

# Optimization of working parameters for 3MGY-200 axial air-assisted sprayer in kiwifruit orchards

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**Abstract:** Axial air-assisted sprayers can distribute pesticides efficiently in kiwifruit orchards. Because of improper parameter settings, most sprayers deliver either too much or too little pesticide. To identify appropriate sprayer parameters for kiwifruit trees, the vertical distribution profiles of the applied liquid spray were examined in this study. The effects of spray fan speed (SFS), spray pressure (SP) and spray distance (SD) on the distributions of the sprayed liquid in the vertical profiles were studied. Combined actions of the above parameters were systematically analysed using the quadratic general rotary design test method. Regression equations for the spray liquid distributions and working factors are presented. Field confirmation experiments were carried out to optimize the parameters. Data analysis showed that the optional sprayer working parameters are those of Group 3, with an SFS equal to 1900 r/min and SP equal to 3.25 MPa. The results of this study provide a reference for future applications of this type of axial air-assisted sprayer in kiwifruit orchards.

**Keywords:** sprayer parameters, quadratic general rotary unitized design, regression equation, optimization, kiwifruit tree

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## 1 Introduction

Kiwifruit are superior to other commonly consumed fruit in terms of nutrition, health benefits, and consumer appeal<sup>[1]</sup>. China's kiwifruit tree planting area was the world's largest, at approximately 230 million hm<sup>2</sup> to 250 million hectares prior to 2017<sup>[2]</sup>. In Shaanxi Province, both the planting area and output are ranked at the top worldwide<sup>[3]</sup>.

However, there have been some questions regarding the kiwifruit industry, such as its lack of dealing with major diseases and insects, and its comprehensive control and prevention technologies. Pest control is one of the industry's most influential aspects. Disease in kiwifruit orchards, including root rot, *Icerya purchasi*, and so on, can cause major destruction and have caused fruit farmers to incur serious economic losses<sup>[2]</sup>.

Pesticide spraying is an efficient way to ensure a bountiful kiwifruit harvest. A field investigation in China's Shaanxi Province showed that the two main spraying systems used for kiwifruit are knapsack sprayers and hand-carried sprayers (Figure 1) due to the special kiwifruit planting and cultivation patterns.

Air-assisted sprayers are used in kiwifruit orchards and have been found to be more conventional and efficient for the orchards' spraying needs than other types of sprayers. Nevertheless, a lack of understanding of the working parameters of these sprayers results in over-application of pesticides. This situation has increased the work difficulties of orchard workers, some of whom even died from inhaling an overdose of pesticides, and increased the input cost of orchard farmers. Therefore, an investigation of suitable sprayer parameter settings is needed.

To identify the influence of the working parameters on sprayer distributions, a vertical patternator was used to illustrate the sprayer's vertical liquid distribution. The spray distributions were affected by various factors, of which the main factors were the air-assisted form of the sprayer and the working settings of the sprayer<sup>[4]</sup>. Sprayers can be divided into three types according to air-assisted form: cross-flow, axial and sprayers with individual spouts<sup>[5]</sup>. The operational settings of the sprayers were found to affect the efficiency of the droplets directly hitting the targets. The setting parameters included fan speeds<sup>[4-7]</sup>, hydraulic pump pressures<sup>[8-11]</sup>, distances from the fan centres<sup>[8-10,12,13]</sup>, heights of the targets<sup>[6,14]</sup>, nozzle types<sup>[8,11,15]</sup>, nozzle positions and orientations<sup>[8]</sup>, driving speeds<sup>[12,16]</sup>, and so on.

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Figure 1 Orchard worker spraying with the currently used sprayers

The majority of spray distribution and deposition studies focused on pome<sup>[5]</sup>, apple and pear trees<sup>[17]</sup>, ornamental crops such as bay laurel<sup>[8]</sup>, pecan<sup>[6,18]</sup>, and potatoes<sup>[19]</sup>. Most of these study objects are trees. Kiwifruit trees are a type of vine, and some relevant vineyard studies have been conducted. Gaskin et al.<sup>[20]</sup> examined the effects of new drift-reducing adjuvants for kiwifruit orchards and assessed the potential improvements in drift mitigation at rates above 100 mL/100 L. Otto et al.<sup>[21]</sup> conducted field studies in vineyards, aiming to clearly define mitigation spray drift, using single and combined vine curtains, spray equipment and field hedgerows. The results showed that low-drift equipment reduced the minimal potential for spray drift by 38%, and hedgerows could provide a mitigation of 98%; the last row treated with or without air-assisted mitigation had drift reduction values of 70% and 74%, respectively<sup>[21]</sup>. Gil et al. developed a prototype that could apply variable-rate spray according to the various canopies along the crop rows for plant protection product application in vineyards<sup>[22]</sup>. Pascuzzi et al.<sup>[11]</sup> estimated the effects of sprayer air supply rates, flow rates, and vegetative development on foliar spray deposition in an Apulian “tendone” vineyard. Pascuzzi<sup>[23]</sup> also examined the spray patterns of two sprayer types, air-blast and mist blower sprayers, in the tendone vineyards of Apulia. The results showed that the air blower sprayer can better match the canopy profile with the spray pattern and that the mist blower sprayer had fewer drawbacks when the spray profiles were asymmetric, even if the profile was not particularly suitable to the vineyard canopy.

Furthermore, according to the results of the vine spray drift study, the spray volume and other factors were determined to affect the deposition in vineyards. The pesticides that do not reach their targets, as well as spray distribution non-uniformity, may negatively impact orchard spraying efficacy while adding environment contaminants<sup>[24]</sup>. Therefore, it is important to study pesticide spray droplet distribution in vertical profiles.

The aim of this study was to investigate the spray distributions from axial sprayers on kiwifruit trees, considering the influence of spray fan speed (SFS), spray pressure (SP) and spray distance (SD) on the vertical profiles in a commercial kiwifruit orchard in the Yangling District of Shaanxi Province, China.

This study contains three sections: (1) The effects of single factors on the vertical spray distributions are analysed; (2) A response surface experiment is conducted to establish the regression equation for parameters with vertical spray volumes, and the significant factors and interactions are analysed; and (3) Field experiments are performed to optimize parameters to determine the best working conditions.

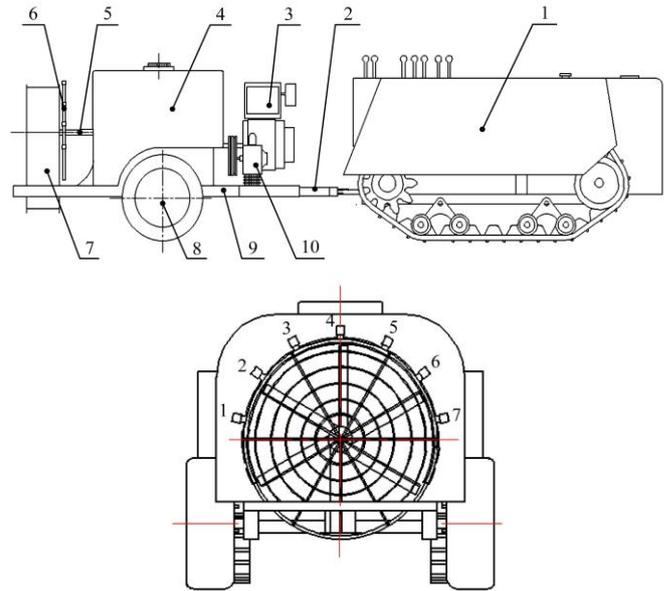
## 2 Materials and methods

### 2.1 Spray application techniques

In this study, a trial model 3MGY-200 axial air-assisted orchard sprayer (Figure 2) designed by the Northwest Agriculture and Forestry (A&F) University with independent power from an air-cooled diesel engine (Yangma Power Machinery Co. Ltd., YM186FA, Chang Zhou, China) was tested. The spray fan and hydraulic pump (German Cager, DINNER23, diaphragm pump) are driven by the engine.

