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Fixed Spraying Systems Application in Citrus Orchards: Nozzle Type and Nozzle Position Effects on Droplet Deposition and Pest Control

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Abstract: Pesticide application is an essential means of controlling plant diseases and pests in citrus orchards. In recent years, fixed spraying systems have gradually been used as alternatives to traditional sprayers and manual sprayers in some hilly citrus orchards. In this paper, influences of fixed system spraying parameters, such as droplet size and spraying height, on spraying quality were elucidated and analyzed. The performances of two nozzle types, pressure-swirl nozzles and fixed spray plate sprinklers, were assessed and compared by effective droplet coverage ratio (DCR), droplet distribution uniformity coefficient of variation (CV), and droplet penetration ratio (DPR). The results showed that appropriately increasing droplet size and spraying height could improve the DCR and distribution uniformity of pressure-swirl nozzles. The DCR and distribution uniformity of fixed spray plate sprinklers had a positive correlation with droplet size, while spraying height had no significant effect on these variables. Additionally, with the increase in droplet size, DPR initially increased and then gradually decreased. The optimized results showed that the optimal parameters for pressure-swirl nozzles were a droplet size of 240 μm and spraying height of 100 cm, while for fixed spray plate sprinklers, the results were a droplet size of 240 μm and spraying height of 50 cm. Comparison results showed that the spraying quality of fixed spray plate sprinklers was better overall, with values of DCR, CV, and DPR being 37.15%, 24.20%, and 71.67%, respectively, while the corresponding values for pressure-swirl nozzles were 39.65%, 35.41%, and 56.02%. Based on the above results and the occurrence rule of citrus pests and disease, the optimal spraying parameters of fixed spraying systems were selected to control the Asian citrus psyllid *Diaphorina citri*. Furthermore, the effect of fixed spraying systems on controlling *Diaphorina citri* reached the maximum at 3 days after spraying, which was 97.83%, and the effect declined at 14 days after spraying, which was 85.47%. This study provides valuable scientific references for guiding the application of fixed spraying systems in hilly citrus orchards.

Keywords: fixed spraying systems; hilly citrus orchards; citrus canopy; spraying quality; spraying parameters; control *D. citri*

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1. Introduction

Citruses hold a prominent status as one of the most widely adored and significant fruit varieties in southern China. In the year of 2008, China surpassed Brazil as the leading nation in terms of citrus production worldwide [1,2]. Citrus orchards are primarily distributed in hilly and mountainous regions in southern China [3,4]. Generally, citrus orchards necessitate spraying pesticides at a frequency of 10 to 15 times annually, constituting roughly 30% of the overall workload in managing the orchards. Nevertheless, in steeply sloped citrus orchards where conventional sprayers are impractical due to various difficulties, hand sprayers are applied to citruses to control pests, which is a very pricy, manpower-intensive application [5,6]. Furthermore, pesticide spraying cannot be achieved quickly, leading to ineffective prevention and control of citrus diseases and pests. The result is that attainment of a high and consistent citrus yield is obstructed [7]. Therefore, China have focused on enhancing mechanization to effectively address the current challenge of preventing citrus pests and diseases [8].

As a possible alternative method, fixed spraying systems have gradually been developed for hilly fruit orchards [9,10]. For instance, significant efforts were devoted to the development and comprehensive research of a solid set canopy delivery system in United States high-density apple orchards [11]. In Italy, preliminary tests of fixed spraying systems were performed in vineyards and apple orchards, which were focused on arrangements of tubes and the efficacy of spraying [12,13]. In China, many scholars have used fixed spraying systems for pesticide spraying, which existed in the 1980′s, with preliminary applications in greenhouse vegetable and hilly citrus orchards [14]. The introduction of fixed spraying systems has led to increased attention due to several advantages, including adaptability to hilly and mountainous terrain, low labor intensity, reduced pesticide exposure, and ease of implementation for automated production [15]. The use of fixed spraying systems provides an effective operating platform for preventing rapid outbreaks of plant diseases and pests in hilly citrus orchards [15,16].

As a new pesticide application method, there are still a range of practical issues for fixed spraying systems, such as inconclusive optimal spraying parameters, lack of penetrability into the citrus canopy, low droplet coverage ratio, and inhomogeneous deposition distribution [9,17]. Recent studies revealed that nozzle type, droplet size, and spraying height were key factors in controlling pests [18,19]. Ranjan et al. [20] and Mozzanini et al. [21] used solid set canopy delivery systems to evaluate the performance of different nozzle combinations and found that an optimally configured nozzle position and combination can provide adequate spray performance in orchards with a minimized risk of off-target pesticide drift. Mozzanini et al. [22] evaluated the suitability of a hydraulic fixed delivery spray system to be adopted as crop protection technology and found that the emitter flow rate, emitter number, and spray mixture volume injected were the three key factors affecting the dose applied, homogeneity of distribution among emitters, and cleaning performance. Sahni et al. [23] investigated the spray effect of a pneumatic spray delivery-based solid set canopy delivery system in a high-density apple orchard, and the results showed that modified reservoirs and a three-tier configuration offered significantly improved zonal coverage uniformity.

Along with the research above, there have been rare reports on the influences of the spraying method and spraying parameters of fixed spraying systems on the droplet deposition uniformity and effect of controlling pests in hilly citrus orchards.

