Effects of spray adjuvants and operation modes on droplet deposition and elm aphid control using an unmanned aerial vehicle

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Abstract: A conventional spraying mode and a fully autonomous fruit tree operation mode using a model DJ T30 unmanned aerial vehicle (UAV) were used to control aphids control on elm trees and to clarify the distribution of droplets in elm trees sprayed by a UAV. The effects of six aviation spray adjuvants on elm canopy droplet deposition and aphid control were evaluated. ImageJ software was used to analyze and measure the droplet density and deposition of water sensitive paper in two modes; this was done to calculate the droplet uniformity, depositional penetration, and droplet penetration, and to verify the aphid control effect. The results showed that the droplet density increased by 79.7%-100.7% in the upper canopy and 0-394.1% in the lower canopy without adjuvants in the fully autonomous fruit tree operation mode. The upper canopy deposits increased by 65.7%-179.3%, and the lower canopy increased by 0-152.8%. When adjuvants were added, the droplet density in the upper canopy increased by 49.7-56.1% using Jiexiaofeng (JXF), and the lower canopy increased by 138.2%-177.8% using JXF, 45.8%-141.3% using Beidatong (BDT), 45.5%-92.9% using Gongbei (GB), 0-93.5% using Maisi (MS), and 0-95.2% using Manniu (MN). The deposits of the upper canopy increased by 888.1-1 154.2% using JXF, 0-1 298.3% using MN, 0-343.9% using BDT, 0-422.5% using GB, 0-580.3% using MS. The lower canopy increased by 746.4%-1 426.0% using JXF, 226.2%-231.0% using BDT, 435.8%-644.0% using GB, 255.0%-322.4% using MS, and 249.3%-360.0% using MN. When JXF was added, the droplet uniformity, droplet penetration and depositional penetration were better than when using other adjuvants. The effects of JXF, BDT and GB in controlling aphids was significantly better than other adjuvants (p<0.05). The following control effects were observed; 94.1% with JXF, 93.1% with BDT, and 93.3% with GB after 3 d of application, and 97.9% with JXF, 95.6% with BDT, and 97.1% with GB after 7 d of application. At the same time, the application of the fully autonomous fruit tree operation mode and JXF can effectively improve the density and deposits, which will produce a superposition optimization effect. Our study focuses on the prevention and control of elm aphid infestations based on the operation mode of a UAV and aviation spray adjuvants, which can provide a baseline for the control of diseases and insect pests using UAVs in agriculture and forestry.

Keywords: adjuvants, UAV, operation mode, droplet deposition, aphid

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1 Introduction

Elm (*Ulmus pumila* L.) is an important landscaping tree in Northwest China. This species is the most suitable tree for urban greening, farmland protection, vegetating barren mountains and serves to provide windbreaks for forests in this region. The occurrence of elm aphids has become a serious issue threatening elm trees. Honeydew secreted by aphids allows mold to form on elm leaves[1]. Currently, garden spray trucks, high-pressure pipeline spray guns, fixed wing aircraft, helicopters and other pesticide application equipment are being used to control elm diseases and insect pests in China[2]. However, traditional ground-based spraying equipment is not useful as a result of some terrain, tree shape and planting density. Pesticide application requires the use of a large quantity of resources and is inefficient when using traditional application methods[3,4]. Using fixed wing aircraft requires the use of a special airport and runways for pesticide spraying, and so are not suitable for garden pest control in a small area. Traditional spraying techniques are limited in their ability to deposit droplets and in pesticide penetration[5]. Spraying by unmanned aerial vehicles (UAVs) can improve the deposition of pesticides on a target crop. In addition, the use of UAVs can prevent any mechanical damage to crops as occurs during pesticide application with ground-based machines and tools while greatly improving the operational efficiency[6]. Several studies on the use of UAVs for wheat[7], rice[8], corn[9], tea[10], citrus[11], cotton[12], and other crops have been reported for the distribution and control effect of droplet deposition in

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crop canopies.

The use of UAVs can increase the deposition of pesticide droplets on the canopy of plants which effectively improves pesticide use and insect control. Fan et al.[13] reported that the deposition density of a P20 UAV(Guangzhou Jifei Technology Co., Ltd., Guangzhou, China) was highest at the top of an apple tree in both the circling and two-way flight modes; the droplet size and the distribution of deposited spray decreased with a decrease of measurement position. The control of *Aphis citricolavander* Goot using both circling and two-way flight modes on the upper apple part reached more than 90%, but the control effect on the middle and lower parts was in the mid-range. Guo et al.[14] studied the optimal operating parameters of single rotor oil powered UAVs in tall palm trees by evaluating the droplet deposition effect. Gao et al.[15] studied an eosin water-based staining method and found that the droplet density, penetration and uniformity of a spray from a UAV were good when the UAV was 2.5-3.5 m from the top of a *Populus deltoides* crown and the flight speed was 1.5-3.0 m/s. Chen et al.[16] and Liao et al.[17] studied the droplet deposition and distribution on the canopy of fruit trees with different UAV parameters and different pesticides and dosages. They reported that the use of aviation spray adjuvants can effectively improve the droplet deposition and pest control effect of UAV pesticide treatment. Han et al.[18] worked on precise aerial spraying on citrus orchards in mountainous and hilly areas under the operation mode of an UAV. They found that the application effect could be effectively improved by adding 1.0% Beidatong, 1.0% Y-20079 or 0.5% 806 adjuvants applied on citrus canopies in hilly areas. However, research on the droplet deposition and control effect of pesticides sprayed by UAVs has mainly focused on fruit trees and field crops. Limited research is available on pesticide application technology related to the occurrence of diseases and pests in green, landscape and even ecological forest. In this study, six aviation spray adjuvants were selected to control the elm aphids in the conventional spraying mode (conventional mode) and with a fully autonomous fruit tree operation mode(fruit tree mode) of the UAV. The effects of aviation spray adjuvants and operation modes on the droplet deposition and the control efficacy of elm aphids were studied.