The atomizer fan diameter is 0.50 m, and seven spray nozzles are bolted around the fan. The layout includes one nozzle located at the top centre of the fan arc and three on each side of the fan's vertical axis. The nozzles can change spray direction, and the number of nozzles in operation can vary. The height from the fan

centre to the ground is 0.50 m. The lowest nozzle position is 0.57 m from the ground. These functions are used to adapt to the orchard's planting pattern and spraying purpose.



1. Small remote-control hillside tractor 2. Connecting shaft 3. Air-cooled diesel engine 4. Spray tank 5. Fan main shaft 6. Nozzle group 7. Fan 8. Spray wheel 9. Sprayer frame 10. Hydraulic pump

Figure 2 Structure of the axial air-assisted orchard sprayer

The spray fan speed ranges from 0 to 2,400 r/min; the spray pressure ranges from 0 to 4 MPa. The settings are evaluated as separate application techniques. During the vertical distribution trial, the top spray nozzle and three of the nozzles facing the vertical patterator were opened, while the other three were closed. In the field experiments, according to the kiwifruit tree characteristics, five nozzles were opened, and the two nozzles positioned nearest the ground were closed to avoid wasted spray volume.

### 2.2 Vertical patterator

In this study, a vertical patterator (Model 904520, AAMS-Salvarani bvba, Maldegem, Belgium, Vliegplein 14A9991) mounted on an aluminium base with ridged water collecting trays was used to measure the liquid spray distributions at different heights for different distances between the vertical patterator and the atomizer. The back of the instrument holds 20 trays to collect the sprayed liquid, routing it through hoses to measuring glasses.

In the experiments, the sprayer was held stationary according to the principle of relative motion. The vertical patterator was driven at a speed of 1 m/s, which is similar to the sprayer's orchard speed. The height was 4 m (standard version) and the vertical distributions were measured at 1.45 m and 2.65 m, based on the kiwifruit tree canopy.

### 2.3 Other equipment

A small, remote-controlled hillside tractor developed by Northwest A&F University was used to pull the sprayer. The tractor operating speed ranges from 2.2 km/h to 4.2 km/h.

The air-cooled diesel engine PTO speed was measured using a digital tachometer, contact and non-contact dual-use table speed/line speed instrument (JIASHIFA model DT2236B; Shenzhen, China). The tachometer was placed in front of a PTO pulley with a reflective marker on the air-cooled diesel engine PTO. There is a reduction ratio of 3:2 between the engine PTO and the spray fan driven pulley, and the spray fan speed can be calculated through the ratio.

For the spray fan outlet flow characterization, measurements were taken using a digital anemometer (air velocity transducer; PEAKMETER model MS6252B; Shenzhen, China), which was placed at horizontal distances in the same plane as the spray nozzle. During the spray fan flow range study process, steel tape and a marker pen were used to measure the fan's air supply range, following the machinery industry standard (JB/T 9782-2014)<sup>[25]</sup>—General test method for plant protection machinery (in China). The temperature and humidity of the environment were also recorded by the digital anemometer prior to testing each experiment group.

**2.4 Determination of the parameters**

In this study's experiment, the parameters that were determined to influence the distribution results were SFS, SP and SD. The first two factors are the key parameters of the axial air-assisted sprayer since SD is the distance between the sprayer and the kiwifruit trees. The sprayer nozzle angles were set in a vertical profile perpendicular to the horizontal plane, as shown in Figure 3.

The spray range of spray fan was tested using the Chinese flow standard of JB/T 9782-2014<sup>[25]</sup>, as shown in Figure 3. The air range was recorded when the air speed was 2 m/s, when the injector was set to the actual height used in practice or configured to the maximum range or injection angle. The horizontal range was the maximum horizontal distance, and the maximum vertical distance was the spray range. The vertical spray range was the maximum distance between the top of the flow and the nozzle. Table 1 shows that the measured air flow spray range through three repetitions was wider when the SFS was higher. It was determined that the lowest air supply range that successfully met the kiwifruit trees' actual row spacing was an SFS of 1400 r/min. The rated speed of the sprayer fan is 2400 r/min. Therefore, the SFS range was selected to be between 1400 and 2400 r/min. The outlet area is multiplied by the air speed to obtain the spray volume. The outlet area is calculated by multiplying the length of fan outlet profile (104 cm) by the distance between the profile and the water tank (6.5 cm). The outlet air speed and air sprayer volume are shown in Table 2.

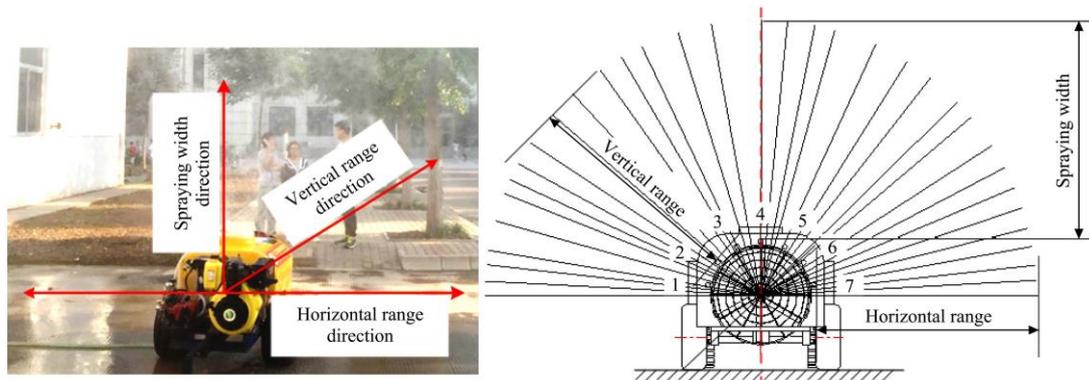


Figure 3 Measurement model of the spray

**Table 1 Measured air supply range of spray fan**

No.	Spray fan speed/r min <sup>-1</sup>	Spray range								
		Horizontal range/cm			Spraying width/cm			Vertical range/cm		
1	1100	195.1	197.1	201.9	132.8	133.3	133.8	155.55	156.05	156.85
2	1200	213.3	215.1	216.9	140.1	141.1	141.9	170.85	171.85	172.25
3	1300	221.7	222.9	225.9	143.8	144.3	144.9	175.35	176.25	176.85
4	1400	228.9	230.3	235.7	146.9	147.3	147.7	182.85	184.05	184.95
5	1500	251.1	252.7	253.9	150.8	151.3	152.3	190.05	191.65	192.95
6	1600	334.7	333.3	341.5	186	187.6	188.8	205.25	206.45	207.55
7	1700	357.7	360.5	363.9	199.2	202.3	201.1	213.95	215.95	216.25

**Table 2 The outlet air speed and air volume under different spray fan speeds**

	Spray fan speed/r min <sup>-1</sup>				
	1400	1600	1900	2200	2400
Outlet air speed/m s <sup>-1</sup>	12	14	16	20	23
Air volume/m <sup>3</sup> s <sup>-1</sup>	0.81	0.95	1.08	1.35	1.55

The spray pressure value limits were tested by the spray volumes according to the standard<sup>[25]</sup>. The spray nozzle is a fan nozzle with a ball valve (model HB4L; obtained from the Guo Haha Agricultural Machinery Co. Ltd., Shandong, China), the hole diameter is 0.5 mm and the fan spray angle is approximately 50°. The volume median diameters (VMDs, Dv0.5) were 170 μm, 130 μm and 193 μm when the spray pressures were 2.5 MPa, 3.25 MPa and 4 MPa respectively, at a distance of 1.4 m, as tested using water-sensitive paper. The spray droplets are finer when the

pressure is higher; consequently, the VMD value is lower at 3.25 MPa than at 2.5 MPa. The droplets are sprayed out at a higher speed when the pressure is 4 MPa, and droplet reunion occurs, which results in a higher VDM at 4 MPa than at 3.25 MPa. The nozzles are numbered from 1 to 7 (Figure 3). It can be seen in the figure that the spray volume increased with spray pressure and that the range of volumetric rate was approximately 1.1 L/min. The lowest pressure suggested by the sprayer manufacturer is 2.5 MPa, which corresponds to a spray volume of 1.8 L/min. The rated flow is 2.5 L/min. To study the best sprayer performance, the evaluated spray pressure range was 2.5 to 4 MPa.

