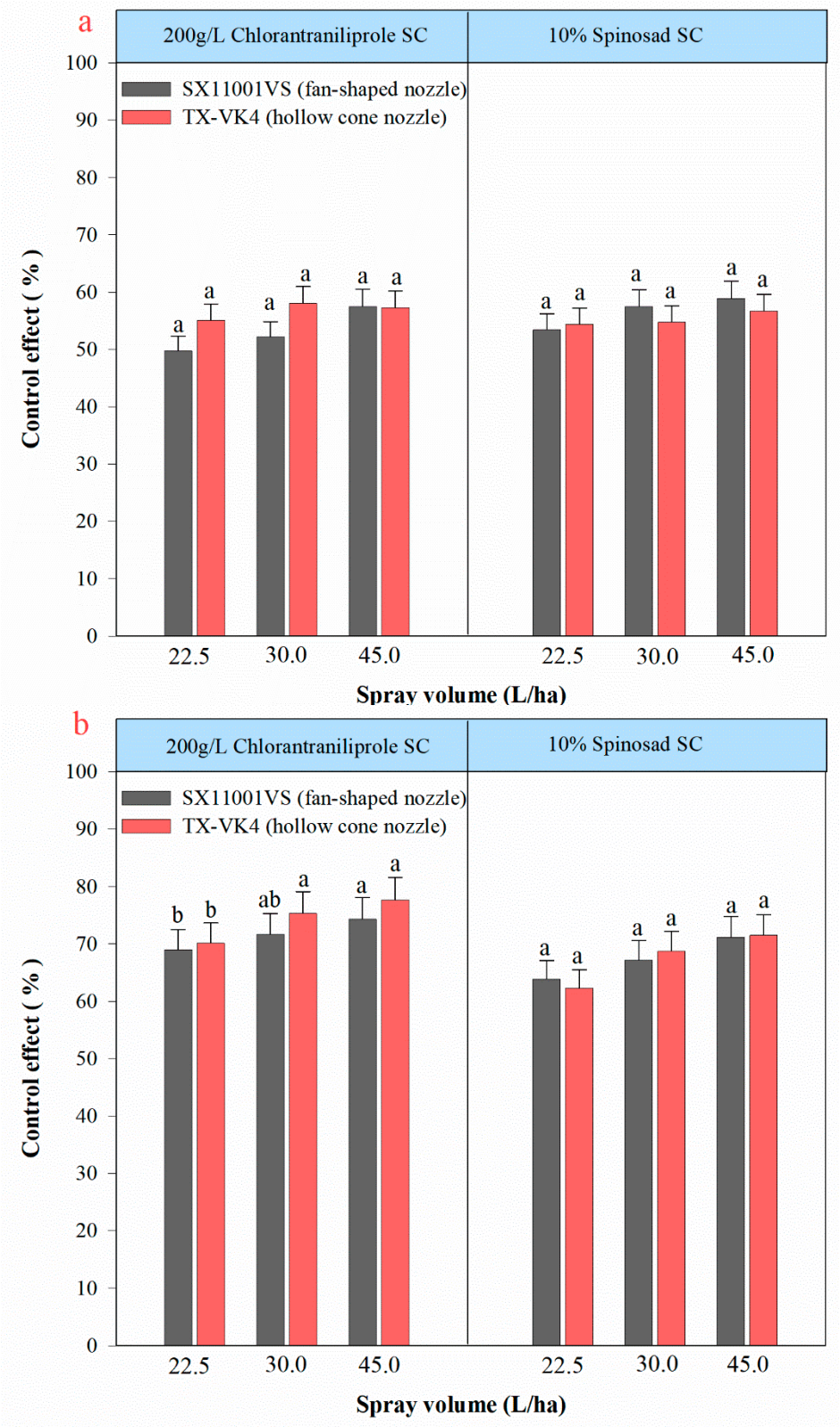


Figure 5. *Cont.*

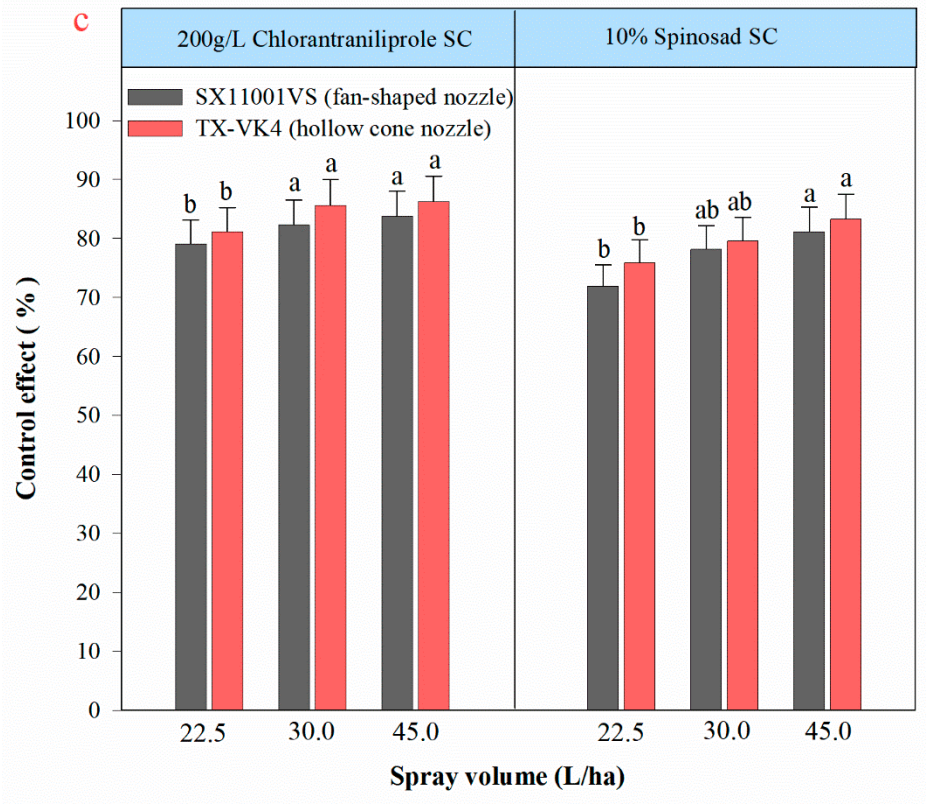


Figure 5. The effect of spraying volume and nozzle types of UAV on the control effect of alfalfa leaf weevil ((**a**) for 3 days after spraying, (**b**) for 7 days after spraying and (**c**) for 10 days after spraying). Different lowercase letters indicate significant differences between treatments at the 5% level.

3.5. The Effect of Spraying Volume and Nozzle Types of UAV on the Residues of Chlorantraniliprole in Alfalfa Plants

Figure 6 presents a comparison of the overall chlorantraniliprole plant residues recovered from alfalfa plant samples sprayed by using a UAV applying spray volumes of 22.5 L/ha, 30.0 L/ha and 45.0 L/ha, respectively (3 days after spraying). For the fan-shaped nozzle (SX11001VS), after the UAV sprayed at three spraying volumes, the residues of chlorantraniliprole in alfalfa plants were 0.2298 mg/kg, 0.2546 mg/kg and 0.3773 mg/kg, respectively. For the hollow conical nozzle (TX-VK4), after the UAV sprayed at three spraying volumes, the residues of chlorantraniliprole in alfalfa plants were 0.2779 mg/kg, 0.3509 mg/kg and 0.4303 mg/kg, respectively. When the hollow conical nozzle (TX-VK4) was sprayed at 45.0 L/ha, the residue of chlorantraniliprole in alfalfa plants was 0.4303 mg/kg, significantly higher than that of the fan-shaped nozzle (SX11001VS) at the same spraying volumes (0.3773 mg/kg). Overall, regardless of whether it was a fan-shaped nozzle (SX11001VS) or a hollow conical nozzle (TX-VK4), the residue of chlorantraniliprole in alfalfa plants increased with the spraying volume, and the hollow conical nozzle was higher than the fan-shaped nozzle. This is consistent with the results of the control effect of alfalfa leaf weevil.

