agriculture

Article

Influence of Spray Control Parameters on the Performance of an Air-Blast Sprayer

Yaohua Hu [1], Huanbo Yang [2], Bingru Hou [2], Ziting Xi [2] and Zidong Yang [1,*]

[1] College of Optical, Mechanical and Electrical Engineering, Zhejiang A&F University, Hangzhou 311300, China
[2] College of Mechanical and Electronic Engineering, Northwest A&F University, Xianyang 712100, China
* Correspondence: 20150032@zafu.edu.cn

Abstract: Orchard plant protection machinery in China still has a low application efficiency. Air-blast sprayers represent the primary development direction of pesticide applications in orchards. The spray control parameters have to be matched to the tree canopy status to achieve precise results. In this study, a vertical patternator was used to determine the accuracy of spraying fruit trees. The influences of three control parameters (blower speed, spray angle, and spray distance) on the spray performance of the air-blast sprayer were analyzed, and the volume of the spray was measured in collection plates at different heights. The quantitative relationship between the overall collection volume and the critical height collection volume was obtained for different parameter values, and the combined effects of any two control parameters on the collection performance and the position of the optimum collection area were obtained. The regression model describing the relationship between the collection volume in the critical height range and the three factors was established, and the main effects of the control parameters were determined. The results showed that if one parameter remained constant, the correlation between the other two parameters was non-significant. The collection volume in the critical height range increased initially and then decreased as the spray distance increased. The maximum collection volume was obtained at a spray distance of 1.762 m. The regression model can be used to obtain the optimum values of the parameters.

Keywords: air-blast sprayer; precision spraying; spray control parameter; three-factor regression analysis

check for updates

Citation: Hu, Y.; Yang, H.; Hou, B.; Xi, Z.; Yang, Z. Influence of Spray Control Parameters on the Performance of an Air-Blast Sprayer. *Agriculture* **2022**, *12*, 1260. https://doi.org/10.3390/agriculture12081260

Academic Editors: Muhammad Sultan, Redmond R. Shamshiri, Md Shamim Ahamed and Muhammad Farooq

Received: 12 July 2022
Accepted: 12 August 2022
Published: 19 August 2022

1. Introduction

The development of orchards in China ranks first in the world in terms of area and yield, but economic losses caused by diseases and insect pests are substantial. The effective control of diseases and insect pests in orchards can recover nearly 10% of economic losses [1–3]. At present, the control of diseases and insect pests has primarily relied on chemical pesticides, which are sprayed 8–15 times annually during the growth cycle of apple trees. The workload accounts for about 30% of the total workload of fruit tree management [4–6]. However, most orchard spraying operations use backpack sprayers and frame-mounted sprayers with low spraying efficiency [7–9]. In addition, spraying causes environmental pollution and affects the quality and competitiveness of Chinese agricultural products [10–12]. Air-blast sprayers have a strong flow generated by a blower to penetrate the dense fruit tree canopy; this ensures that the pesticide can reach most parts of the leaves, and the utilization rate of the pesticide is 30–40% [13–16].

The existing orchard spraying equipment does not meet the requirement of accurate detection and spraying on demand, which is a common problem in the world at present [17]. In order to achieve the effect of pest control, excessive spraying is mostly used in actual operation, which leads to a large number of chemical pesticide residues, seriously polluting the ecological environment and threatening the safe production of fruits [18]. Therefore, it will be helpful for the development of orchard spraying machinery to study the intelligent control technology of spraying amount, in order to realize the target variable spraying and the control method of wind variable to realize the on-demand air supply. The existing spraying control technologies mainly include: the total dosage control pipeline method, and the independent dosage control nozzle method. The total dosage control pipeline method can use the flow sensor to monitor the spraying quantity in real time, and use the electric regulating valve to change the spraying pressure of the pipeline according to the spraying demand, so as to control the spraying quantity. The existing control methods mainly include hysteresis switch control [19], classical PID control [20,21], fuzzy control [22–24] and artificial neural network [25]. In the independent control spray nozzle method, spray nozzles with different flow rates are arranged at different heights to realize different spray amounts. In order to control the nozzle flow, a proportional valve can be added in the front section of the nozzle, and the nozzle flow can be regulated by adjusting the opening of the proportional valve in real time [26–33].

Air-blast sprayers have the advantages of good spray performance, low cost, high efficiency, and low labor intensity; therefore, they are the primary development direction of pesticide applications in orchards [34–39]. In recent years, many researchers worldwide have focused on optimizing the spraying parameters according to the crop canopy status to increase the pesticide utilization rate of air-blast sprayers and improve the precision of spraying technology. In Refs. [39–41], different blower speeds were tested to investigate the influence of the airflow on the collection volume. Farooq & Landers [42] analyzed the wind field of an air-blast sprayer and adjusted the spray distance to achieve the desired effect. He et al. [43] determined the effect of wind speed on the collection volume of the pesticide. The results showed that the penetration and collection volume in the canopy were positively correlated with the wind speed. Lü et al. [44] tested different levels of spray pressure, blower outlet wind speed, driving speed, and sampling height to determine the influence of the parameters of the air-blast sprayer on the collection volume and pesticide distribution. Reichard et al. [45] presented the air velocity distribution of an air-driven orchard sprayer at different driving speeds in the open field and in the peach orchard. With the change of driving speed, the airflow velocity distribution had no significant change, but the tree structure and natural wind speed had a certain influence on the auxiliary airflow velocity. As the distance between the monitoring point and the nozzle outlet increased, the airflow speed decreased rapidly, and the decreasing rate depended on the airflow rate. By establishing a mathematical model, Fox [46,47] calculated the energy of airflow velocity at different positions in the air jet field and estimated the power requirements for designing an axial-flow air-fed sprayer. At the same time, they also simulated the deflection of the auxiliary airflow under the influence of the natural wind speed and the speed of the sprayer, pointing out that the narrower the width of the airflow outlet, the more significant the deflection of the airflow path. Fox and Svebsson [48–50] showed that the combination of two fans with transverse airflow formed a constant airflow organization to improve airflow penetration in low apple trees.