2 Materials and methods

2.1 Experimental materials

The experiment was conducted in cooperation with DJI model T30 and model Phantom 4 RTK UAV (P4R) (DJI, Shenzhen, Guangdong, China). After Phantom 4 RTK UAV (P4R) mapping, DJI Terra software was used to design the UAV route, and finally a T30 UAV was used to spray pesticides (Figure 1), T30 UAV (DJI, Shenzhen, Guangdong, China) had dimensions of 2858 mm× 2685 mm×790 mm (length×width×height) (arm deployment, paddle deployment), 6 rotors. The parameters are shown in Table 1. Two operation modes were used: conventional and fully autonomous fruit tree operation spraying modes. The conventional and fruit tree mode nozzles were a fan-shaped nozzle model SX11001VS and a hollow cone nozzle model TX-VK4, respectively.

a. Conventional

b. Fully autonomous

Figure 1 T30 model unmanned aerial vehicles in conventional and fully autonomous fruit tree spraying operation modes

Table 1 Main parameters of a T30 unmanned aerial vehicle (DJI)

Spray operation modes	Number of rotor	Nozzle type	Number of nozzles	Nozzle maximumflow/L·min^{-1}	Maximum amplitude/m	Maximum pesticideload/L
Conventional spraying mode	Six rotor	SX11001VS	16	7.2	9	30
Fully autonomous fruit tree operation mode		TX-VK4	16	3.6	9	30

The handheld model NK5500 weather station was used (Nielsen-Kellerman Co., Boothwyn, PA, USA). A Filescan 2500 scanner was used (Shanghai Zhongjing Technology Co., Ltd., Shanghai, China). Water sensitive paper (WSP, 3×5 mm^2) was obtained from Chongqing Liuliushanxia Plant Protection Technology Co., Ltd., Chongqing, China.

2.2 Pesticide and adjuvants

The tested pesticide was 10% fluridoxamide water dispersible granules (Dongguan Ruidefeng Biotechnology Co., Ltd., Guangdong, China). Table 2 lists the aviation spray adjuvants used in the study.

Table 2 Details of aviation spray adjuvants

Adjuvants	Abbreviation	Types	Manufacturer
Beidatong	BDT	Vegetable oil	Hebei Mingshun Agricultural Technology Co., Ltd., Shijiazhuang, China
Gongbei	GB	Mineral oil	Momentive Performance Materials Co., Ltd., Shanghai, China
Jiexiaofeng	JXF	Polyether modified silane	Momentive Performance Materials Co., Ltd., Shanghai, China
Maisi	MS	Vegetable oil	Grand AgroChem Co., Ltd., Beijing, China
Manniu	MN	Mixed orange essential oil	Qingdao Risheng Crop Nutrition Co., Ltd., Qingdao, Shandong, China
Nongjianfei	NJF	High molecular polymer	Guilin Jiqi Group Co., Ltd., Guilin, China

2.3 Field plots

This study was conducted at Xinjiang Production and Construction Crops in Beiquan town, Shihezi, Xinjiang, China (44°17′9″N, 86°0′57″E) during May and June 2021. The main tree species at the test site was 5 years old *Ulmus pumila*, with a diameter at breast height of 15-17 cm. The elms were about 6 m tall with a plant spacing of 3.1 m, row spacing of 3.6 m, and a 3.5 m thick canopy layer. The test site had an elevation of 394-413 m, with generally flat land that was free of obstacles.

2.4 Experimental treatment

One of the three test areas is shown in Figure 2a; the other two test areas were arranged in the same way. This figure shows the distribution of sampling points along three routes; two operation modes using the same adjuvants were conducted along each route. Two elms with similar growth in the area were selected as sampling plants, one in the west for the conventional mode, and one in the east for the fruit tree mode. Among the three UAV routes, each route was connected by the tree center and the UAV flew from east to west. Several pieces of WSP were placed on the front of the blade, including six and four pieces of the upper and lower canopy, respectively (Figure 2d).