Therefore, this research aims to investigate the laws governing droplet deposition distribution on the citrus canopy, the effects of droplet size and spraying height on droplet deposition uniformity and penetrability, as well as to evaluate the efficiency of controlling *Diaphorina citri* (*D. citri*). This study will provide theoretical support and data for the application of hydraulic fixed spraying systems in controlling plant diseases and pests in hilly citrus orchards.

2. Materials and Methods

2.1. Orchards and Characterization of Vegetation

The experimental site was an 11-year-old citrus orchard of the Citrus Scientific Research Base in Ganzhou City (25.77° N, 114.86° E), Jiangxi Province, China. *D. citri*, red spiders, and other pests occur from time to time, and some citrus canopies were infected with *Candidatus* Liberibacter asiaticus (CLas). Tests were carried out at BBCH75 of citrus. The citrus trees were planted at a density of 800 trees/ha with between-row spacing of 4.0 m and between-tree spacing of 3.0 m. The canopy of citrus trees naturally forms a rounded shape with a diameter of 3.0 m and height of 2.5 m.

2.2. Experimental Materials

The prototype of a hydraulic fixed spraying system developed by our team was tested in citrus orchards, as shown in Figure 1. It was mainly composed of an electro-motor (POOSS Co., Ltd., Taizhou, China), plunger pump (Himore Co., Ltd., Suzhou, China), pressure gage (Hongqi Co., Ltd., Yueqing, China), time relay (CHINT Co., Ltd., Yueqing, China), solenoid valve (SNS Co., Ltd., Yueqing, China), tank, hose, distribution valve, support frame, nozzle, and other related component parts. The main technical parameters are shown in Table 1. During operation, the tank is connected to the nozzle device through the hose interface, the spraying pressure is supplied by the plunger pump, and the amount of spraying is controlled by the time relay driver.

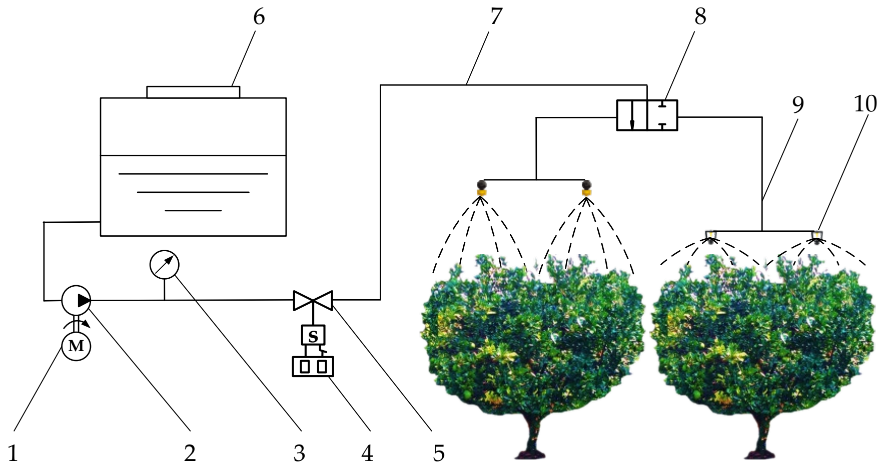

Figure 1. Fixed spraying system prototype: 1. Electro-motor; 2. Plunger pump; 3. Pressure gage; 4. Time relay; 5. Solenoid valve; 6. Tank; 7. Hose; 8. Distribution valve; 9. Support frame; 10. Nozzle.

Table 1. Parameters for fixed spraying system prototype.

Equipment	Parameter	Value
Electro-motor	Power/kW	2.2
Plunger pump	Flow-rate range/L·min^{-1}	14–22
Pressure gage	Accuracy class	0.4
Time relay	Precision values/s	0.01
Solenoid valve	Pressure range/Mpa	0–0.5

The nozzles were categorized into two types: Pressure-swirl nozzles (Lanao Co., Ltd., Suzhou, China) and fixed spray plate sprinklers (Lemiao Co., Ltd., Ningbo, China). Figure 2 illustrates these two nozzle types. Pressure-swirl nozzles utilize a slotted swirl vane at the entrance of the swirl chamber to generate swirl and produce a solid-cone spraying pattern. Fixed spray plate sprinklers utilize a high-pressure liquid jet that hits the refracting plate through a central cylindrical port, resulting in a disc-shaped spraying pattern. The main parameters of the nozzles can be seen in Table 2.

According to characteristics of two nozzle types, the spraying units of fixed spraying systems were set up in two different ways. A gantry framework was utilized for installing pressure-swirl nozzles, which was positioned in the center of the citrus canopy, as shown in Figure 3a. The nozzles were mounted vertically downwards on both ends of the gantry crossbar, with a spacing of 1.5 m between the two nozzles. The height of the nozzles above the canopy top was adjustable and denoted as h_n. On the other hand, a twin vertical rod construction was utilized for installing fixed spray plate sprinklers, which was positioned in the center of canopy, as shown in Figure 3b. The sprinklers were mounted vertically at the top of the vertical rods, with a spacing of 1.5 m between two sprinklers. The height of the sprinklers above the canopy top was adjustable and denoted as h_s, as shown in Figure 4.

Figure 2. Tested nozzles: (**a**) pressure-swirl nozzles; (**b**) fixed spray plate sprinklers.

Table 2. Parameters of nozzles.

Nozzle Type	Nozzle Model	Flow Rate/L·min^{-1}	Droplet Size (VMD[1])/µm
Pressure-swirl nozzles	YZS80-01	0.20	100
	YZS80-02	0.80	220
	YZS80-03	1.20	240
	YZS80-04	1.60	280
Fixed spray plate sprinklers	LM-1201	0.55	180
	LM-1202	0.90	240
	LM-1203	1.30	300
	LM-1204	1.80	350

[1] VMD indicates droplet volume medium diameter.