The line space is from 2 m to 6 m, according to the actual planted pattern of the kiwifruit trees. However, there is not a standard planting form for kiwifruit trees planted in the Yangling District of Shanxi Province. The row spacing is determined by the orchard area. Therefore, the spray distance range between the

sprayer fan centre and vertical patternator was between 1 and 3 m in order to successfully accommodate the kiwifruit orchard’s planting pattern.

Due to the requirement of combining farming machinery with agronomy technology, the chosen spray heights were 1.45 m, 2.05 m, and 2.65 m; these heights represent the lowest average kiwifruit position, the centre of the inner branches, and the external kiwifruit tree branches, respectively.

**2.5 Experimental methods**

The independent variables’ influence on the spray vertical profile was studied at the West Agricultural Machinery Laboratory of the College of Mechanical and Electronic Engineering of Northwest A&F University on October 19, 2017. A vertical patternator was implemented in accordance with the Chinese National Standard GB/T 24683-2009<sup>[26]</sup>, as detailed in Figure 4.



Figure 4 Vertical spray distribution

First, after the location was chosen, the determined single influencing factors were examined to assess their impacts on the spray distribution when two of the factors were held constant.

Second, Table 5 presents the three-factor quadratic general rotary unitized design used in this study<sup>[27]</sup>. With this design approach, the test time can be reduced to acquire more consistent polynary quadratic regression equations in the actual results. Additionally, this design enables more consistent forecasting

precision<sup>[28]</sup>. The factors’ codes were calculated based on a quadratic general rotary unitized design method (Table 3). Three codes were assigned:  $x_1$ ,  $x_2$  and  $x_3$ , representing the SFS, SP and SD factors, respectively, which were calculated according to Equations (1)-(4). The SFS, SP and SD were the independent variables, and the spray volume used to express the vertical spray distribution was the dependent variable. In Table 5,  $Y_1$  to  $Y_3$  are indexes representing the spray liquid volume acquired by the measuring cylinder at different heights (1.45 m, 2.05 m and 2.65 m).

**Table 3 Coding table of the factors.**

Factors	SFS/r min <sup>-1</sup>	SP/MPa	SD/m
Zero level, $z_0$	1900	3.25	1
Variation radius, $\Delta j$	300	0.45	0.6
1.682	2400	4	3
1	2200	3.7	2.6
0	1900	3.25	2
-1	1600	2.8	1.4
-1.682	1400	2.5	1

The final spray experiments were carried out on October 21, 2017 (Figure 5), in the most common Yangling kiwifruit orchards. The orchard was located 1500 km from Northwest A&F University. The orchard row spacing is approximately 1.9 m, the line spacing is approximately 3.0 m, the scaffolding height is 1.85 m above the ground, and the leaf canopy thickness is approximately 0.5 m. Water-sensitive paper (WSP) (26 cm by 76 cm; Syngenta, Greensboro, NC) was fixed on the two sides of the kiwifruit leaves to capture the spray results. The arrangement of the paper on the leaves is shown in Figure 5. A red nylon rope was used along the WSP positions to identify the paper after spraying. WSP is known as an accurate paper method because its surface is coated with the chemical indicator bromophenol blue<sup>[29]</sup>, and the colour changes from yellow to blue when the paper contacts water (Figure 6). A software deposit scan was used to analyse the percentage area covered by spray on each card, and the number of droplets were counted<sup>[30]</sup>.

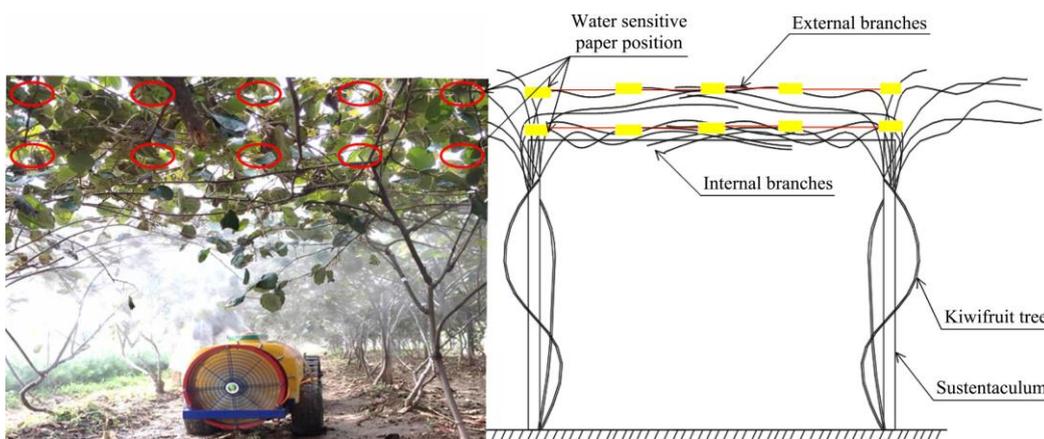


Figure 5 Field spray distribution experiment, and Water-sensitive



Figure 6 Water sensitive paper before and after use

$$x_{0j} = \frac{x_{1j} - x_{2j}}{2} = \frac{x - r_j + x_{2j}}{2} \tag{1}$$

$$\Delta j = \frac{x_{rj} - x_{0j}}{r} \tag{2}$$

$$x_{2j} = x_{0j} + \Delta j \tag{3}$$

$$x_{1j} = x_{0j} - \Delta j \tag{4}$$

where,  $x_{0j}$  denotes the factor’s zero level;  $x_{rj}$  are the highest level and  $x_{-rj}$  are the lowest levels;  $\Delta j$  represents the variation radius;  $x_{2j}$  are the higher level and  $x_{1j}$  lower levels.

The experiment was conducted in accordance with the Testing Methods for air-assisted sprayer plant protection machinery on shrubs and tree crops<sup>[26]</sup>, and each spray application was repeated three times. The spray liquid was collected when the vertical patternator passed the sprayer twice. The tubes were filled with sufficient liquid amounts collected at the different heights. The collected volume was read by placing the measuring glasses at eye level to determine the sprayer’s distribution in order to ensure that there was enough spray volume for each part of the fruit tree.

**2.6 Weather conditions**

Weather condition data were recorded during the spray distribution experiments. Field trial applications used the digital anemometer. All the climatic variables were recorded before each trial. Table 4 shows the mean weather condition values for each experiment.