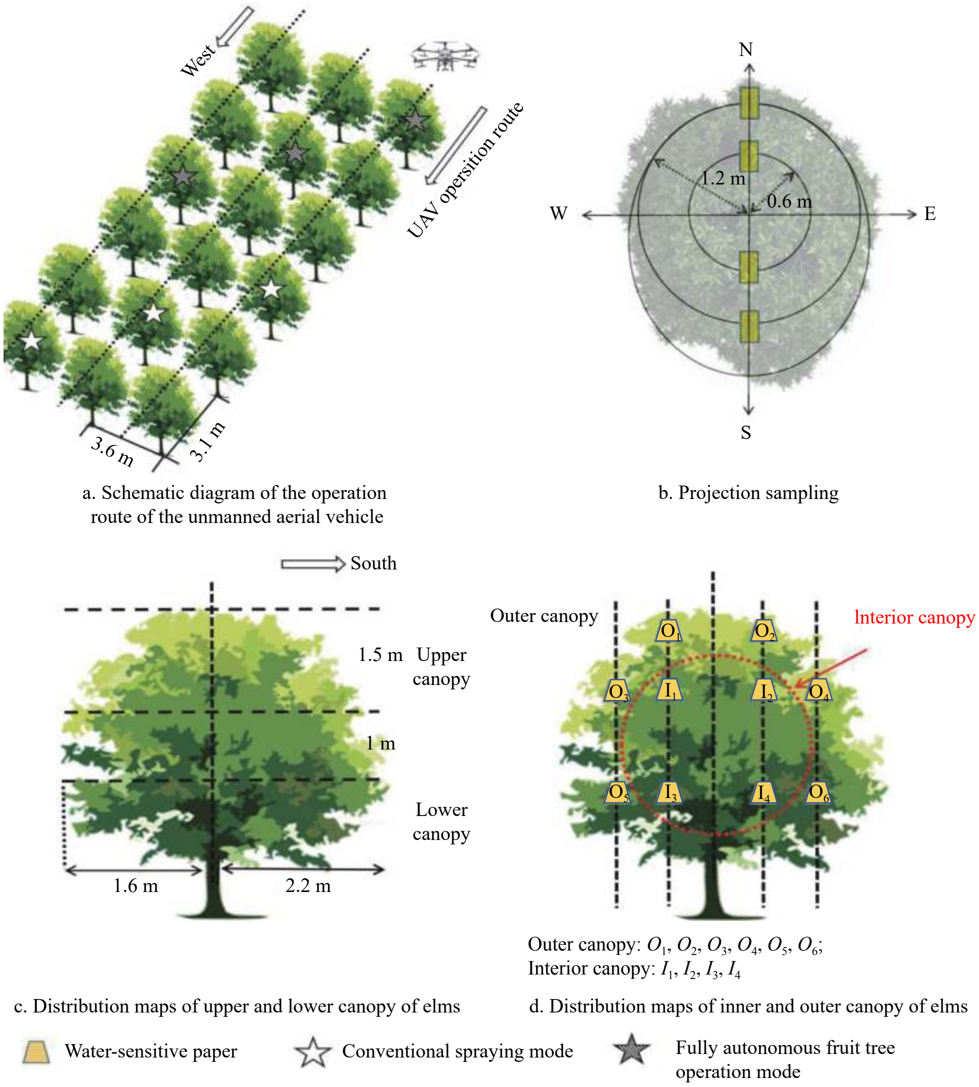


Figure 2 Schematic diagram of test methods

2.4.1 Elm canopy sampling method

Each elm plant was divided into two parts: upper and lower canopy with an interval of 1.5 m (Figure 2c). The sampling points of the upper and lower canopy were named as O_1, O_2, O_3, O_4, I_1, and I_2 as well as I_3, I_4, O_5, and O_6, respectively, where O and I represent positions in the outer and inner canopy, respectively (Figure 2d). Projection sampling showed that the canopy was larger in the south than in the north. The southernmost and northernmost ends of the canopy were 2.2 m and 1.6 m from the trunk, respectively (Figure 2c). In these two directions, the same distance from the trunk was selected as the sampling point, in which the internal canopy locations I_1, I_2, I_3, and I_4 were 0.6 m away from the trunk. The outer canopy locations identified as O_1 and O_2 were 0.6 m away from the trunk, and the outer canopy locations O_3, O_4, O_5, and O_6 were 1.2 m away from the trunk (Figure 2b).

2.4.2 Spraying parameters

The experiment consisted of 14 treatments (Table 3). Each test used a UAV flight speed of 2 m/s, a flight altitude of 3 m (from the tree), and a spraying volume of 3 L·elm/tree. The dosage of 10%

Table 3 Test design and parameters

Test No.	Spraying mode	Nozzles	Adjuvants	Dosage of adjuvants/mL
1	Conventional spraying mode	SX11001VS	BDT	60
3			GB	15
5			JXF	2
7			MS	15
9			MN	5
11			NJF	16
CK1			Water	/
2	Fully autonomous fruit tree operation mode	TX-VK4	BDT	60
4			GB	15
6			JXF	2
8			MS	15
10			MN	5
12			NJF	16
CK2			Water	/

Note: Table 1 defines the adjuvant acronyms.

fluridoxamide water dispersible granules for each treatment was 45 g/hm². The pesticide was sprayed from 9:00 a.m. to 12:00 a.m. on May 24, 2021. At that time, the relative humidity was 42.2%, the temperature was 13°C-28°C, and the north wind was less than grade 3 measured with a Kestrel 5500 weather meter (Nielsen-Kellerman, Boothwyn, PA, USA).

2.5 Test method

2.5.1 Droplet density and deposits

After the UAV spraying, each WSP sample was dried, classified, sealed individually, given a serial number, and returned to the laboratory for data collection. After the spraying, each WSP was scanned into 600 dpi images using the Filescan 2500 scanner. After processing and analyzing the data using ImageJ software (National Institute of Health, Bethesda, US), the number of droplets in the selected area on each WSP sample were scanned to obtain the droplet density. The software calculated the diffusion area of droplets on each WSP sample and calculated the deposits per unit area[19].