Figure 3. Spraying units of fixed spraying systems: (**a**) spraying unit equipped with pressure-swirl nozzles; (**b**) spraying unit equipped with fixed spray plate sprinklers.

Water sensitive paper (WSP) (Syngenta Biotechnology (China) Co., Ltd.) was used to collect the droplets and estimate the droplet coverage (%) during the experiments.

2.3. Experimental Treatments

2.3.1. Experiment of Parameter Optimization

Experiment Design

In order to ensure the scientific nature of the experimental design, multiple preliminary experiments were conducted. The rough results of the experiments indicated that for better atomization effect and coverage, the recommended spraying height between the pressure-swirl nozzles and the top of canopy was in the range of 40 to 100 cm, while the recommended spraying height for the fixed spray plate sprinklers was in the range of 10 to 50 cm. The spraying pressure for each experimental treatment was 0.3 MPa and the amount of liquid used per tree was 2.0 L in order deliver a volume equal to 1600 L/ha. Each nozzle model was tested at three heights above the top of the canopy, and the pressure-swirl nozzles were tested at 40, 70, 100 cm and the fixed spray plate sprinklers at 10, 30, and 50 cm. A total of twenty-four treatments are shown in Table 3 with their respective treatment parameters. Three valid repetitions for each treatment were conducted to ensure the accuracy of the obtained data.

Table 3. Treatments and parameter combinations.

Pressure-Swirl Nozzles			Fixed Spray Plate Sprinklers		
Treatment No.	**Nozzle Model**	***h*/cm**	**Treatment No.**	**Nozzle Model**	***h*/cm**
A1	YZS80-01	40	B1	LM-1201	10
A2	YZS80-01	70	B2	LM-1201	30
A3	YZS80-01	100	B3	LM-1201	50
A4	YZS80-02	40	B4	LM-1202	10
A5	YZS80-02	70	B5	LM-1202	30
A6	YZS80-02	100	B6	LM-1202	50
A7	YZS80-03	40	B7	LM-1203	10
A8	YZS80-03	70	B8	LM-1203	30
A9	YZS80-03	100	B9	LM-1203	50
A10	YZS80-04	40	B10	LM-1204	10
A11	YZS80-04	70	B11	LM-1204	30
A12	YZS80-04	100	B12	LM-1204	50

Sampling Point Arrangements

According to characteristics of the citrus canopy structure during the autumn shooting period and their requirements for plant protection, the canopy was divided into three dimensions for sampling, including the horizontal direction, vertical direction, and circumferential direction [23,24].

The citrus canopy was divided into four sampling circles from the center to the outside in the horizontal direction (First, Second, Third, and Fourth) and according to the position of each sampling circle. Additionally, it was divided into three sampling layers along the vertical direction (Upper, Middle, and Lower) and according to the position of each sampling layer. Furthermore, it was divided into eight vector directions along the circumferential direction (VA to VH) and the position of each sampling vector direction was denoted as *k*. The field sampling layout is shown in Figure 4.

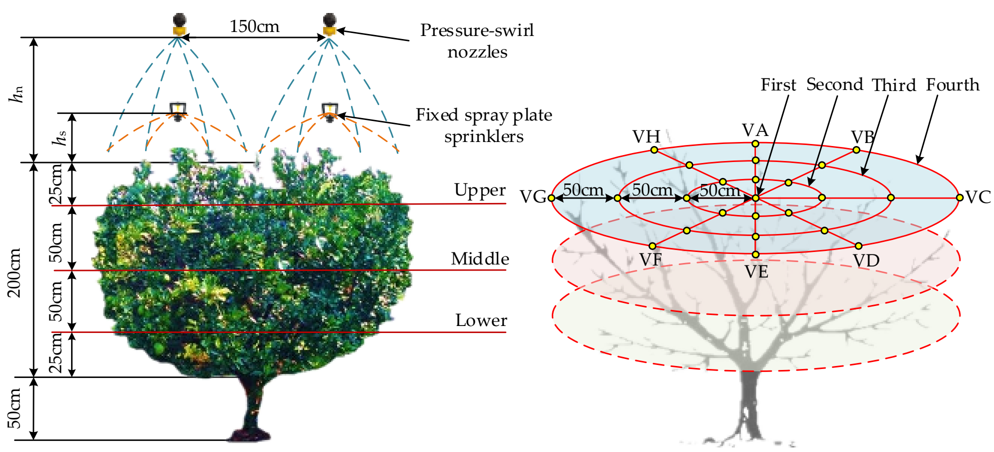

Figure 4. The field sampling layout.

2.3.2. Control Effect Experiments

To investigate the effect of fixed spraying systems on controlling *D. citri*, citrus trees were sprayed with the optimal spraying parameters. Thiamethoxam (30%) (Shandong Huayang Technology Co., Ltd., Taian, China) was applied using fixed spraying systems for controlling *D. citri*. The experimental citrus orchard was divided into three areas: pressure-swirl nozzle spraying area, fixed spray plate sprinkler spraying area, and untreated control area [25], with each area comprising three neighboring citrus trees, as shown in Figure 5. The optimal treatments A9 (YZS80-03, spraying height of 100 cm) and B6 (LM-1202, spraying height of 50 cm) were used for spraying in the test areas, respectively. The CK area was reserved as blank control group.