In these studies, the effects of various control parameters on the amount of pesticide at different heights of the canopy were not investigated. In addition, no regression models have been developed to describe the relationship between manually controlled parameters and the spray height.

The blower speed, spray angle, and the distance from the sprayer to the canopy have to be matched to the tree canopy conditions to reduce spray drift. Therefore, the objectives of this study are (1) to analyze the influence of single control parameters on the collection volume of pesticide at different heights; (2) to determine the influence of any two control parameters on the collection volume; (3) to assess the influence of three control parameters on the collection volume at the critical height and establish a regression model; (4) to provide a strategy for precise spray control based on the optimization of the control parameters.

2. Materials and Methods

2.1. Materials and Equipment

The experiment was performed on 20 May 2021 outside of the Agricultural Machinery Laboratory of the College of Mechanical and Electronic Engineering at Northwest A & F University. The daily ambient temperature was 27 ± 1 °C, and the relative humidity was 73%; the influence of wind was negligible.

The equipment used in the experiment included a vertical patternator with a guide rail (Salvarani BVBA, AAMS Company, Maldegem, Belgium); a lead-acid battery (NP-12-24, Ruiwu Electric, Shanghai, China); a tape measure (A5, Aicevoos, Wuhan, China); and an air-blast sprayer (self-developed).

There were 20 collection plates in the vertical patternator, numbered 1–20, as shown in Figure 1. The 20 collection plates were positioned intwo columns (left and right), with odd-numbered plates on the left and even-numbered plates on the right. The height range of plate 1 was 225–425 mm, and that of plate 2 was 450–650 mm. Each board was 200 mm tall, and the distance between the boards was 225 mm. The height parameters of the collecting plate of the vertical distributor are shown in Table 1.

Figure 1. Experimental equipment and experimental ground.

Table 1. The height parameters of collecting plate of vertical distributor.

Number	Height Range (mm)	Number	Height Range (mm)	Number	Height Range (mm)	Number	Height Range (mm)
1	225–425	6	1350–1550	11	2475–2675	16	3600–3800
2	450–650	7	1575–1775	12	2700–2900	17	3825–4025
3	675–875	8	1800–2000	13	2825–3025	18	4050–4250
4	900–1100	9	2025–2225	14	3150–3350	19	4275–4475
5	1125–1325	10	2250–2450	15	3375–3575	20	4500–4700

The vertical patternator was powered by matching lead-acid batteries and achieved a constant speed of 1 m/s on the guide rail; the length of the guide rail was 6 m. A liquid pump was used in the experiment. The sprayer used in the experiment was a self-developed sprayer (2.75 m × 1.15 m × 1.16 m) with 5 sprinklers (TR80, Lechler, Metzingen, Germany) on one side. The parameters of the sprinkler and liquid pump are shown in Table 2. The spray head was installed on a rotating plate, and the angle of the spray head changed as the plate rotated. An axial-flow fan (SFG4-4, Shanghai Zaize Electric Machinery Factory, Shanghai, China) with 3000 r/min maximum speed was used. The axis of the blower was parallel to the face of plates, and the distance from the ground to the axis was 780 mm.

Table 2. The parameters of main experimental equipment.

Project	Sprinkler	Liquid Pump	Axial-Flow Fan
Diameter (mm)	57	130	415
Length (mm)	155	290	331
Working flow (m^3/h)	0.04–0.96	2400	5870
Working pressure (bar)	0.25	1.70	1.49
Range (m)	2.50–10.70	—	—
Angle adjustment	0–180°	—	—
Power (W)	—	400	550
Voltage (V)	—	220	220

2.2. Experimental Methods

The influence of the spray control parameters on the collection volume was analyzed. The blower speed (N), the spray angle (W), and the spray distance (L) were the control parameters. In this research, it was 0° when the sprinkler was horizontal to the ground, and the counterclockwise direction was the positive direction of the sprinkler movement. The spray angle was controlled by changing the angle of the rotating plate using a stepper motor, the blower speed was controlled by a hydrostatic device (a speed of 2000 r/min), and the spray distance between the axis of the blower and the axis of the vertical patternator was controlled by moving the blower; the distance was measured with a tape. The control parameters were selected based on previous investigations, a literature review, and the requirements of practical applications. The plates were rotated by controlling the variables and using bilateral spraying of the air-blast sprayer. All the experiments were conducted five times, and the average was obtained. The experimental data of this research would be imported into Origin 2018 for a data analysis and graph drawing.

3. Results and Discussion

3.1. Single-Factor Analysis of Spray Control Parameters for All Collection Plates

Figure 2 shows the relationship between the blower speed and the collection volume for constant values of the spray angle (45°) and the spray distance (1.0 m). Figure 3 shows the relationship between the spray angle and the collection volume for constant values of the spray distance (1.5 m) and blower speed (2400 r/min). Figure 4 shows the relationship between the spray distance and the collection volume for constant values of the spray angle (45°) and blower speed (2400 r/min).