2.5.2 Droplet uniformity and penetration

The changes of droplet density and deposits were comprehensively analyzed because the droplet density can only reflect the change of the number of droplets, but not the actual amount of pesticide deposited on the leaves. The droplet uniformity within the same canopy was measured laterally by comparing the coefficient of variation (CV) of droplet density at different sampling points in the same canopy (upper or lower part of an elm)[16]. The data of the upper canopy sampling points were identified as O_3, O_4, I_1, and I_2, while the data of sampling points in the lower canopy were identified as I_3, I_4, O_5, and O_6 (Figure 2d).

By comparing the CVs of droplet density and deposits at different sampling points of elm internal or outer canopy, the droplet penetration and deposition penetration between different parts of the canopy could be measured longitudinally. The data of outer canopy sampling points were identified as O_1, O_3, and O_5 and O_2, O_4, and O_6, while the data of internal canopy sampling points were identified as O_1, I_1, and I_3 and O_2, I_2, and I_4; odd and even numbers were used to indicate the south and north sides of the canopy, respectively. The variance was calculated as:

$$S = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{(n-1)}} \tag{1}$$

$$\mathrm{CV} = \frac{S}{\bar{x}} \times 100\% \tag{2}$$

where, S is the variance; CV is the coefficient of variation, %; x_i is the droplet information (droplet density) of each droplet acquisition card; $\bar{x}$ is the average value of droplet information (droplet density) at different sampling points of an elm; n is the total number of WSP at different sampling points of an elm.

2.5.3 Investigation on control effect of elm aphids

Sampling was done according to the National Standard Guidelines for the field efficacy trials-insecticides for treatment of fruit tree aphids in China (GB/T 17980.9-2000). Two elm trees were investigated for each treatment. Each elm tree was marked with five points based on the four cardinal directions or sides of the tree canopy east, south, west, and north as well as in the middle of each tree. The number of live aphids on five leaves of each tree point was investigated after 0, 1, 3, and 7 d of pesticide spraying. The rate of decline in the aphid population was calculated as:

$$\text{Decline rate of insect population (\%)} = \frac{N_i - N_f}{N_i} \times 100\% \tag{3}$$

where, N_i and N_f are the numbers of insects before and after pesticide spraying, respectively. The control effect was calculated as:

$$\text{Control effect (\%)} = \frac{P_T - \mathrm{CK}}{100 - \mathrm{CK}} \times 100\% \tag{4}$$

where, P_T is the rate of decline in insect numbers in a pesticide spraying area and CK is the rate of decline in insect numbers in a control area treated by spraying with clean water as a treatment.

2.6 Data statistics and processing

Data were analyzed across different spraying rates using analysis of variance (Origin 2021 software, OriginLab, Northampton, MA, USA). Means were compared using a least significant difference (LSD) test. The confidence interval was set to 95% and p<0.05 was chosen to indicate a significant difference between the two groups. The figures were prepared by SigmaPlot 12.5 and Origin 2021 software.

3 Results and discussion

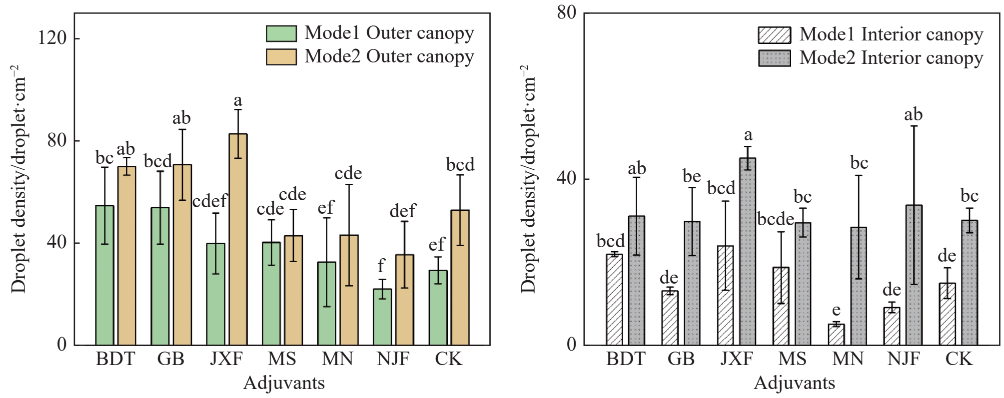
3.1 Droplet distribution

3.1.1 Droplet density in the upper canopy

When no adjuvant was added, the droplet density of the fruit tree mode was significantly higher than that of the conventional spraying operation mode (p<0.05). The droplet density increased by 79.7% in the outer canopy and 100.7% in the interior canopy. When adjuvants were added, the droplet density of the two operation modes increased again. The results in the outer canopy in the conventional spraying operation mode showed that adding BDT and GB produced significant different results (p<0.05); the droplet density increased by 85.6% and 82.9%, respectively compared with CK1 (Figure 3a). In the fruit tree mode, the droplet density with JXF increased significantly by 56.1% compared with CK2. The results in the interior canopy in the conventional spraying operation mode showed that compared with CK1, the droplet density of JXF, BDT and MS increased insignificantly (Figure 3b). However, in the fruit tree mode, the droplet density with JXF increased significantly by 49.7% compared with CK2. In addition, the difference of droplet density in the outer canopy decreased. Among them, compared with the conventional spraying operation mode, after adding JXF, the droplet density in the upper canopy of the fruit tree mode increased significantly (p<0.05) by 27.9% compared with the conventional spraying operation mode. It is worth noting that the difference of droplet densities between interior canopy layers was further improved after adding adjuvants. After adding GB, JXF, MN and NJF, the droplet density under the fruit tree mode increased significantly by 127.0%, 87.71%, 447.1% and 266.9%, respectively, compared with the conventional spraying operation mode. This shows that in the fruit tree mode, the droplet density of the interior canopy was increased by changing the angle of the nozzles on both sides to spray. After adding adjuvants, the droplet density of the interior canopy further increased. If the two were applied at the same time, this produced the effect of superposition optimization.