**Table 4 Weather condition**

Experiment	Data	Temperature/ °C	Relative humidity/%	Wind speed/m s <sup>-1</sup>
Spray distribution	10/19/2017	21.4	61.9	0
Field spray	10/21/2017	20.3	63.1	0

**3 Results and discussion**

**3.1 Single factor test**

**3.1.1 Influence of fan speed on the spray distribution**

The impacts of the SFS on the spray distribution are detailed in Figure 7. The figure illustrates the vertical spray liquid distributions at the different SDs from the spray fan centre at the SFSs of 1400 r/min, 1900 r/min and 2400 r/min, with an SP of 3.25 MPa. According to the three charts shown below, the maximal volume did not appear with the highest SFS. However, the gathered spray volume for the different SFSs differed as the SD increased. The spray volume first increased from the distances of

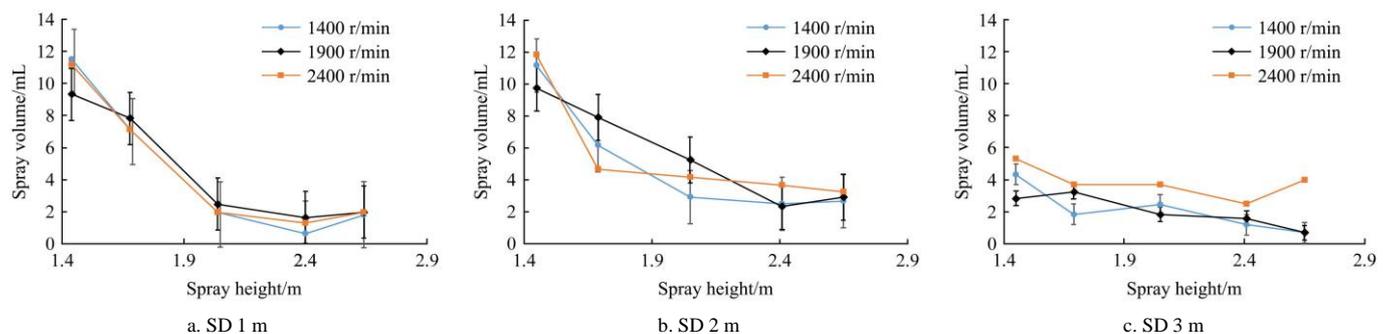
1 m (Figure 7a) to 2 m (Figure 7b) and then decreased from the SD of 2 m (Figure 7b) to 3 m (Figure 7c). The spray volume sharply decreased at a distance of 1 m (Figure 7a) and slowly decreased to 3 m (Figure 7c).

The following trend was observed: the higher the collector is, the lower the gathered spray volume is. These findings indicate that less liquid is distributed when the collecting position is higher, which is because the flow weakened and because of the action of gravity on the droplets. The reason for the lower spray volume at the 2.4 m height for a 1 m SD than for a 2 m SD is that most of the liquid is sent farther than 1 m by the air flow, and deposits more from the height of 2.4 m at a 2 m SD. The maximal spray volume is shown in Figure 7b and is approximately two times that in Figure 7c. As Figure 7a shows, the spray volume distribution was at a medium level.

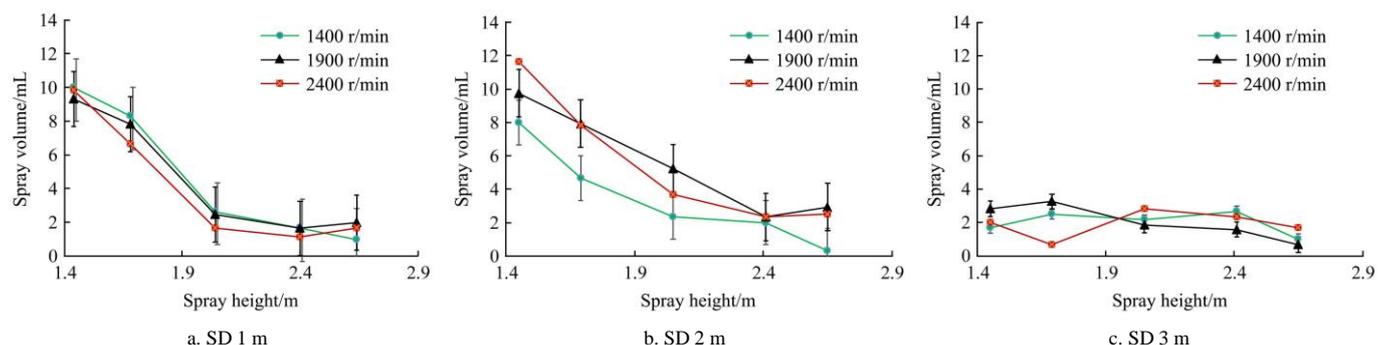
**3.1.2 Effects of spray pressure on spray volumes**

Figure 8 presents the influences of the SP on the vertical spray liquid distribution at different SDs for SPs of 2.5 MPa, 3.25 MPa, and 4 MPa, with an SFS of 1900 r/min. This study compared different SDs, as shown in Figures 8a-8c. It was found that the influences of the SP were not apparent according to each of the line graphs and that the highest pressure did not result in the maximum volume. A meaningful trend was observed between the SP and spray distribution in the vertical profile when comparing the different SDs in each plot. The trends detailed in Figures 8a-8c display an overall slowdown, which first increased slightly from the SD of 1 m (Figure 8a) to 2 m (Figure 8b) and then decreased sharply from 2 m (Figure 8b) to 3 m (Figure 8c). This finding was determined to be similar to previous related research results<sup>[31]</sup>. The trend is due to the influence of air flow.

Among the three charts, the maximum collected liquid volume at the SD of 2 m was almost four times that of the volume at the SD of 3 m, and the liquid volume shown in Figure 8a was between that of Figures 8b and 8c.



**Figure 7 Comparison of the vertical spray liquid distribution along with different SFSs at various SDs under the condition of the SP set at 3.25 MPa**



**Figure 8 Comparison of the vertical spray liquid distribution long with different SPs at the various SDs and at a SFS of 1900 r/min**

3.1.3 Effects of spray distances on spray distributions

In this study, the effect of spray distance on vertical profile spray volume distributions was evaluated at an SP of 3.25 MPa and an SFS of 1900 r/min. Figure 9 presents the results of the SD distinctive influence experiment, showing a consistent appearance from Figure 9a to Figure 9c. The collected vertical patternator

volumes at the 2 m SD were greater than those at the other two distances (1 m and 3 m). These findings confirm that the volume first increased for SDs between 1 and 2 m and then decreased for larger spray distances (between 2 and 3 m). The vertical spray volume distribution along the height was the same in Figures 7 and 8.

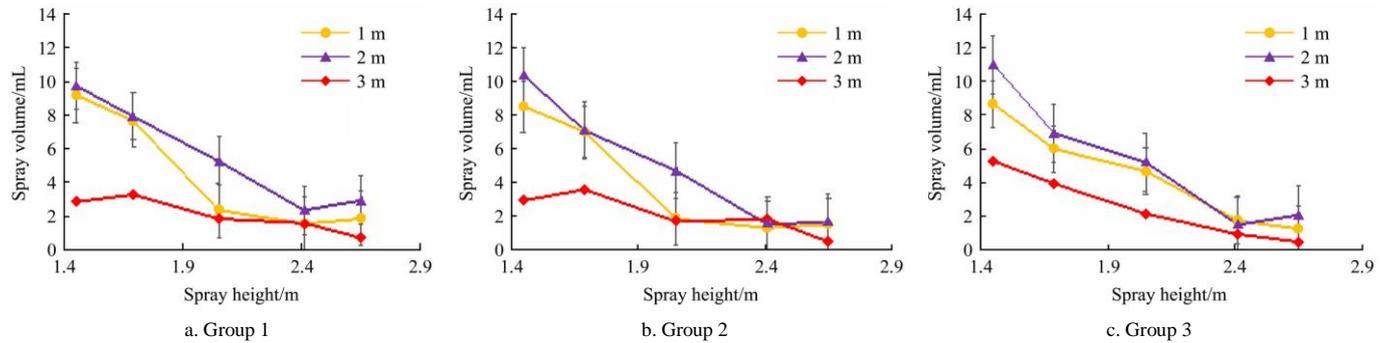


Figure 9 Comparison of the vertical spray liquid distribution at the different SDs with the same SFS and SP

3.2 Results and analysis of the response surface experimental design

The spray distribution response surfaces are shown in Figures 12 to 14. The dependent variable interactions can be analysed from the quadratic regression response surfaces. The factor significance levels are ordered as follows according to the ANOVA results: SP, SFS and SD.