The middle of the tree crown is the crucial target area for spraying; therefore, the collection volumes obtained at heights of 1.35–1.55 m are of primary importance.

As shown in Figure 2, as the blower speed increased from 2000 r/min to 2800 r/min, the collection volume at high heights increased gradually, whereas that at low heights decreased. The total collection volume increased from 532 mL to 627 mL, and that at the height of 1.35–1.55 m decreased from 123 mL to 72 mL.

Figure 3 shows that, as the spray angle increased from 45 ° to 85 °, the collection volume of the lower and middle heights decreased and that of the high heights increased; the total collection volume increased from 592 mL to 653 mL and that at the height of 1.35–1.55 m decreased from 151 mL to 73 mL.

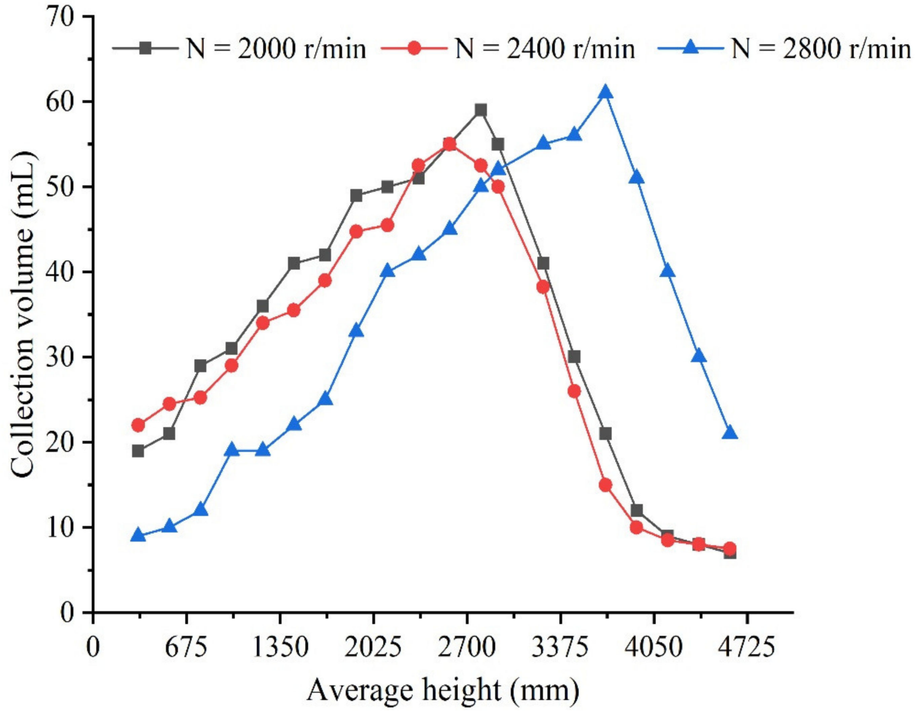


Figure 2. Influence of blower speed on the collection volume (W = 45 °, L = 1.0 m).

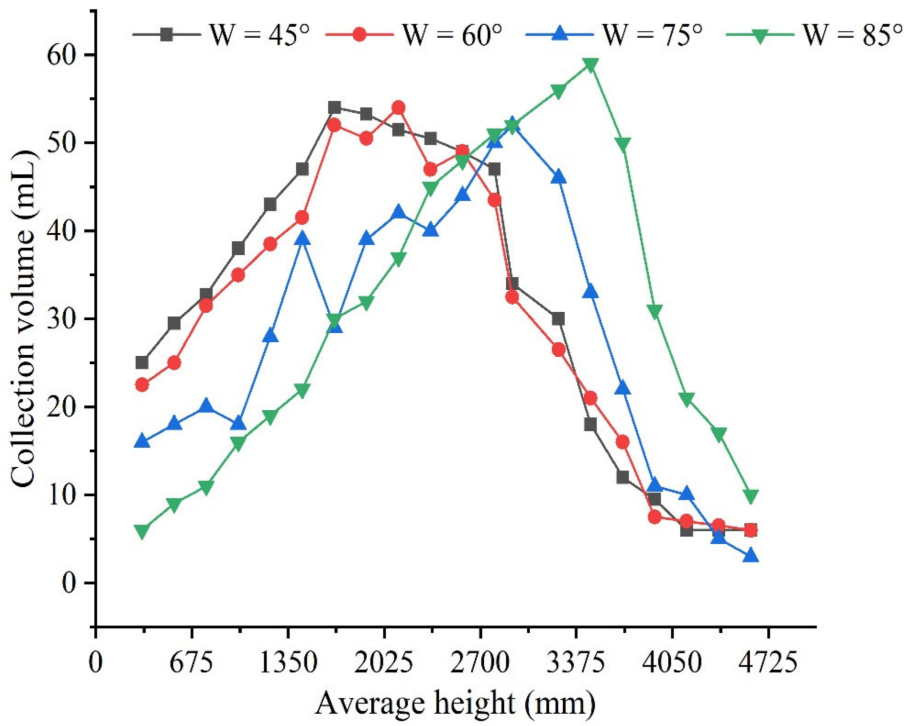


Figure 3. Influence of spray angle on the collection volume (N = 2400 r/min, L = 1.5 m).