3.1.2 Droplet density in the lower canopy

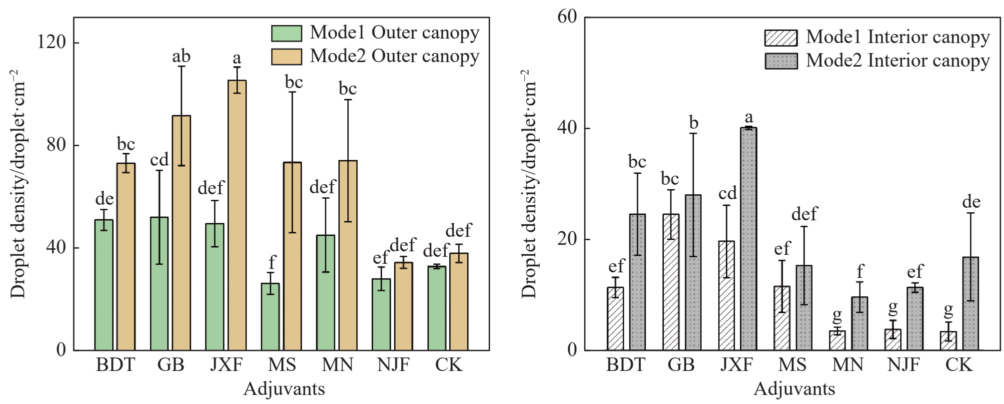
The interior of the lower canopy is the most difficult position for spray to penetrate in all areas; the present study also evaluated the significance of the advantages and disadvantages of the operation mode of a UAV and the effect of adjuvants. When no adjuvants were added, the droplet density of the fruit tree mode was significantly different from that of the conventional spraying operation mode only in the interior canopy (p<0.05). The droplet density increased by 394.1% when using the fruit tree mode. This shows that the droplets can effectively penetrate the upper canopy to reach the interior part of the lower canopy under the fruit tree mode. At the same time, under the fruit tree mode, more droplets will fly into the gaps on both sides of the tree obliquely and will not be blocked by the leaves. When adjuvants were added, the advantage of the fruit tree mode was further amplified. The results in the outer canopy with use of the conventional spraying operation mode showed that adding BDT and GB had significant differences (p<0.05); with these two adjuvants, the droplet density increased significantly by 55.1% and 58.3%, respectively, when compared with CK1 (Figure 4a). In the fruit tree mode, the droplet density with JXF increased significantly by 177.8% compared with CK2. The results for the interior canopy in the conventional spraying operation mode showed that by adding GB and JXF, the droplet density increased by 722.1% and 479.5%, respectively, when compared with CK1 (Figure 4b). When BDT and MS were added, the droplet density increased by 232.4% and 238.2%, respectively. In the fruit tree mode, when JXF was added, a significant increase (138.2%) of droplet density was observed when compared with CK2. When BDT and GB were added, the droplet density increased significantly by 45.8% and 45.5%, respectively. It is worth noting that after adding GB and JXF, the density of interior canopy droplets in both modes increased significantly. The effect of increasing droplet density is the best after applying the fruit tree mode and JXF.



a. Outer canopy b. Interior canopy

Note: Mode 1 and Mode 2 represent conventional and fully autonomous fruit tree spraying operation modes, respectively. The same as below.

Figure 3 Distribution of pesticide droplets in the upper canopy of elm



a. Outer canopy b. Interior canopy

Figure 4 Distribution of pesticide droplets in the lower canopy of elm

3.1.3 Droplet density in different directions of elm canopy

In a natural forest growing outside equatorial areas in the northern hemisphere, the southern part of an elm has a larger canopy, higher leaf density and stronger canopy closure. The results showed that the droplet density in the southern part of a tree was less than that in the north; meanwhile, the fruit tree mode was better than the conventional mode, which can effectively improve the droplet density in the southern and northern parts of an elm tree. In the conventional mode, adding JXF, GB, BDT and MS can effectively increase the droplet density on the southern and northern sides of a tree (Figure 5a). In the fruit tree mode, after adding JXF and MS, the droplet density on the southern and northern sides of a tree changed little, which can effectively increase the droplet density on the southern side. The application of fruit tree mode and adding JXF can greatly improve the droplet density in the southern part of a tree. This phenomenon was more obvious in the lower canopy (Figure 5b). In the conventional mode, adding JXF, GB, BDT, MS, and MN can effectively increase the droplet density in the southern and northern sides of a tree. In the fruit tree mode, after adding JXF, BDT, and GB, the droplet density in the southern and northern sides of a tree changed little, which can effectively increase the droplet density on the southern side.