3.2.1 Experimental design and results

The influences of the three operational factors on the spray volume distributions were studied. To further establish the optimal combination of the three working parameters, a quadratic regression response surface experiment was applied; the results are shown in Table 5.

3.2.2 ANOVA for the vertical spray distributions

The experimental results of spray volume distribution were analysed using Design-Expert 8.0.8 software. To obtain the optimal mathematical model, three test methods were used: sequential model sum of the squares, lack of fit tests and model summary statistics<sup>[32]</sup>. ANOVA is used to analyse the quadratic model and reveal the significance of the independent variable to the dependent variable. Table 6 shows the results of the pooled ANOVA.

Table 5 Experimental scheme and results expressed by the codes

No.	Factors			Indexes/mL		
	SFS	SP	SD	Y <sub>1</sub>	Y <sub>2</sub>	Y <sub>3</sub>
1	-1	-1	-1	4.42	1.25	0.75
2	-1	-1	1	6.53	2.25	0
3	-1	1	-1	9.17	4.42	1.5
4	-1	1	1	7.83	2.61	1.67
5	1	-1	-1	9.67	3.5	2.33
6	1	-1	1	5	2.5	2.17
7	1	1	-1	10.53	3.83	1.67
8	1	1	1	6	4.5	2.5
9	-1.682	0	0	11.17	2.92	2.67
10	1.682	0	0	11.83	4.17	3.25
11	0	-1.682	0	8	2.33	0.33
12	0	1.682	0	11.67	3.67	2.5
13	0	0	-1.682	9.17	2.33	1.83
14	0	0	1.682	2.83	1.83	0.67
15	0	0	0	9.75	5.25	2.92
16	0	0	0	10.33	4.7	1.67
17	0	0	0	9.33	3.92	2.5
18	0	0	0	11	5.2	2.08
19	0	0	0	11.42	3.62	2.08
20	0	0	0	10.83	4.417	1.75

Table 6 ANOVA for the regression models and the model terms

Source	Spray distribution: Y/mL									
	Height (1.45 m)			Height (2.05 m)			Height (2.65 m)			
	Degree of freedom	F value	p-value Prob>F	Degree of freedom	F value	p-value Prob>F	Degree of freedom	F value	p-value Prob>F	
Model	9	8.05	0.0015	9	3.98	0.021	9	4.33	0.0159	Significant
x <sub>1</sub>	1	0.88	0.37	1	4.66	0.0562	1	8.37	0.0160	
x <sub>2</sub>	1	9.19	0.0126	1	8.81	0.0141	1	8.41	0.0158	
x <sub>3</sub>	1	16.9	0.0021	1	0.52	0.4854	1	0.88	0.3692	
x <sub>1</sub> x <sub>2</sub>	1	1.39	0.2658	1	0.33	0.5790	1	3.30	0.0995	
x <sub>1</sub> x <sub>3</sub>	1	7.87	0.0186	1	0.053	0.8232	1	0.68	0.4285	
x <sub>2</sub> x <sub>3</sub>	1	0.87	0.3737	1	0.30	0.5979	1	1.59	0.2360	
x <sub>1</sub> <sup>2</sup>	1	0.0007	0.9340	1	1.98	0.1902	1	2.45	0.1489	
x <sub>2</sub> <sup>2</sup>	1	2.87	0.1213	1	5.73	0.0377	1	5.33	0.0437	
x <sub>3</sub> <sup>2</sup>	1	33.51	0.0002	1	16.51	0.0023	1	7.41	0.0215	
Lack of fit	5	4.02	0.0765	5	1.48	0.3390	5	1.57	0.3152	Not significant

Note: In the table, x<sub>1</sub> is the SFS; x<sub>2</sub> denotes the SP; and x<sub>3</sub> represents the SD.

3.2.3 Regression equation

The p-value of model was less than 0.05, which indicates that the relationships between the regression equation of the working parameters (SFS, SP, and SD) and the text indexes ( $Y_1, Y_2, Y_3$ ) were significant<sup>[33]</sup>. The lack of fit tests was determined to be non-significant. The p-values (0.0765, 0.3390 and 0.3152) were all greater than the mean value of 0.05. The proportion of abnormal error between the equation and the actual fitting is small. The relationships between the regression equation of the dependent and independent variables were found to be effective<sup>[33]</sup>. The determination coefficient ( $R^2$ ) values were 87.87%, 78.2%, and 79.58% for  $Y_1, Y_2,$  and  $Y_3,$  respectively, which indicates that the proposed model adequately represents the process. The regression equations were confirmed to have a good fit<sup>[32,34]</sup>.

The regression results are shown in Equations (5)-(7).

$$Y_1=10.50+0.32x_1+1.03x_2-1.40x_3-0.52x_1x_2-1.25x_1x_3-0.41x_2x_3+0.028x_1^2-0.56x_2^2-1.92x_3^2 \quad (5)$$

$$Y_2=4.51+0.43x_1+0.59x_2-0.15x_3-0.15x_1x_2+0.06x_1x_3-0.14x_2x_3-0.027x_1^2-0.47x_2^2-0.79x_3^2 \quad (6)$$

$$Y_3=2.18+0.42x_1+0.42x_2-0.14x_3-0.34x_1x_2+0.16x_1x_3+0.24x_2x_3+0.22x_1^2-0.33x_2^2-0.38x_3^2 \quad (7)$$

3.2.4 Normal plot of the residual analysis

The normal plot of the residuals (Figures 10a-10c) showed that 95% of the residuals fall within the confidence interval and are distributed along the line. The imitative effects of the multinomial model were estimated. The errors were found to be normally distributed<sup>[35]</sup>. Furthermore, Figures 11a-11c show that the actual values correspond to the predicted values calculated from the model. More corresponding points were predicted, and the actual values were close to the plotted line, which indicates that the model is more suitable for the regression equation. Since both plots (Figures 10 and 11) satisfied the error normality and forecasting ability standards, this study concluded that the ANOVA results catalogued in Table 4 are reasonable<sup>[32]</sup>.