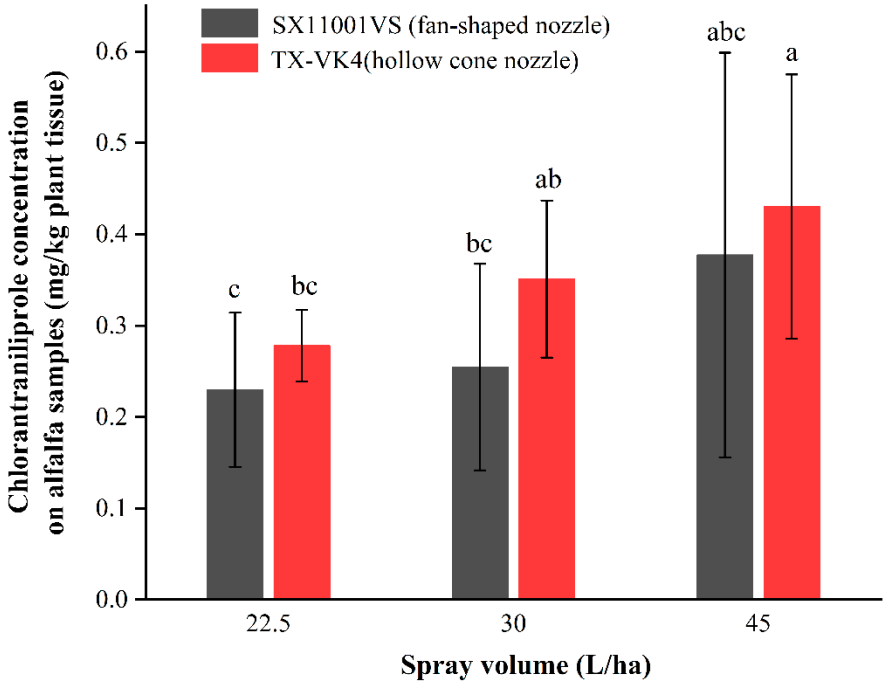


Figure 6. The effect of spraying volume and nozzle types of UAV on the residues of chlorantraniliprole in alfalfa plants (3 days after spraying). Different lowercase letters indicate significant differences between treatments at the 5% level.

4. Discussion

The nozzle is one of the key components of agricultural aviation spraying and the most important atomizing component in plant protection machinery. The droplet size directly affects the adhesion, sliding and drifting effects. A good nozzle could improve the uniformity of droplet deposition, increase the deposition amount of pesticide, reduce drift, and improve the prevention and control effect [23]. The type of nozzle directly affects the size, movement track and atomization effect of the droplets. The size and movement track of the droplets directly affect the three main indicators that determine the quality of spray—the coverage rate, drift rate and uniformity—and then affect the pest control effect of crops [24]. The droplet size of the hollow cone nozzle is proportional to the spraying pressure, but this phenomenon is not significant when the pressure increases to a certain value [22]. The fan-shaped nozzle can atomize fan-shaped spray with a larger impact force, and the lateral deposition of droplets presents the characteristics of normal distribution [25]. The installation of an anti-drift nozzle on the UAV could significantly reduce the droplet drift and the loss of spraying volume during the spray process. Ma et al. found that the UAV with a fan-shaped nozzle (IDK120-01) to control *Chilo suppressalis* could effectively decrease droplet drift and increase the deposition per unit area and thus promote the control efficacy of 10% cyantraniliprole OD against *C. suppressalis* [26]. Qin et al. posited that when the nozzle types were the same, the effect of UAV spray on cucumber powdery mildew showed an increasing trend with the increase in the pesticide solution concentration. When the concentration of the pesticide solution was constant, the prevention and control effect of a nozzle with a small droplet size was better than that of a nozzle with a large droplet size. This may be due to the large leaf area of cucumbers and the big droplets being obstructed by the leaves, resulting in a poor penetration effect and affecting the prevention effect [27].