3.2 Deposits

3.2.1 Deposits in the upper canopy

Figure 6 provides the data related to amount of deposition in various treatments (unit: μL/cm^2). When no adjuvant was added, the deposits in the fruit tree mode in the outer and inner canopy was 0.246 μL/cm^2 and 0.580 μL/cm^2, respectively. Compared with the conventional mode, the deposits increased significantly (p<0.05), with increases in the outer and inner canopy of 179.3% and 65.7%,

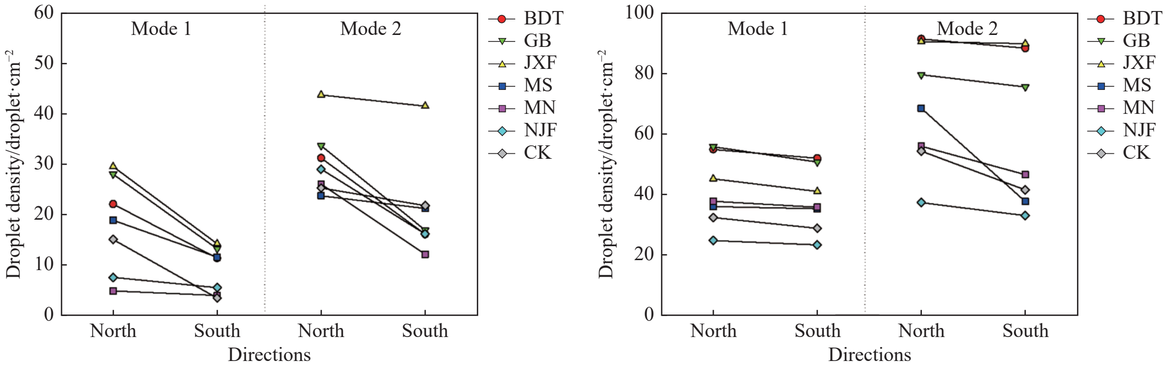
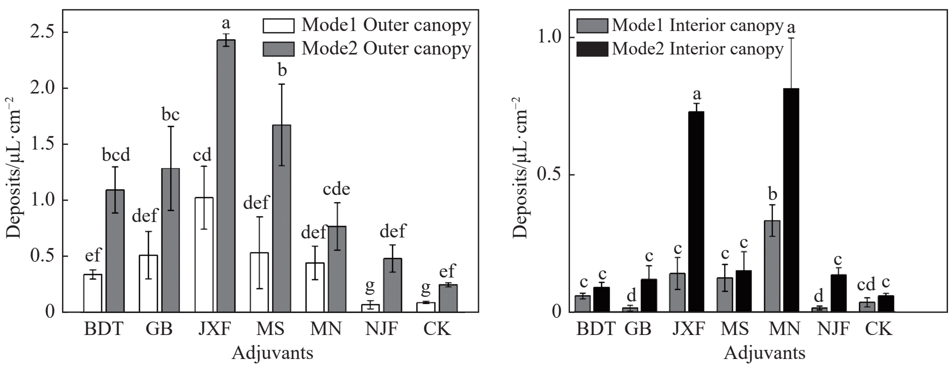


Figure 5 Droplet density in different directions of elm canopy

respectively. When adjuvants were added, the deposits of the two operation modes increased to varying degrees. In the conventional mode of the outer canopy, the deposits when adding JXF had the highest value of 1.021 μL/cm^2, and when compared with the deposits of CK1, increased by 1060.8% (Figure 6a). When BDT, GB, MS, and MN were added, the deposits of CK1 increased significantly, by 284.1%, 479.8%, 504.3%, and 401.1%, respectively. When NJF was added, the deposits were similar to those of CK1. The deposits of the outer canopy in the fruit tree mode when adding JXF were the highest with a value of 2.428 μL/cm^2; Compared with the deposits of CK2, deposits increased by 888.10%. When MS, BDT, and GB were added, the deposits increased significantly compared with CK2, increasing by 580.3%, 343.9%, and 422.5%, respectively. In the conventional mode of the interior canopy, the deposits when MN was added had the highest value of 0.332 μL/cm^2; when compared with the deposits of CK1, this was an increase of 848.6% (Figure 6b). The deposits of BDT, JXF, and MS increased significantly compared with CK1, increasing by 67.1%, 298.6%, and 254.3%, respectively. The amounts of deposits of GB and NJF were similar to that of CK1. The deposits of the interior canopy after adding JXF and MN in the fruit tree mode were 0.727 μL/cm^2 and 0.811 μL/cm^2, respectively; when compared with CK1, the deposits increased significantly, increasing by 1154.2% and 1298.3%, respectively. When BDT, GB, MS, and NJF were added, the deposits were similar to that of CK2. This corresponds well to the results of droplet density. The application of the fruit tree mode with added adjuvants had a superimposed effect on the amounts of increase in the deposited spray. The application of aviation spray adjuvants can reduce the drift and evaporation of droplets in the air[20-23], increase the adhesion of droplets and their diffusion ability on crops, as well as increase the amount of pesticide deposited in each canopy[24,25].