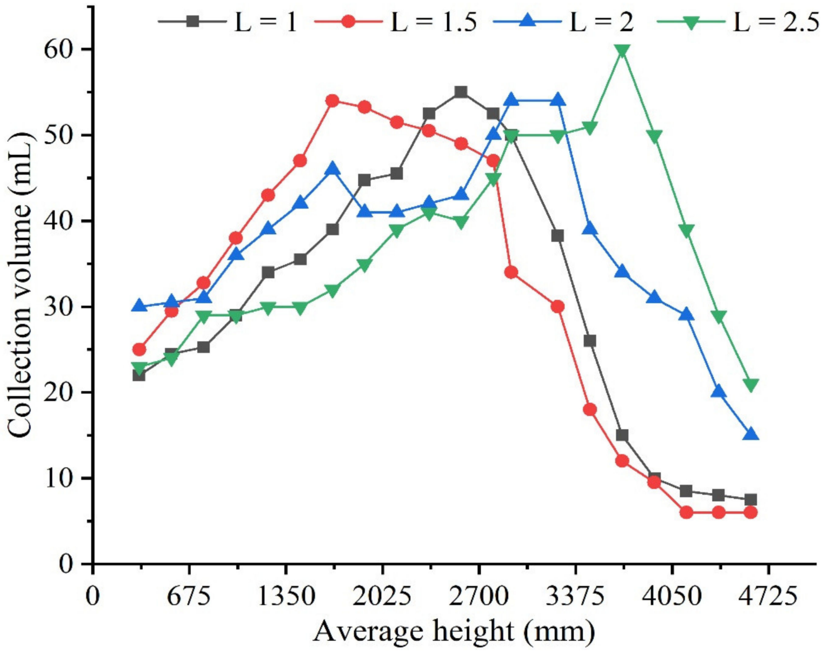


Figure 4. Influence of spray distance on the collection volume (W = 45 °, N = 2400 r/min).

As shown in Figure 4, as the spray distance increased from 1.0 m to 2.5 m, the collection volume of the middle heights increased; the collection volume of the high and lower heights decreased and reached the peak value at a spray distance between 1.5 m and 2.0 m. Then, as the distance increased further, the collection volume of the low heights increased, and that of the high and middle heights decreased. The total collection volume increased from 584 mL to 576 mL, and that at the height of 1.35–1.55 m decreased from 110 mL to 76 mL.

In summary, it is concluded that when the other two factors remain unchanged, the increase in the blower speed and spray angle results in an increase in the collection volume, but the collection volume differs for different heights. When the blower speed increased, the collection volume was larger at high heights and lower at the middle and lower heights. With an increase in the spray angle, the collection volume was larger in the upper plates and lower in the middle and lower plates.

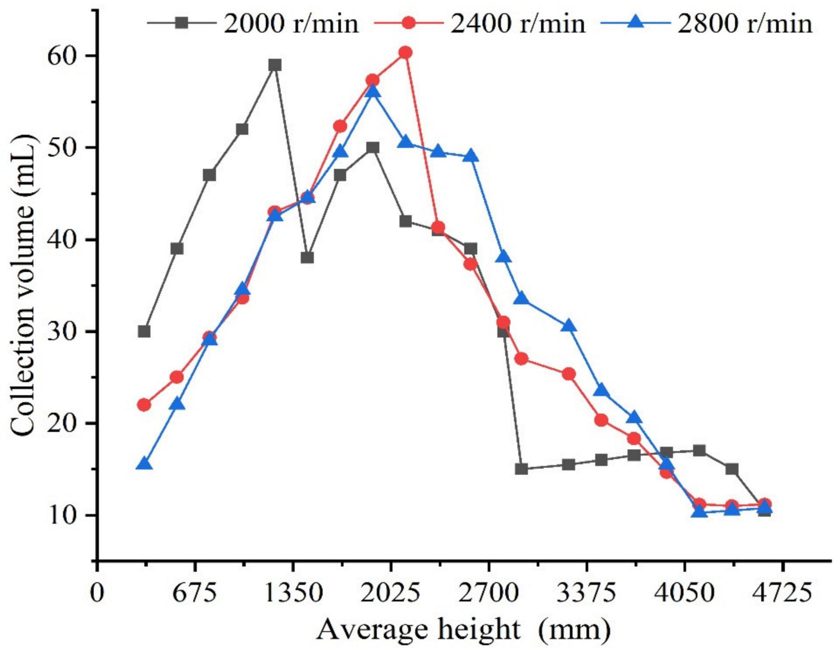
Due to the parabolic trajectory of the droplets, the spray distance affects the collection volume; at a relatively short spray distance, an increase in the spray distance increases the collection volume at higher and middle heights. However, when the spray distance is relatively large, the collection volume is larger at high heights and lower at low heights.