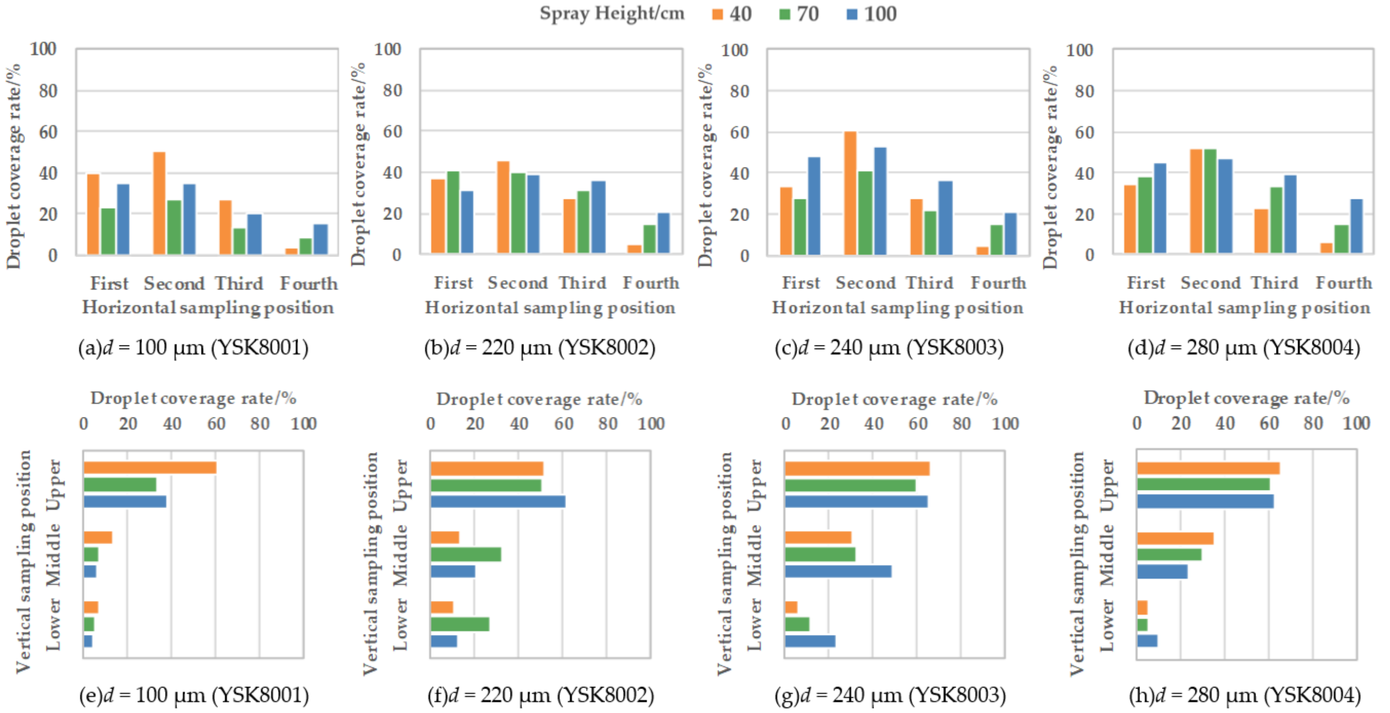

Figure 5. DCR of pressure-swirl nozzles in citrus canopy: (**a**–**d**) represent DCR in horizontal direction; (**e**–**h**) represent DCR in vertical direction.

During the pesticide spraying experiment, the average relative humidity was 54%, the average temperature was 33.4 °C, the average wind speed was 1.2 m/s, and the predominant wind direction was SW. The meteorological data were provided by the local plant protection bureau. The experimental pesticide used was Thiamethoxam (30%), diluted 500 times with water. The spraying volume for each test tree was 2 L.

2.4. Data Process and Analysis

WSP was scanned at 1200 dpi to obtain digital images by Deskjet 4720 series Scanner (Hewlett-Packard Co., Ltd., Shanghai, China). The droplet coverage ratio (DCR) on each WSP was calculated using the DepositScan software [26]. Furthermore, the droplet distribution uniformity coefficient of variation (CV) and droplet penetration ratio (DPR) were further analyzed.

The droplet coverage ratio was an important indicator for assessing the quality of droplet deposition on tree canopies, measured in %. It was calculated using the following equation:

$$DCR = \frac{1}{n}\sum_{i=1}^{n} X_i, \tag{1}$$

$$X_i = \frac{1}{n_j n_k} \sum_{k=1}^{n_k} \sum_{j=1}^{n_j} P_{(i,j,k)}, \tag{2}$$

where X_i is the droplet coverage of each sampling circle, in %; P is the droplet coverage of each sampling WSP, in %; n is the number of sampling circles in the horizontal direction, which is 4; n_j and n_k are the number of samples in the vertical and circumferential directions which are contained within each sampling circle, respectively.

The droplet distribution uniformity in the horizontal direction of the tree canopy was evaluated with CV, in % [27]. The CV calculation equation was as follows:

$$\mathrm{CV} = \frac{S}{\mathrm{X}} \times 100, \tag{3}$$

$$S = \sqrt{\sum_{i=1}^{n} \frac{(X_i - \mathrm{DCR})^2}{(n-1)}}, \tag{4}$$

where S is the standard deviation and n is the number of sampling circles in the horizontal direction, which is 4.