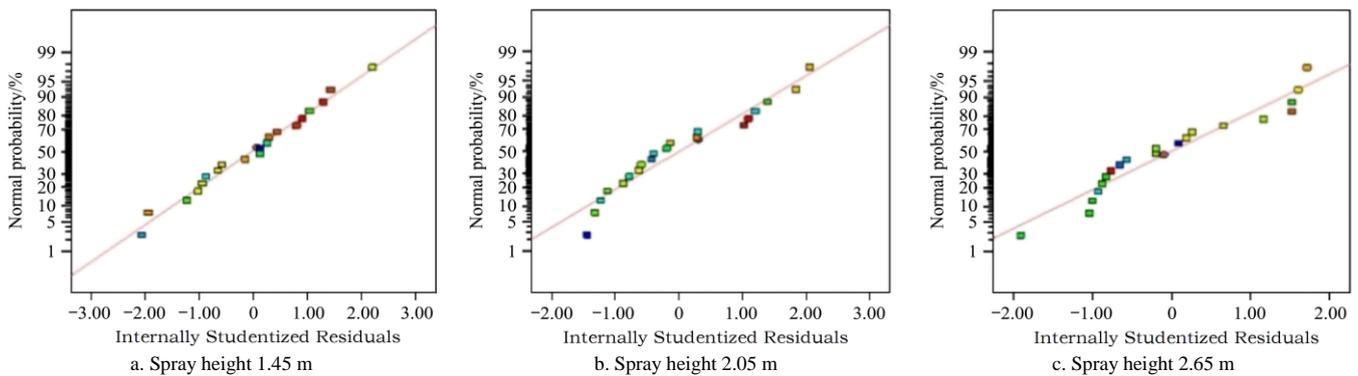


Figure 10 Normal plot of the residuals for the collected water volumes at different heights

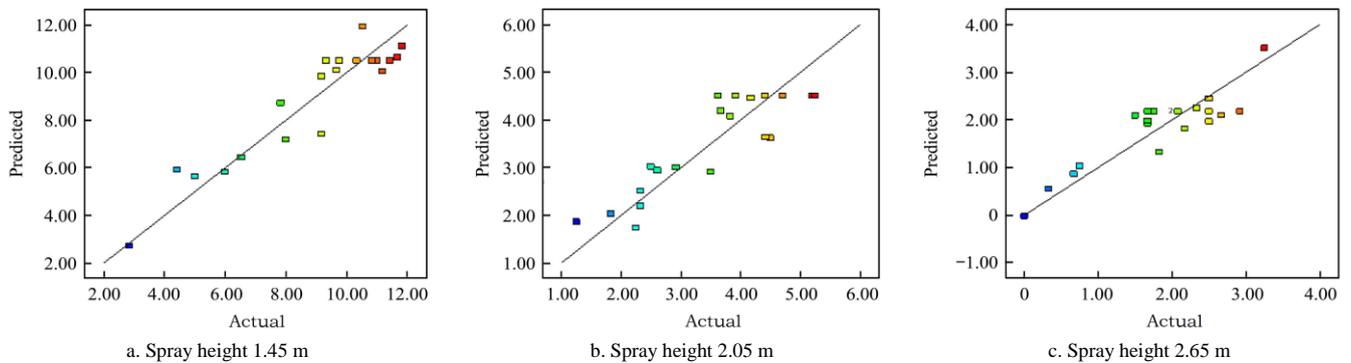


Figure 11 Plot of the corresponding relationships between the predicted and actual values of the collected water volumes at different heights

3.2.5 Response surface analysis

In this section, any two factors of SFS, SP and SD were chosen as interaction factors. The spray distribution three-dimensional (3D) response curves at heights of 1.45 m, 2.05 m and 2.65 m were analysed.

The response surface plot of Figure 12a shows the collected water volumes under the interactive influences of SFS and SP when SD was at a zero level of 2.0 m. A peak was observed on the plot when the SFS was between 1900-2050 r/min and the SP was in the range of 3.457 to 3.7 MPa. Because the plot shows that the value increased sharply with the SP, the SP had a more significant impact than the SFS on the contour map spray distribution, which corresponds with the ANOVA results shown in Table 6.

The response surface drawing is shown in Figure 12b. The Y value was observed to slowly rise before quickly falling, and the fluctuation was significant. The maximum points on the response

surface occur when the SD was between 1.5 and 1.9 m, and the SFS ranged from 1600 to 1750 r/min. It could be concluded from the counter drawing that the SD affected the water volume distributions more strongly than the SFS did, a result that is similar to the ANOVA.

The response surface map of Figure 12c details the variations in collected water with the SD and SP factors when the SFS was at its zero level of 1900 r/min. The spray distributions were found to be improved with higher values of SP and SD. However, the distributions were observed to quickly decrease when an upper limit was reached. The largest values of the spray distributions occurred when the SD was 1.55 m and 1.85 m and the SP ranged from 3.475 to 3.7 MPa. The contour plot shows that the impact of the SD on the spray distribution is more significant than that of the SP, a result that is also consistent with the ANOVA results.

The order of factor influence (from largest to smallest) is SD,

SP, and SFS when the spray height was 1.45 m, which corresponds with the ANOVA results.

Figure 13a details the spray distribution value response surface plot under the combined influence of the SFS and SP when the SD was 2.0 m. The value of the spray distribution was found to increase as the SFS and SP increased. There was a peak observed on the plot when the SFS was between 1900-2050 r/min and the SP ranged from 3.25 to 3.48 MPa.

The response surface drawing displayed in Figure 13b shows the spray distribution effects of the SFS and SD factors when the SP was 3.25 MPa. The Y value increased faster than it decreased. The maximum points on the response surface occurred when the SD ranged from 1.8 to 2.2 m and the SFS ranged from 2050 to 2200 r/min.

Figure 13c shows the variations in the collected water along with the influences of the SD and SP factors when the SFS was at its zero level of 1900 r/min. The spray distribution was found to improve with higher values of SP and SD and decreased quickly when an upper limit was reached. The maximum spray

distribution occurred when the SD was at 1.8 m and 2.2 m and the SP was between 3.48-3.7 MPa.

The effects of the three elements on the spray distribution (ordered from large to small) were  $SP > SFS > SD$  when the spray height was 2.05 m, a result that corresponds with the ANOVA results.

The response surface plot shown in Figure 14a confirms the values of the collected water volumes under the combined influences of the SFS and SP when the SD was at a zero level of 2.0 m. The spray distribution values fluctuated as the SFS and SP increased. A peak was observed on the contour plot when the SFS was between 2050-2200 r/min and the SP was approximately 3.25-3.48 MPa.

The response surface drawing shown in Figure 14b details the effects of the SFS and SD factors on the spray distribution when the SP was 3.25 MPa. The Y value was observed to fluctuate as the SFS and SD increased. A maximum point occurred on the response surface when the SD ranged from 1.8 to 2.1 m and the SFS was between 2050-2200 r/min.

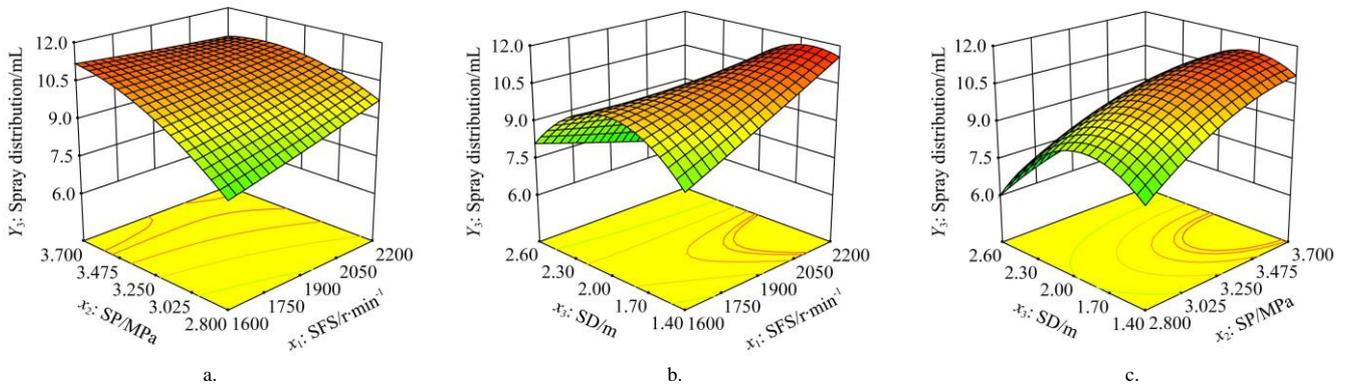


Figure 12 Interaction analysis of the influencing factors at the height of 1.45 m