Feng et al. found that the UAV equipped with a venturi nozzle, the amount of sediment in the upper and lower parts of the rice canopy and the overall amount of sediment exceeded that of the conventional nozzle, the control effect on rice false smut was better than that of a backpack spray, and the control effect on sheath blight was equivalent to that of a backpack spray [28]. In addition, the spraying volume also has a significant

impact on the physicochemical properties of the pesticide solution, which in turn affects the wetting and spreading properties of the droplets on the surface of plant leaves [29]. Research such as that carried out by Xin et al. found a positive correlation between the spraying volume by using a UAV and the cotton defoliation rate [30]. Xie et al. found that during the herbicide spraying on winter wheat, the droplet density of the anti-drift nozzle (DG11003, 27.9–73.0/cm^2) was significantly higher than that of the fan-shaped nozzle (SX11001VS, 13.7–47.2/cm^2), while there was no significant difference in droplet coverage between the two. The coverage and density of droplets increase with the spraying volume and had no significant effect on the uniformity of droplet deposition [31].

In this study, when the fan-shaped nozzle (SX11001VS) was used, the proportion of effective droplets with a particle size of 100~300 μm was 76.8%, which was higher than that with a hollow conical nozzle (TX-KV4, 28.3%). At a spraying volume of 45.0 L/ha, 90.9% of the droplets sprayed with the hollow conical nozzle (TX-KV4) were concentrated in 50~150 μm, while 87.9% of the droplets sprayed by the fan-shaped nozzle (SX11001VS) were concentrated at 50–150 μm. When the spray volume was 45.0 L/ha, the droplet coverage and droplet density of the fan-shaped nozzle (SX11001VS) were 8.9% and 390.1/cm^2, respectively, and for the hollow conical nozzle (TX-KV4) was 9.1% and 465.4/cm^2, respectively. When the spraying volume of the UAV was 45.0 L/ha, the droplet deposition in the fan-shaped nozzle (SX11001VS) and hollow conical nozzle (TX-VK4) was 0.86 μL/cm^2 and 1.13 μL/cm^2, respectively, and for the hollow conical nozzle, it was superior to the fan-shaped nozzle. Results from the three spraying volumes were comparable for overall residue levels on alfalfa plants and insect control. These results provide significant data that support the consideration of UAV use in small-canopy crops to control leaf-feeding lepidopteran pests in alfalfa hay fields.

5. Conclusions

This study characterized the effect of aerial pesticide application methods, specifically, the evolving autonomous small payload multi-rotor UAV. We compared the droplet deposition characteristics, control effects of alfalfa leaf weevil and residue of chlorantraniliprole in alfalfa plants under two types of nozzles, two insecticides and three spraying volumes. Effective control of alfalfa leaf weevils was achieved in commercially grown alfalfa hay in Xinjiang, China, by following the product label recommendations. The specific findings include:

(1) The droplet size of the fan-shaped nozzle (SX11001VS) was largely more than 100 μm, and that of the hollow conical nozzle (TX-VK4) was mostly less than 100 μm. Therefore, the effective droplet proportion of the fan-shaped nozzle (SX11001VS) was higher than that of the hollow conical nozzle (TX-VK4), and increasing the spraying volume cannot significantly improve that situation. When the spraying volume increased from 22.5 L/ha to 45.0 L/ha, the average droplet coverage, density and deposition of the two types of nozzles increased with the spraying volume. However, when the spraying volume was 30.0 L/ha and 45.0 L/ha, the average deposition of the two types of nozzles was similar.

(2) The control effect of chlorantraniliprole on alfalfa leaf weevils sprayed by using a UAV was higher than that of spinosad. There was a positive correlation between the spraying volume and the control effect, and the prevention effect of the hollow conical nozzle was better than that of the fan-shaped nozzle.

(3) The residues of chlorantraniliprole in alfalfa plants after spraying increased with the spraying volume, whether it was through a fan-shaped nozzle or a hollow conical nozzle.

Supplementary Materials: The chromatogram of chlorantraniliprole in alfalfa can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13092287/s1.

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