3.2. Two-Factor Analysis of the Spray Control Parameters

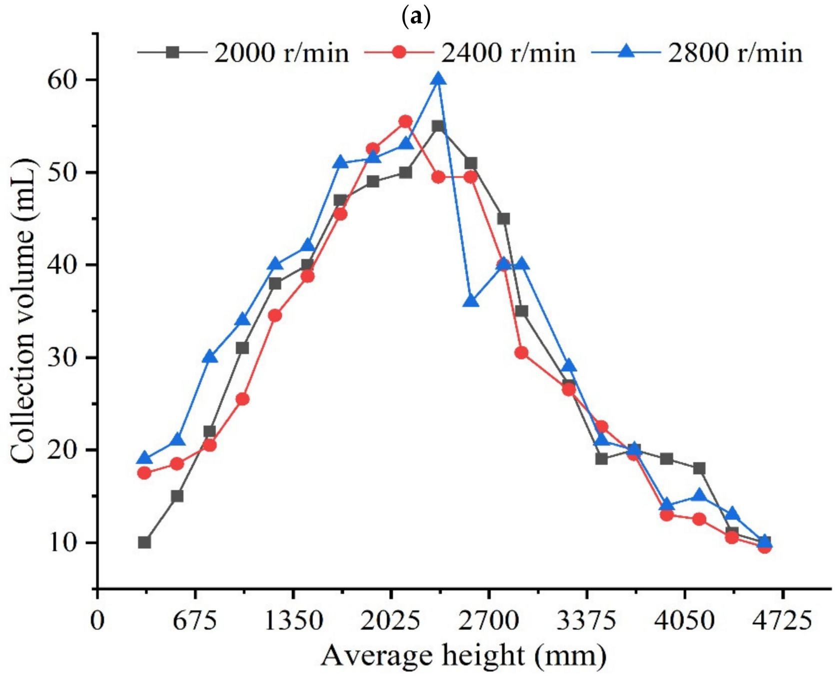
The average height range of 0.325–3.25 m was selected for the two-factor analysis because it provided a good representation of the changes in the collection volume, as shown in Figures 2 and 3.

In this experiment, the spray distance was 1.0 m, and the spray angles were 60° and 75°. As shown in Figure 5a,b, when the spray angle and blower speed both increased, the peak of the curve moved to the right. When the blower speed increased and the spray angle decreased, the peak moved to the right, the peak value was higher, and the curve was more even.

In practical applications, when the blower speed and spray angle both increase, the collection volume is higher in the upper part of the tree crown, but the overall collection volume does not change. When the spray angle increased and the blower speed decreased in the experiment, the optimum spray area moved to the higher height, but the collection volume was low; in the other plates, the collection volume was higher and exhibited fewer fluctuations.



(**a**)



(**b**)

Figure 5. Influence of the blower speed on the collection volume at different spray angles (L = 1.0 m). (**a**) Influence of the blower speed on the collection volume (W = 60°). (**b**) Influence of the blower speed on the collection volume (W = 75°).

Figure 6 shows the influence of the spray distance on the collection volume at different blower speeds (2400 r/min and 2800 r/min) for a spray angle of 60°. The results shown in Figure 6a,b indicate that at a constant spray angle, when the blower speed and the spray distance increased, the peak of the curves moved to the right and increased slightly. The rate of increase was unchanged, and the rate of increase became higher while the collection volume of the lower collection plate decreased.

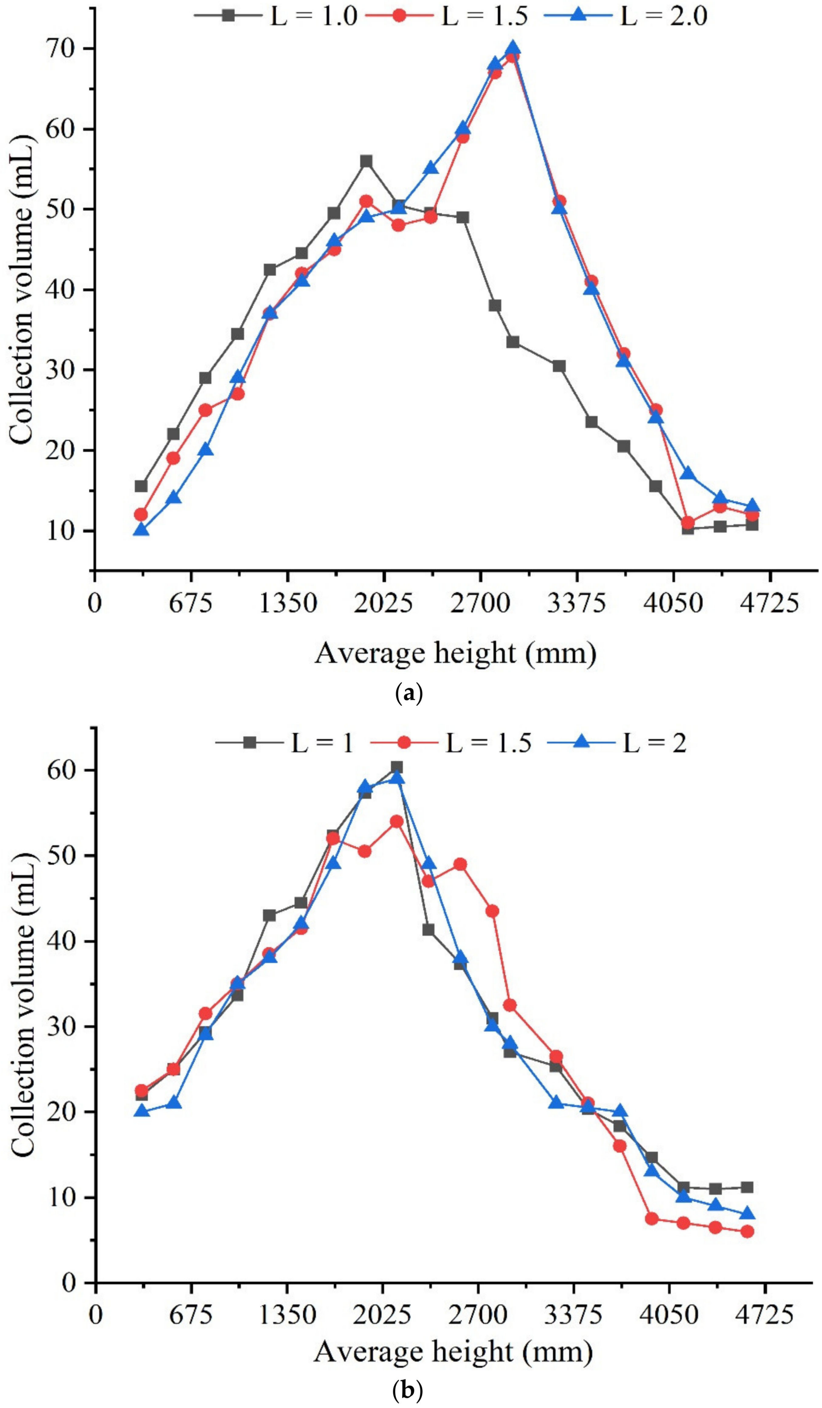
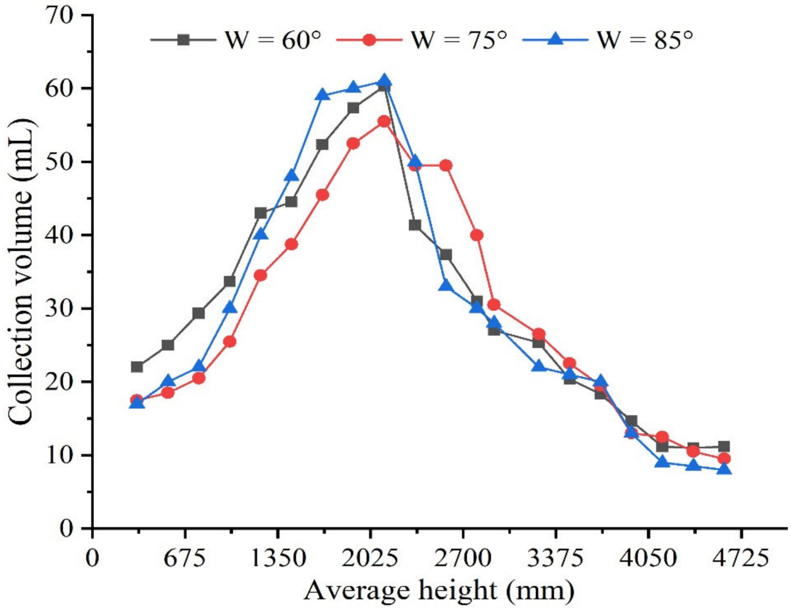