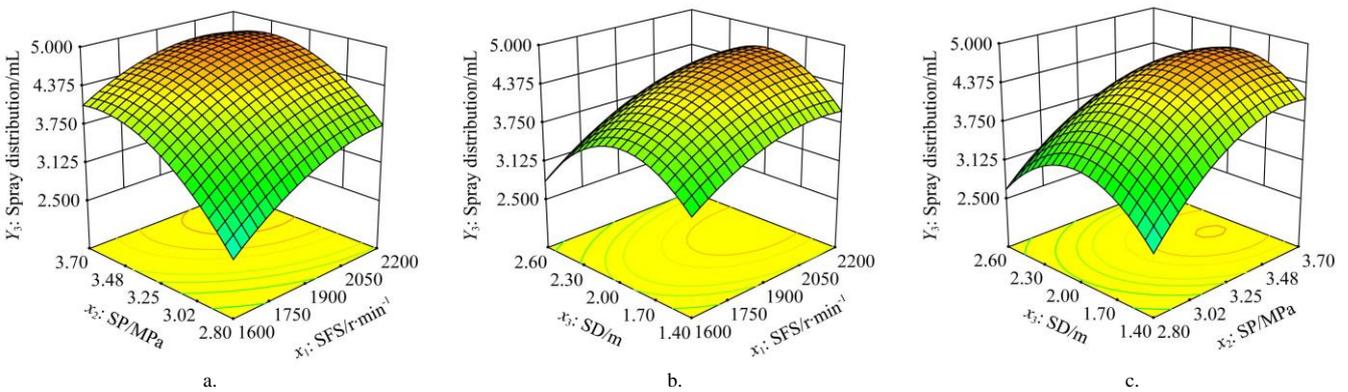


Figure 13 Interaction analysis of the influencing factors at the height of 2.05 m

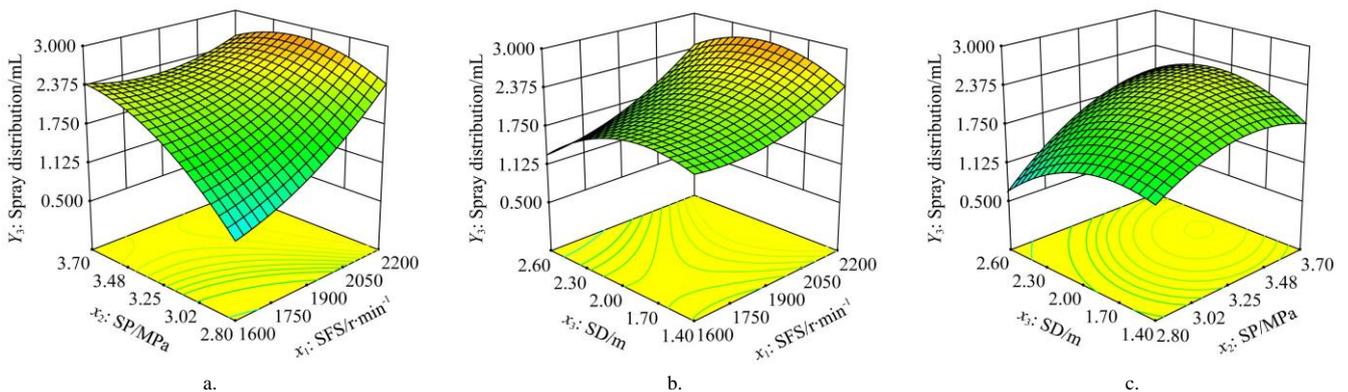


Figure 14 Analysis of the interactions of the influencing factors at a height of 2.65 m

Figure 14c displays the response surface map of the variations in the collected water volumes under the effects of the SD and SP factors when the SFS was 1900 r/min. The spray distributions improved as the values of SP and SD increased. However, the spray distributions decreased quickly when an upper limit was reached. The maximum spray distribution occurred when the SD was between 2.0-2.2 m and the SP ranged from 3.25 to 3.48 MPa.

From Figures 14a-14c, the order of the impact of factors (from large to small) was  $SP > SFS > SD$  when the spray height was 2.65 m; the results corresponded to the ANOVA results.

It was found that the spray distributions are affected by the SFS, SP, and SD in a different order at different heights. The SD had the largest influence when the height was 1.45 m but had the smallest effect at the other tested heights. Therefore, it was concluded that the SD was the least influential factor in the experimental results. In contrast, the SP was determined to have the highest influential effects on the spray distribution due to its direct influence on the spray volume<sup>[16,36]</sup>. Additionally, the SFS was found to be another important influencing factor, with the parameters determining the droplet sizes and the spray distances from the axial fan.

### 3.2.6 Optimization of the spray operating parameters

It is widely known that a higher spray volume is not necessarily better, but an appropriate dosage is necessary. In the NY/T 992-2006 standard<sup>[37]</sup>—the operation quality for an air-assisted orchard sprayer—the spray volume is required to achieve a spray deposition density of 25 droplets/cm<sup>2</sup> for a low-volume spray and 70 droplets/cm<sup>2</sup> for typical fungicides. A field experiment in a kiwifruit tree orchard was used to determine the spray volume to achieve a spray deposition density on the tree leaves.

The kiwifruit orchard characters and the WSP distribution are

described in Section 2.5. The field trial parameters were set at different levels (Table 7).

**Table 7 Field experiment parameters**

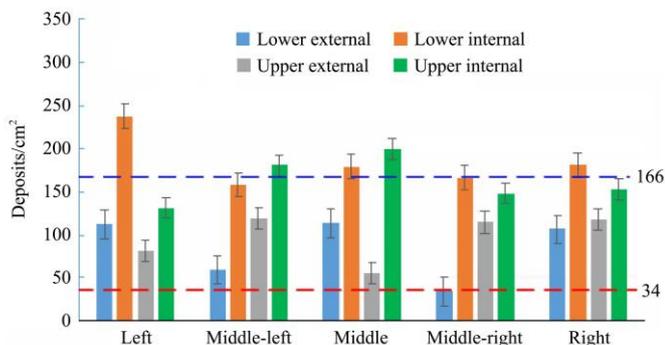
Group number	SFS/r min <sup>-1</sup>	SP/MPa
1	1600	2.7
2	1900	2.5
3	1900	3.25
4	1400	3.25

After the experiment, the WSP was collected and analysed. The spray droplets per square centimetre and the liquid diameter were analysed. The results are shown in Figures 15 and 16.

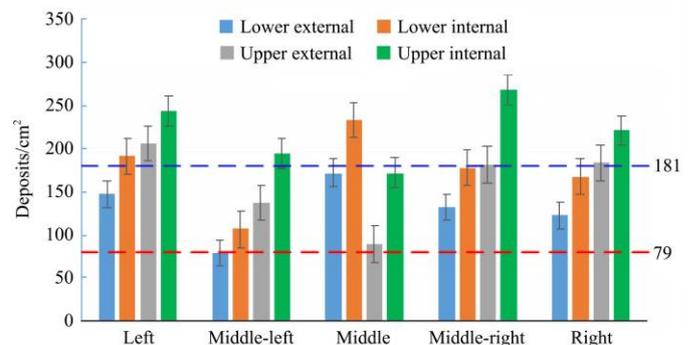
As shown in Figure 15, all data greater than 25 droplets per square centimetre satisfy the requirements of NY/T 992-2006. In group 2, the deposit distribution was more homogeneous than in group 1; the SP in group 2 was set at 2.5 MPa lower than in group 1, but the SFS (1900 r/min) was higher than 1600 r/min. Group 2 and group 3 had better spray distributions than did group 1 and group 4. For the same spray fan speed, the higher group 3 spray pressure of 3.25 MPa resulted in better uniformity. There were no differences in deposits under the spray line of 70 droplets/cm<sup>2</sup> with a common fungicide. The SFS of 1400 r/min in group 1 and SP of 3.25 MPa in group 4 decreased the uniformity; therefore, these groups are not suggested.