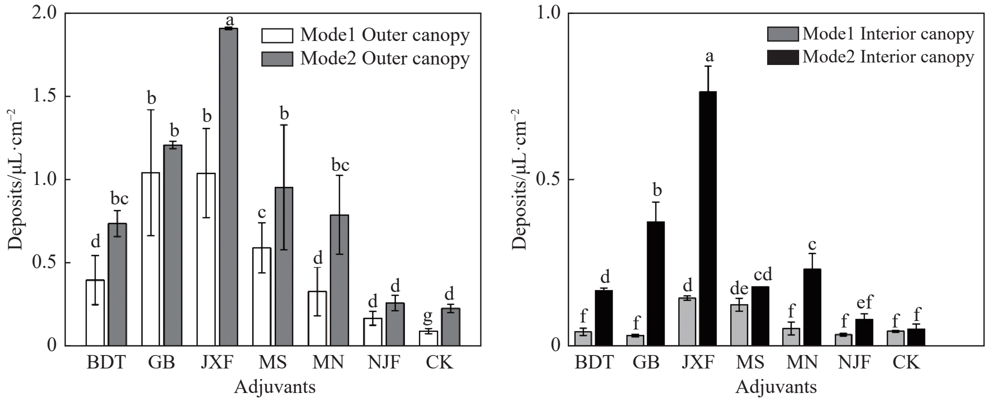
a. Outer canopy

b. Interior canopy

Figure 6 Deposits in the upper canopy of elm

3.2.2 Deposits in the lower canopy

When no adjuvant was added, the amount of spray deposited with the fruit tree mode in the outer canopy was 0.225 μL/cm^2; when compared with the conventional mode, the quantities of deposits increased significantly by 152.8%. The deposits in the interior canopy of the fruit tree mode were similar to that of the conventional mode. When adjuvants were added, the amount of spray deposited using the two operation modes increased. When GB and JXF were added, the amount of spray deposited in the outer canopy in the conventional mode was 1.039 μL/cm^2 and 1.036 μL/cm^2, respectively; when compared with the deposits of CK1, these increased significantly by 1067.4% and 1064.0%, respectively (Figure 7a). In the fruit tree mode in the outer canopy, the amounts of spray deposited when adding JXF had the highest value of 1.905 μL/cm^2; Compared with the deposits of CK1, the amounts increased by 746.4%. When BDT, GB, MS, and MN were added, the deposits increased significantly compared with CK2, increasing by 226.2%, 435.8%, 322.4%, and 249.3%, respectively. In the conventional mode of the interior canopy, the deposits of the lower canopy when adding JXF and MS were 0.144 μL/cm^2 and 0.124 μL/cm^2; when compared with the amount of spray deposited in CK1, the amounts increased significantly by 226.1% and 180.7%, respectively (Figure 7b). In the fruit tree mode of the interior canopy, the amount of spray deposited when adding JXF was the highest at 0.763 μL/cm^2; Compared with the deposits of CK2, the amounts increased by 1426.0%. When BDT, MS, and MN were added, the deposits increased significantly compared with CK2, increasing by 231.0%, 255.0%, and 360.0%, respectively. It is worth noting that after adding adjuvants, a significant difference was observed between the two operation modes for the interior canopy, which was most obvious on JXF.



a. Outer canopy b. Interior canopy

Figure 7 Deposits in the lower canopy of elm

3.3 Droplet uniformity and penetration

3.3.1 Droplet uniformity

Table 4 provides the data related to droplet uniformity. The data related to droplet uniformity were obtained by comparing the coefficient of variation for droplet density in each canopy layer based on the obtained droplet density of each treatment. The uniformity of spray droplets for the fruit tree mode in the upper and lower canopy of elm was better than that of the conventional spraying mode (Table 4). In the conventional mode, after adding different adjuvants, the uniformity of droplets in the upper canopy could be ranked as JXF<NJF<MS<BDT<GB<MN; JXF provided the best uniformity of droplets. In the fruit tree mode, the droplet uniformity could be ranked as JXF<BDT<NJF<MN<GB<MS; JXF provided the best uniformity of droplets. In the conventional mode, the droplet uniformity in the lower canopy could be ranked as MS<GB<JXF<BDT<NJF<MN; MS provided the best uniformity of droplets. In the fruit tree mode, the droplet uniformity could be ranked as JXF<BDT<NJF<GB<MN<MS; JXF provided the best uniformity of droplets. It is worth noting that after adding JXF, both the upper and lower canopy had good droplet uniformity. This phenomenon was more obvious in the application of the fruit tree mode.

Table 4 Droplet uniformity and penetration on outer canopy of elm

Test No.	Adjuvants	Droplet uniformity/%		Depositional penetration/%		Droplet penetration/%	
		Upper canopy	Lower canopy	Outer canopy	Interior canopy	Outer canopy	Interior canopy
1	BDT	46.9	74.0	56.8	60.1	22.3	106.1
2		36.3	58.3	42.2	57.9	4.9	74.3
3	BG	58.9	50.4	86.8	63.1	25.8	161.1
4		52.3	65.1	44.7	70.7	29.7	128.4
5	JXF	40.6	53.3	46.0	50.0	26.0	82.6
6		29.7	52.0	33.1	37.8	15.5	59.5
7	MS	41.1	49.1	58.2	41.2	28.5	105.6
8		53.0	97.6	51.1	96.3	60.9	95.8
9	MN	83.2	99.1	74.1	93.2	49.9	91.5
10		51.9	95.0	54.7	77.0	45.8	67.1
11	NJF	41.1	90.0	75.6	75.1	19.7	79.3
12		37.8	58.7	60.2	57.3	41.4	76.3

Note: Table 1 defines the adjuvant acronyms.