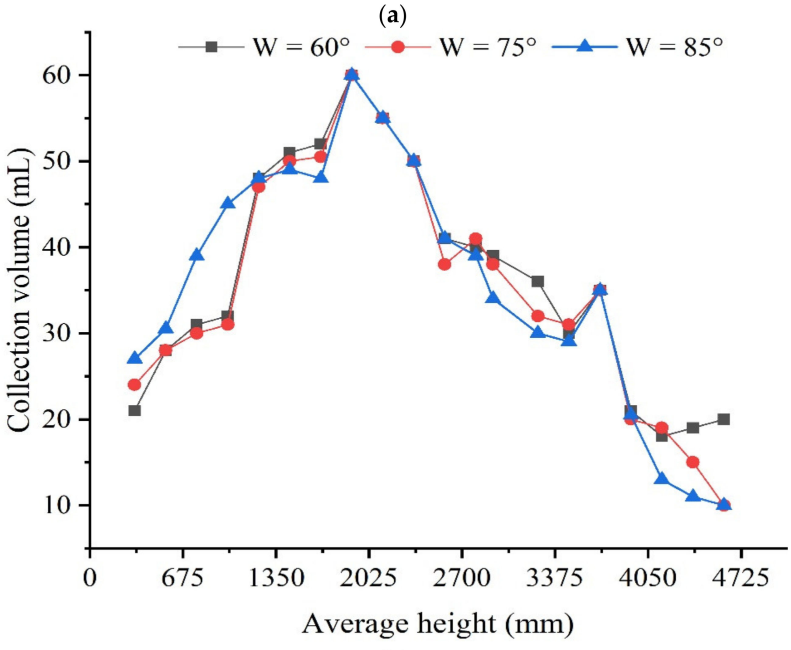
Figure 6. Influence of the spray distance on the collection volume at different blower speeds (W = 60°). (**a**) Influence of the spray distance on the collection volume (N = 2800 r/min). (**b**) Influence of the spray distance on the collection volume (N = 2400 r/min).

When the blower speed increased, the spray distance decreased, and the peak of the curve moved to the right and increased slightly; the increase range decreased first and then increased with the decrease in the spray distance. In practical applications, when the blower speed and spray distance both increase, the collection volume increases, and the optimum spray move upward in the tree crown. In the experiment, the collection volume was slightly higher in the optimum collection area. It did not change, whereas the collection volume decreased in the lower part of the tree crown, and the variability of the collection volume increased as the blower speed increased. At a small spray distance, the optimum collection area occurred at a greater height, and the collection volume was slightly higher; the range of improvement increased first and then decreased with the increase in the spray distance.

Figure 7 shows the influence of the spray angle on the collection volume at different spray distances (1.0 m and 2.0 m) and a blower speed of 2400 r/min. Figure 7a,b show that as the spray angle and spray distance increased, the maximum spray volume remained unchanged, and the peak decreased slightly. The collection volume of the lower collection plates first decreased and then increased. As the spray angle increased, the spray distance decreased, the peaks increased slightly, and the increase range first decreased and then increased with a decrease in the spray distance.