Figure 16 shows that group 3, with the highest SFS and SP, had the lowest droplet VMD. The droplet diameter was more uniform than that in the other groups. Compared with those in group 2 and group 4, the higher SP and SFS resulted in finer droplets. A lower SP and SFS result in larger droplet VMDs.

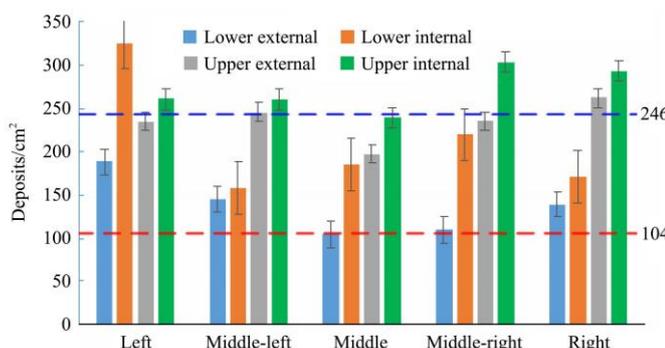
Through field experiment data analysis, the group 3 parameters (SP of 3.25 MPa and SFS of 1900 r/min) accommodate the use of different pesticides and provide suitable parameter levels.



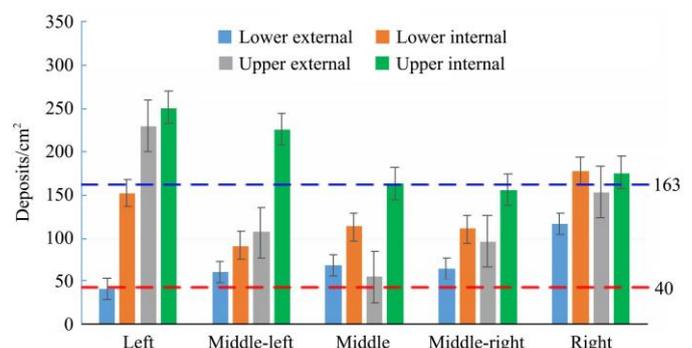
a. Group: 1, SFS: 1600 r/min, SP: 2.7 MPa



b. Group: 2, SFS: 1900 r/min, SP: 2.5 MPa



c. Group: 3, SFS: 1900 r/min, SP: 3.25 MPa



d. Group: 4, SFS: 1400 r/min, SP: 3.25 MPa

Figure 15 Droplets/cm<sup>2</sup> on the WSP with Group 1 to Group 4 in field experiments at different position of the canopy

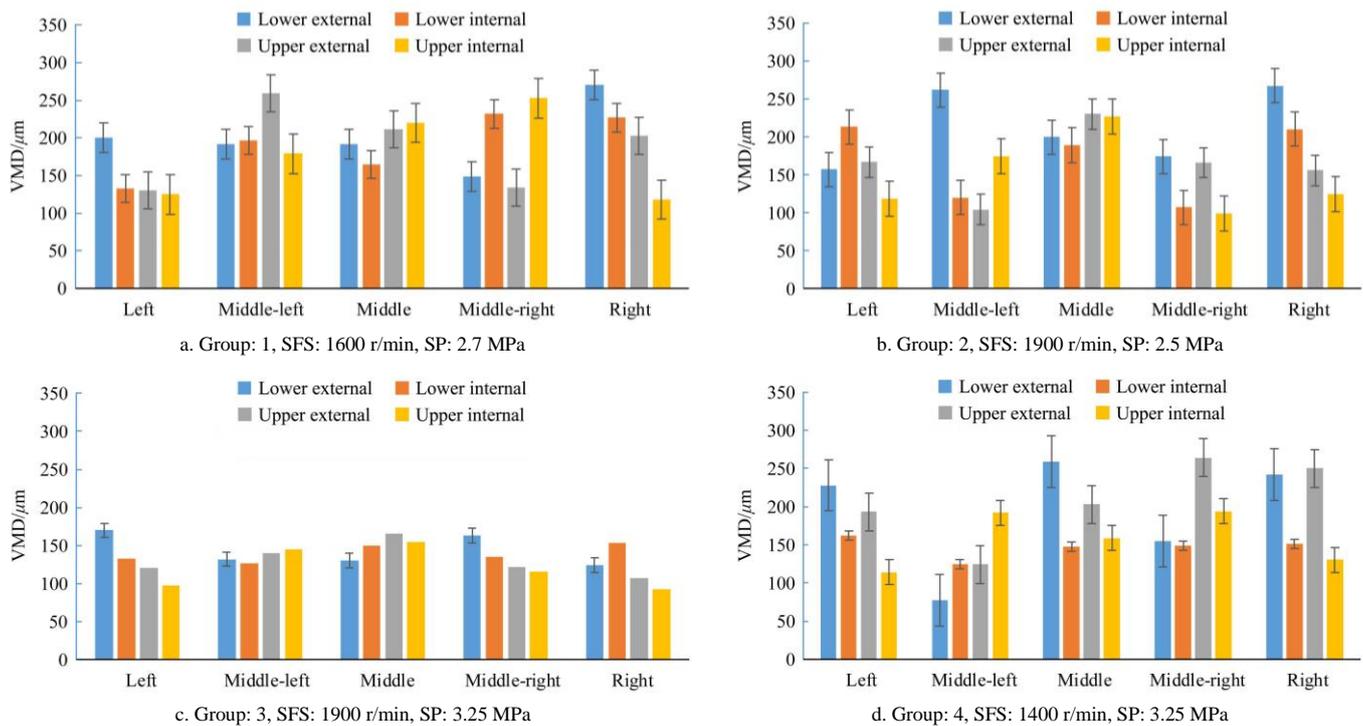


Figure 16 Droplets VMD on the WSP with Group 1 to Group 4 in field experiments at different position of the canopy

## 4 Conclusions

This research confirmed that SFS, SP and SD significantly influence the spray distributions. A response surface method was used to optimize the spraying parameters for an axial air-assisted sprayer. Approximate models for the spraying distributions at vertical profiles were constructed. The significance of the models was verified and proven to be reasonable and reliable by ANOVA. The key factor interactions were evaluated from the response surface and contour. The results show the order of significance were  $SD > SP > SFS$  at the spray height of 1.45 m and  $SP > SFS > SD$  at the spray heights of 2.05 m and 2.65 m. From the field experiments, the spray data in droplets/cm<sup>2</sup> and droplet VMD on the WSP was analysed; the optional sprayer working parameters were determined to be an SFS of 1900 r/min SP of 3.25 MPa.

In this study, the speed of the tractor was a constant at 1 km/h. However, tractor speeds may vary according to the different growth stages and years of cultivation of the kiwifruit trees. Further tests are necessary for more effective analyses of the sprayer depositions and spray drift in different kiwifruit groves. In-depth assessments of these axial air-assisted sprayers can potentially reduce not only labour costs but also the costs related to orchard spraying in general.

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