The droplet penetrability in the vertical direction was expressed by the droplet penetration ratio, in % [23], which is calculated using the following equation:

$$\mathrm{DPR} = \frac{Y_2 + Y_3}{2Y_1}, \tag{5}$$

$$Y_j = \frac{1}{n_i n_k} \sum_{k=1}^{n_k} \sum_{i=1}^{n_i} P_{(i,j,k)}, \tag{6}$$

where Y_1, Y_2, and Y_3 are the droplet coverage of the upper, middle, and lower layers, respectively, in %; and n_i and n_k are the number of samples in the horizontal and circumferential directions which are contained within each sampling layers, respectively.

The distribution trend of droplet deposition in the circumferential direction was evaluated by analyzing the droplet coverage ratio in eight vector directions [24]. The droplet coverage ratio in the vector direction is obtained from Equation (7).

$$Z_k = \frac{1}{n_i n_j} \sum_{j=1}^{n_j} \sum_{i=1}^{n_i} P_{(i,j,k)}, \tag{7}$$

where Z_k is the droplet coverage of each vector direction, in %; and n_i and n_j are the number of samples in the horizontal and vertical directions which are contained within each vector direction, respectively.

A two-way analysis of variance (ANOVA) was conducted to verify the significant impact of the nozzle model, spraying height, and the interaction of the nozzle model and spraying height on DCR, CV, and DPR [28]. The main effects of the nozzle model and spraying height on DCR, CV, and DPR were subjected to multiple comparisons using the Student–Newman–Keuls (SNK) method [29].

According to the evaluative information available in the literature, spraying quality was positively associated with DCR and DPR and negatively with CV [24,30]. The spraying quality can be calculated by using the indicators offered in Equation (8).

$$Q = 0.5DCR - 0.25CV + 0.25DPR, \tag{8}$$

where Q is the spraying quality of fixed spraying systems, in %.

A Least Squares Means (LS Means) was conducted to compare the spraying quality with different spraying parameter combinations [31].

2.5. Investigation of Effect of Spraying on Controlling D. citri

We investigated the effect of spraying on controlling *D. citri* for ten branches of each citrus tree (four directions: north, east, south, and west of the canopy) and surveyed the population numbers of *D. citri* in each area before spraying and 1, 3, 7, and 14 days after spraying [32].

The effect was obtained based on the population numbers of live insects in each area before spraying and after spraying [33], which was calculated using the following equation:

$$E_1 = \frac{R_P - R_{CK}}{100 - R_{CK}} \times 100, \tag{9}$$

$$R = \frac{IPB_{be} - IPB_{af}}{IPB_{be}} \times 100, \tag{10}$$

where E_1 is the correction control effect, in %; R_P is the insect population reduction rate in the spraying area and R_{CK} is the insect population reduction rate in the CK, in %; R is the insect population reduction rate, in %; and IPB_{be} is the insect population base before spraying and IPB_{af} is the insect population base after spraying.

3. Results

3.1. Deposition Distribution

3.1.1. Deposition Distribution in Horizontal and Vertical Direction

The results of the pressure-swirl nozzle types are presented in the following order: Figure 5a (YSK8001), Figure 5b (YSK8002), Figure 5c (YSK8003), and Figure 5d (YSK8004) representing the DCR in the horizontal direction, and Figure 5e (YSK8001), Figure 5f (YSK8002), Figure 5g (YSK8003), and Figure 5h (YSK8004) representing the DCR in the vertical direction. Additionally, the droplet coverage ratios of the fixed spray plate sprinkler types are presented in the following order: Figure 6a (LM-1201), Figure 6b (LM-1202), Figure 6c (LM-1203), and Figure 6d (LM-1204) representing DCR in the horizontal direction, and Figure 6e (LM-1201), Figure 6f (LM-1202), Figure 6g (LM-1203), and Figure 6h (LM-1204) representing DCR in the vertical direction. The results show that DCR in the center of the citrus canopy exhibited significantly higher values compared to those in the outer regions. Additionally, the DCR value in the upper sampling layer was higher than that in the lower sampling layer.

Droplet coverage ratio, CV, and DPR were calculated according to Equations (1), (3), and (5). According to the pressure-swirl nozzle data, the DCR threshold ranged from 18.19% (A2) to 39.65% (A12), and the value average was 30.63%, the CV threshold ranged from 21.91% (A12) to 73.16% (A7), and the value average was 46.44%, the DPR threshold ranged from 14.77% (A3) to 58.46% (A5), and the value average was 30.62%. Based on the fixed spray plate sprinkler data, the DCR threshold ranged from 31.15% (B3) to 42.35% (B12), and the value average was 37.93%, the CV threshold ranged from 17.22% (B10) to 40.09% (B4), and the value average was 28.53%, the DPR threshold ranged from 38.16% (B10) to 73.81% (B4), and the average value 59.02%.

3.1.2. Deposition Distribution in Circumferential Direction

Figure 7 shows the deposition distribution of eight vector directions in the citrus canopy. These results showed that the DCR of each vector direction had certain differences. Overall, the DCR of the VC and VG vector was better than that of the VA and VE vector. In the circumferential direction, the droplet distribution uniformity of two nozzle types was majorly affected by droplet size. The droplet distribution uniformity of pressure-swirl nozzles was positively correlated with spraying height under the same droplet size, while the corresponding results for the fixed spray plate sprinklers was not abruptly changed.