(**a**)



(**b**)

Figure 7. Influence of the spray angle on the collection volume at different spray distances (N = 2400 r/min). (**a**) Influence of the spray angle on the collection volume (L = 1.0 m). (**b**) Influence of the spray angle on the collection volume (L = 2.0 m).

In practical applications, this would mean that when the spray angle and spray distance increased, the collection volume and the optimum spray area would not change. In the experiment, the collection volume of the optimum collection area decreased, and the collection volume of the lower part of the tree canopy first decreased and then increased with an increase in the values of both parameters. As the spray angle increased, the spray distance decreased, and the collection volume decreased. The optimum collection area did not change, and the collection volume of the optimum collection area increased with the range of improvement, increasing first and then decreasing with an increase in the spray distance.

In summary, it can be concluded that when one of the parameters remained unchanged, the influence of the other two parameters was relatively small. An increase in the blower speed and spray angle were, respectively, the primary and secondary reasons for the upward movement of the optimum collection area. As the blower speed and spray angle increased, the collection efficiency of the optimum collection area remained unchanged; as the blower speed increased, and the spray distance decreased, the collection volume of the optimum collection area decreased. The spray distance had little effect on the position of the optimum collection, and the collection volume of the optimum collection area first increased and then decreased with the increase in the spray distance. The collection volume was higher at lower heights and lower at higher heights.

3.3. Three-Factor Analysis of the Control Parameters of the Key Collection Plates

The literature [10–12] indicates that the crown height of apple trees in the young fruit stage is about 2.5–3.5 m; the middle part of the crown is the spray target area. The results of the two-factor analysis showed that the collection volume was stable in the range of 1.35–1.55 m. Therefore, the collection volume in this range was selected as the dependent variable, and the spray angle, spray distance, and blower speed were used as the independent variables in the regression.

Figure 8 shows the influence of the three control parameters blower speed, spray angle, and the spray distance on the collection volume. The results show that due to the parabolic trajectory of the droplets, the increase in the spray angle and the spray distance will cause the collection volume in the range of 1.35–1.55 m to decrease, and the increase in the blower speed will increase the collection in the range of 1.35–1.55 m to some extent.

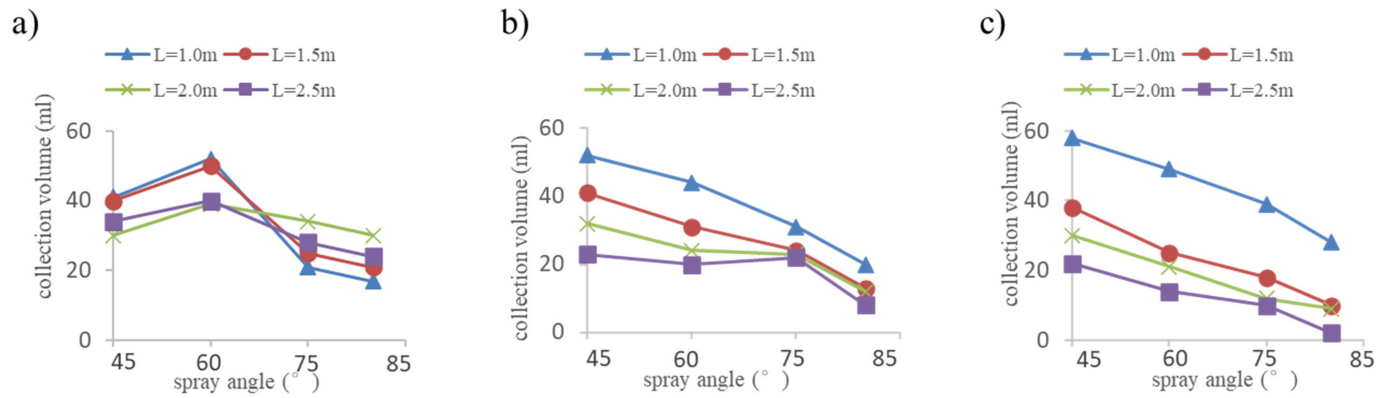


Figure 8. Influence of the three control parameters on the collection volume. (**a**) Influence of the spray angle and spray distance on the collection volume (N = 2000 r/min). (**b**) Influence of the spray angle and spray distance on the collection volume (N = 2400 r/min). (**c**) Influence of the spray angle and spray distance on the collection volume (N = 2800 r/min).

The inter-subject effect test results of the model are shown in Table 3. The dependent variable was the collection volume, and the independent variables were the blower speed, spray angle, spray distance, and position of collection plates. From Table 3, it can be concluded that the SIG of spray angle and spray distance is less than 0.0001, so it has a significant impact on the spray effect, and the SIG of the fan speed is less than 0.005, so it has a significant impact on the spray effect to a certain extent.

Table 3. Inter-subject effect test.

Data Source	Sum of Squares	DF	Mean Square	F	SIG	Non-Central Parameter
Calibration model	59,803.112	18	3130.032	85.239	0.0000	1782.298
Intercept	208,942.321	1	208,942.321	620.019	0.0000	6201.230
Spray distance	12,230.031	2	6108.120	178.040	0.0000	317.271
Spray angle	72.132	2	26.200	1.324	0.0001	3.042
Blower speed	13.024	3	6.171	0.314	0.0054	0.431
Collection plate position	43,831.211	9	3103.121	98.141	0.0000	1235.020

Abbreviation: DF: degrees of freedom; SIG: significance.