3.3.2 Penetration

1) Droplet penetration

Table 4 provides the data related to droplet penetration. In the conventional mode, the droplet penetration of outer canopy could be ranked as NJF<BDT<GB<JXF<MS<MN; NJF provided the best droplet penetration (Table 4). In the fruit tree mode, droplet penetration could be ranked as BDT<JXF<GB<NJF<MN<MS; BDT provided the best droplet penetration. In the conventional mode, the droplet penetration of interior canopy could be ranked as NJF<JXF<MN<MS<BDT<GB; NJF provided the best droplet penetration. In the fruit tree mode, droplet penetration could be ranked as JXF<MN<BDT<NJF<MS<GB; JXF provided the best droplet penetration. It was worth noting that NJF had the highest droplet penetration in the conventional mode, but the volume of the deposits were low. This may have occurred because the base number of NJF droplet density was very small, and little difference was observed between the interior and outer canopy droplet density, so the results should be compared and analyzed with the depositional penetration. Using JXF in the fruit tree mode resulted in higher droplet penetration in both the interior and outer canopy layers.

2) Depositional penetration

Table 4 displays the data related to depositional penetration. In summary, in the conventional mode, the depositional penetration of outer canopy could be ranked as JXF<BDT<MS<MN<NJF<GB; that is, JXF had the best depositional penetration (Table 4). In the fruit tree mode, the depositional penetration could be ranked as JXF<BDT<GB<MS<MN<NJF; that is, JXF had the best depositional penetration (Table 4). In the conventional mode, the interior canopy depositional penetration could be ranked as MS< JXF< BDT<GB<NJF<MN; that is, MS had the best depositional penetration. In the fruit tree mode, the depositional penetration could be ranked as JXF<NJF<BDT<GB<MN<MN; that is, JXF had the best depositional penetration. It is worth noting that JXF has a high depositional penetration in both modes, especially in the fruit tree mode. Therefore, combined with the results of droplet penetration, it can be concluded that using JXF in the fruit tree mode can ensure high droplet density in the interior and outer canopy and provide large deposits at the same time.

3.4 Control effect on elm aphids

Table 5 provides the data related to control of aphids. In the conventional mode, the control effect of elm aphids could be ranked as JXF>BDT>GB>MS>MN>NJF (81.6%) after 1 day of spraying. After 3 d of spraying, JXF still showed the best effect, followed by GB, BDT, MS, MN and NJF in descending order of aphid control. After 7 d of spraying, the best control effect was recorded by JXF followed by GB. On day 1, 3, and 7 after comprehensive spraying, the control effect of the fully autonomous fruit tree mode was significantly higher than that of conventional spraying operation mode. On day 3 and day 7 after spraying, the control effect was significantly improved by adding adjuvants, in both spraying operation modes. It is worth noting that no matter in which operation mode JXF was added, the control effect was good within 1 d, 3 d, and 7 d after spraying, which may be due to the synergistic effect of silicone adjuvants and pesticides[26]. Organosilicon adjuvants improved the insecticidal activity of the three agents and prolonged the validity period[27].

Table 5 Control effect on elm aphid

Test No.	Adjuvants	Control effect/%		
		1 d	2 d	7 d
1	BDT	82.10±1.00^{e}	87.88±0.44^{c}	92.49±0.18^{c}
2		85.18±1.65^{bc}	93.05±0.79^{a}	95.64±0.28^{b}
3	GB	82.40±3.09^{de}	90.47±0.47^{b}	94.65±0.29^{b}
4		87.02±1.66^{ab}	93.31±1.10^{a}	97.11±0.42^{a}
5	JXF	84.91±1.14^{bcd}	92.94±0.83^{a}	96.80±0.36^{a}
6		88.87±1.65^{a}	94.13±1.00^{a}	97.92±0.53^{a}
7	MS	82.43±0.38^{de}	86.68±1.23^{cd}	88.89±0.81^{d}
8		86.20±1.15^{b}	90.18±0.52^{b}	92.94±1.30^{c}
9	MN	81.83±0.98^{e}	85.72±1.19^{de}	87.73±0.53^{e}
10		83.58±2.79^{cde}	87.11±1.45^{cd}	89.50±1.35^{d}
11	NJF	81.61±0.45^{e}	84.49±1.28^{ef}	86.33±1.35^{f}
12		82.78±2.88^{cde}	86.04±1.05^{de}	87.70±0.57^{e}
CK1	Water	76.87±0.67^{f}	80.18±1.19^{g}	84.20±0.70^{g}
CK2		81.17±0.58^{e}	84.02±1.40^{f}	86.01±0.93^{f}

Note: The data in the table are mean±SE. Data followed by different small letters are significantly different among different treatments at $p<0.05$ level by Duncan's new multiple range test. Table 1 defines the adjuvant acronyms.

4 Conclusions

The present study analyzed the effects of six aviation spray adjuvants sprayed by a UAV and two operation modes on droplet deposition and elm aphid control; the following conclusions can be drawn.

1) The fruit tree model of T30 UAV had better droplet deposition and penetration than the conventional mode, and had better control effect on elm aphids.

2) Adding aviation spray adjuvants could effectively improve the droplet deposition and penetration in the two operation modes, while the effect of silicone adjuvants JXF showed the best effect.

3) In the control of elm aphids, using the fruit tree mode and adding JXF adjuvant could achieve the optimal droplet deposition and aphid control effects.

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