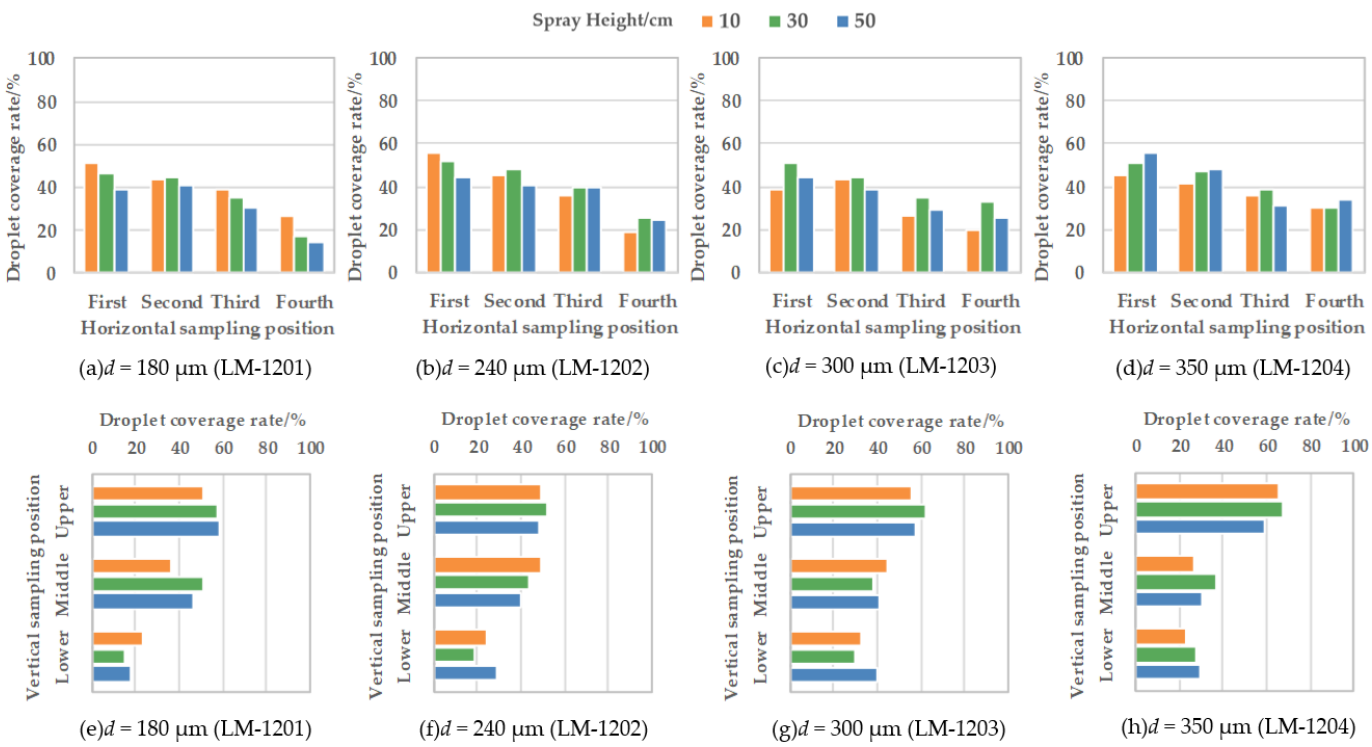

Figure 6. DCR of fixed spray plate sprinklers in citrus canopy: (**a**–**d**) represent DCR in horizontal direction; (**e**–**h**) represent DCR in vertical direction.

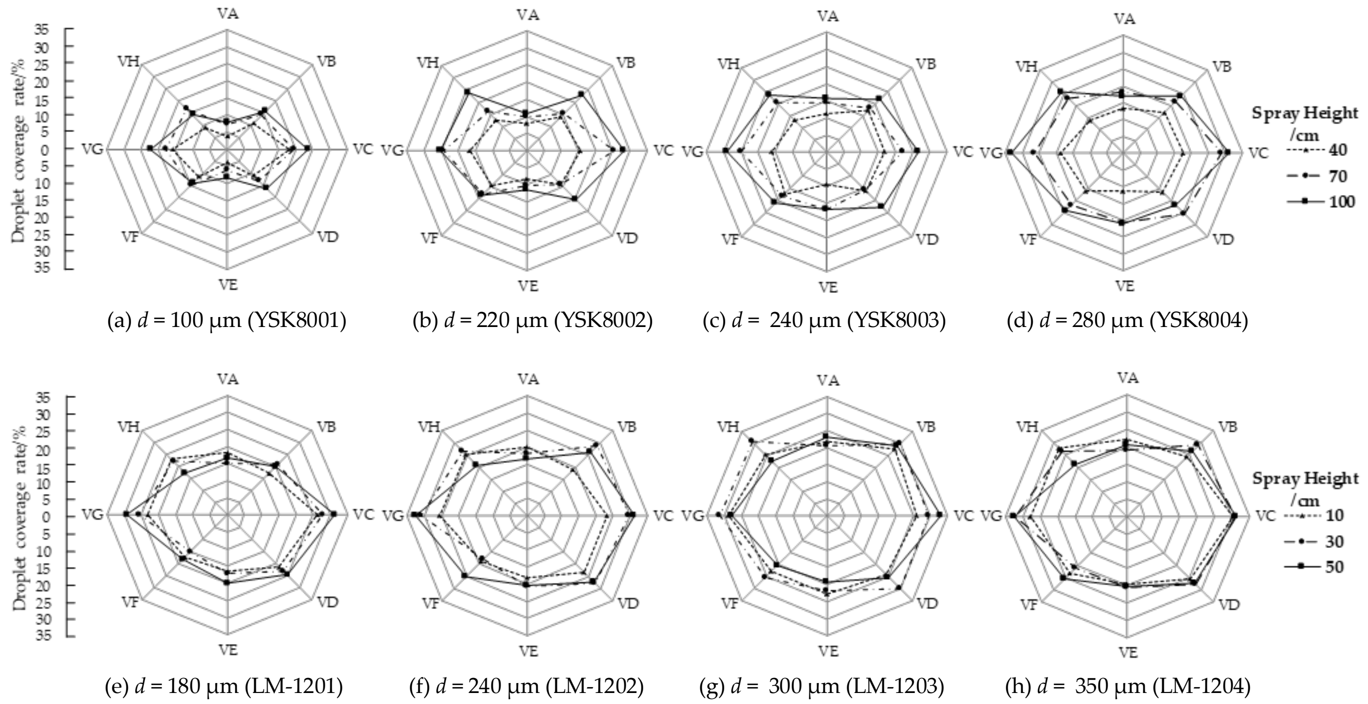

Figure 7. DCR of the eight vector directions in the citrus canopy.

3.2. Effects of Droplet Size and Spraying Height on Deposition Distribution

The ANOVA analysis results are shown in Table 4. The results from the pressure-swirl nozzle tests show that the nozzle model and spraying height had a highly significant effect on the droplet coverage ratio, CV, and DPR ($p < 0.01$); the interaction of the nozzle model and spraying height had a highly significant impact on the DCR and DPR ($p < 0.01$), while it had no significant impact on CV ($p = 0.0635 > 0.05$). According to the results of the fixed spray plate sprinklers, the nozzle model had a highly significant effect on the DCR, CV and DPR ($p < 0.01$); spraying height no significant impact on the DCR, ($p = 0.0920 > 0.05$), CV ($p = 0.3741 > 0.05$), and DPR ($p = 0.1202 > 0.05$); the interaction of the nozzle model and spraying height had a highly significant impact on the DCR and CV ($p < 0.01$), while it had no significant impact on the DPR ($p = 0.1072 > 0.05$).

Table 4. The ANOVA analysis for DCR, CV, and DPR.

Nozzle Type	Source of Variance	DCR			CV			DPR		
		df	F	*p*-Value	df	F	*p*-Value	df	F	*p*-Value
Pressure-swirl nozzles	Nozzle model	3	31.09	<0.001	3	10.57	<0.001	3	39.29	<0.001
	Height	2	27.26	<0.001	2	210.09	<0.001	2	14.46	<0.001
	Nozzle model × Height	6	13.52	<0.001	6	2.79	0.0635	6	17.77	<0.001
Fixed spray plate sprinklers	Nozzle model	3	17.56	<0.001	3	14.98	<0.001	3	14.45	<0.001
	Height	2	3.03	0.0920	2	1.02	0.3741	2	2.32	0.1202
	Nozzle model × Height	6	11.44	<0.001	6	13.25	<0.001	6	1.99	0.1072

Note: DCR denotes the droplet coverage ratio; CV denotes the droplet distribution uniformity coefficient of variation; DPR denotes droplet penetration ratio; *p*-value denotes the significance level of the factor affecting the result; $p < 0.01$ denotes that factors had a highly significant impact on test result; $p < 0.05$ denotes that factors had a significant impact on test result. Nozzle model × Height denotes the interaction of droplet size and spraying height.

The SNK analysis results are shown in Table 5. For two nozzle types, the DCR could be improved and the CV could be reduced by appropriately increasing the droplet size, and the DPR was shown to increase at the beginning and then decrease with the augment of droplet size. The spraying height was positively correlated with the DCR and CV of the pressure-swirl nozzles, while it had no significant impact on the relevant variables of the fixed spray plate sprinklers.

Table 5. The results of multiple tests.

Indicator	Pressure-Swirl Nozzles						Fixed Spray Plate Sprinklers					
	d/μm	Mean/%	SNK	*h*/cm	Mean/%	SNK	*d*/μm	Mean/%	SNK	*h*/cm	Mean/%	SNK
DCR	280	34.34	aa	100	34.30	a	350	40.77	aa	30	39.98	a
	240	32.54	ba	70	29.79	b	240	39.29	a	10	37.48	bb
	220	30.78	aa	40	27.77	c	300	35.95	bb	50	36.32	b
	100	24.84	c				180	35.70	b			
CV	100	51.25	aa	40	67.31	a	180	34.57	aa	50	30.34	aa
	220	51.09	a	100	43.33	b	240	31.71	bab	10	29.65	a
	280	45.11	bb	70	31.08	c	300	28.04	b	30	28.16	aa
	240	41.51	b				350	23.21	c			
DPR	240	40.59	aa	70	36.01	a	240	69.06	aa	50	62.22	aa
	220	36.69	a	100	31.56	b	300	65.17	bab	10	60.55	aa
	280	29.56	b	40	24.97	c	180	57.39	b	30	55.44	a
	100	16.55	c				350	45.98	c			

Note: SNK denotes the Student–Newman–Keuls method, for each dose treatment, different letters in columns indicate significant differences ($p < 0.05$); DCR denotes the droplet coverage ratio; CV denotes the droplet distribution uniformity coefficient of variation; DPR denotes droplet penetration ratio.

As shown in Table 6, the results of the LS Means comparisons showed that the spraying quality value was maxima in treatment A9 with pressure-swirl nozzles and that the spraying quality was significantly distinct from the other treatments. The spraying quality value was maxima in treatment B6 with fixed spray plate sprinklers, whereas the spraying quality had no significantly distinction from most treatments (B1, B4, B5, B8, B9, B11, and B12).

Table 6. The results of LS Means for spraying quality.

Pressure-Swirl Nozzles			Fixed Spray Plate Sprinklers		
Treatment No.	***Q*/%**	***p*-Value for A9**	**Treatment No.**	***Q*/%**	***p*-Value for B6**
A1	2.42	<0.001	B1	28.43	0.4179
A2	1.86	<0.001	B2	22.78	<0.001
A3	7.53	<0.001	B3	19.62	<0.001
A4	5.41	<0.001	B4	28.04	0.3682
A5	20.87	0.0174	B5	28.69	0.4674
A6	16.44	<0.001	B6	30.44	-
A7	4.38	<0.001	B7	25.17	0.018
A8	11.98	<0.001	B8	28.95	0.5638
A9	24.97	-	B9	28.16	0.2949
A10	5.46	<0.001	B10	24.35	<0.001
A11	13.83	<0.001	B11	27.20	0.1459
A12	20.86	0.0172	B12	27.15	0.1314

Note: *Q* denotes the spraying quality of fixed spraying system.

3.3. Control Effect of Fixed Spraying Systems on D. citri

To clarify the control effect of fixed spraying systems, we compared the effect of treatment A9 and B6 spraying, and CK on controlling *D. citri*; the investigation results are shown in Table 7.

Table 7. The investigation results of controlling *D. citri*.

Treatment	Insect Population Base/Ind.	Control Effect ± SEM/%			
		1 Day after	**3 Days after**	**7 Days after**	**14 Days after**
A5	78 ± 4.2	78.84 ± 3.64	95.85 ± 3.61	94.80 ± 6.87	73.24 ± 7.64
B6	85 ± 5.4	88.70 ± 2.71	97.83 ± 5.24	95.84 ± 4.57	85.47 ± 5.84
CK	82 ± 3.7	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0

Note: Insect Population Bases were averaged from the citrus tree of spraying area. SEM means standard error of mean.

4. Discussion

The results showed that the droplet size and spraying height had an influence on the droplet coverage ratio, CV, and DPR, but they had markedly different influence extents and trends. Analysis showed that an increasing droplet size within a certain range can improve droplet diffusion and penetration ability. However, oversized droplets lead to droplet accumulation on the upper layer of citrus canopy, which in turn reduces droplet penetration ability, which is consistent with existing studies [19,34]. Considering that the spraying angle of the pressure-swirl nozzles (80°) was significantly smaller than that of the fixed spray plate sprinklers (170°), a higher spraying height was required during the atomization process [35,36]. However, the evaporation and drift of the droplets could be increased with a higher spraying height. Fixed spray plate sprinklers would be selected when DCR, CV and DPR indicators are preferred.

Considering *D. citri* preferred to settle and feed on the upper segments of young or old leaves [37], DCR and CV should be considered as a priority. In practice, the weights of assessment indices should be adjusted according to the control needs of pests in hilly citrus orchards. For example, the weights of the DPR would be increased when droplet penetration is preferred.

Considering characteristics of diverse control, different requirements are required for different pests and diseases. Take citrus as an example; *D. citri* mainly occurs at the upper part of the canopy [37], *Colletotrichum gloeosporioides* (*C. gloeosporioides*) mainly occurs at the middle and lower part of the canopy [38,39]. Therefore, selection of suitable spraying parameters can better control *D. citri*. When controlling *D. citri*, DCR and CV should be considered as a priority, while when controlling *C. gloeosporioides*, priority should be given to increasing the DPR and the spraying volume should be larger.

5. Conclusions

In this paper, we investigated different nozzle types and nozzle positions to explore the influences of spraying quality to control *D. citri* and revealed spraying parameters for improving spraying quality. The main conclusions are as follows.

(1) For pressure-swirl nozzles, the droplet coverage ratio and distribution uniformity could be improved by appropriately increasing the droplet size and spraying height. Furthermore, the results of fixed spray plate sprinklers showed that droplet size was positively correlated with DCR, but was negatively correlated with CV. For two nozzle types, DPR increases at the beginning and then decreases with the augmentation of droplet size. In the circumferential direction, the DCR of the VC and VG vector was better than that of the VA and VE vector.

(2) The comparison results showed that the optimal treatment of pressure-swirl nozzles was A9 with a droplet size of 240 μm and spraying height of 100 cm and the optimal treatment of fixed spray plate sprinklers was B6 with a droplet size of 240 μm and spraying height of 50 cm. Overall, the spraying quality of fixed spray plate sprinklers was better and the maximum was 30.44%.

(3) The investigation results showed that the effect of spraying A9 and B6 treatments to control *D. citri* reached the maximum at 3 days after spraying and the effect significantly declined at 14 days after the treatment. The maximum effect of A9 treatment spraying on *D. citri* was 95.85%, while that of B6 treatment spraying was 97.83%. The final effect of the A9 treatment was 73.24%, while that of the B6 treatment was 85.47%. According to the investigation results, fixed spraying systems had a remarkable suppression effect on *D. citri*, and the final control effect of the B6 treatment was higher than that of the A9 treatment.

The above study provides a basis for optimizing the spraying parameters of fixed spraying systems. In the future, pest control tests of citrus trees for different pests and diseases could be conducted to verify the universality of fixed spraying systems.

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