A regression analysis on three control parameters was made, and the *p*-values of the spray distance, spray angle, and blower speed were less than 0.05, indicating that these parameters had significant effects on the collection volume. The regression equation in the height range of 1.35–1.55 m is:

$$Y = 123.3499 - 0.5242X_1 + 5.5833X_2^2 - 30.4583X_2 - 0.0110X_3 \tag{1}$$

where Y is the collection volume at heights of 1.35-1.55 m; X_1, X_2, and X_3 are, respectively, the values of the spray angle (°), the spray distance (m), and the blower speed (r/min).

The coefficient of determination R^2 of the regression equation was 0.80, the corrected R^2 was 0.82, and the standard error was 7.62, indicating a good fit.

The partial derivatives of the three factors were obtained:

$$\frac{\partial Y}{\partial X_1} = -0.5242 \tag{2}$$

$$\frac{\partial Y}{\partial X_2} = 11.1666X_2 - 30.4583 \tag{3}$$

$$\frac{\partial Y}{\partial X_3} = -0.0110 \tag{4}$$

The analysis of the three factors in the crown height range of 1.35–1.55 m shows that an increase in the spray angle and blower speed results in a decrease in the collection volume due to the parabolic trajectory of the droplets. The effect of the spray angle on the collection volume is the most obvious.

In addition, the proposed regression model can be modified using data from field experiments because differences exist in the canopy density and surface characteristics between the vertical patternator and real trees.

4. Conclusions

In this study, the influences of different control parameters on the spray performance of an air-blast sprayer were determined. A regression equation was established to describe the relationship between the collection volume at the critical height range and the spray angle, blower speed, and spray distance. The influences of the three spray parameters on the collection volume at different heights were analyzed:

(1) Under the experimental conditions, an increase in the spray angle and blower speed increased the overall spray volume and decreased the spray volume at the critical height.

(2) The influence of any single parameter on the other parameters was relatively small. The increase in the blower speed and spray angle were the primary and secondary reasons for an increase in the height of the optimum collection area.

(3) The spray distance affected the collection volume due to the parabolic trajectory of the droplets. The collection volume in the critical height range first increased and then decreased as the spray distance increased, and the largest collection volume was obtained at a distance of 1.762 m.
(4) A quadratic regression model was established to predict the collection volume at the critical height of the tree crown based on the spray distance, spray angle, and blower speed. When one parameter is given, the other two parameters can be adjusted to achieve the desired spray effect.

Author Contributions: Conceptualization, Y.H. and Z.Y.; methodology, Y.H. and H.Y.; software, B.H.; validation, Z.Y.; formal analysis, Z.X.; investigation, H.Y.; resources, Z.Y.; data curation, Y.H.; writing—original draft preparation, Y.H.; writing—review and editing, Z.Y.; project administration, Y.H.; funding acquisition, Z.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Talent start-up Project of Zhejiang A&F University Scientific Research Development Foundation No. 2021LFR066 and the National Key R & D Program of China (2016YFD0200700).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no conflict of interest regarding this research.

References

1. Zhou, L.F.; Xue, X.Y.; Zhou, L.X.; Zhang, L.; Ding, S.M.; Chang, C.; Zhang, X.J.; Chen, C. Research situation and progress analysis on orchard variable rate spraying technology. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 80–92.
2. Shen, C.J.; Jia, S.X.; Tang, Z.H.; Zhou, Y.; Meng, X.J.; Yuan, L.Q. Research Actuality and Application Prospects of Pesticide. *Electrost. Spray. J. Agric. Mech. Res.* **2010**, *32*, 10–13.
3. Liu, H.; Feng, X.; Liu, J.; Li, J. Design and experiment of Orchard Air-blast Sprayer. *J. Anhui Agric. Sci.* **2011**, *39*, 20911–20913.
4. Zhang, H.F.; Xu, L.Y. Summary of research status on orchard sprayer. *J. Chin. Agric.* **2014**, *35*, 112–118.
5. Li, J.; Xu, J.T.; Yang, Z.; Niu, M.; Xue, K.; Mo, M. Design and experiment on real-time mixing system for air-assisted sprayer. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 62–69.
6. Gil, E.; Arnó, J.; Llorens, J. Advanced technologies for the improvement of spray application techniques in Spanish viticulture: An overview. *Sensors* **2014**, *14*, 691–708. [CrossRef]
7. Li, H.; Zhai, C.; Zhang, B.; Yang, S. Status analysis of orchard spray target detection technology. *J. Agric. Mech. Res.* **2016**, *38*, 1–5.
8. Ding, T.H.; Cao, S.M.; Xue, X.Y.; Ding, S. Current situation and development trend of air-assistend orchard sprayer. *J. Chin. Agric. Mech.* **2016**, *37*, 221–226.
9. Yuan, Q.; Hu, L.; Luo, X.; Zhang, M.; Zhou, H.; Zhao, R. Design and Experiment of Online Mixing Spraying System. *Trans. Chin. Soc. Agric. Mach.* **2016**, *47*, 176–181.
10. Qi, L.; Fu, Z. The droplet distribution on apple trees atomized by an air-assisted sprayer. *Trans. CSAE* **1998**, *03*, 140–144.
11. Mac, N.A.Z.; Teske, M.E.; Barry, J.W. A technique to characterize spray deposition orchard and tree canopies. *Trans. ASAE* **1997**, *40*, 1529–1536.
12. Cross, J.V.; Walklate, P.J.; Murray, R.A. Spray deposits and losses in different sized apple trees from an axial fan orchard sprayer: 2. Effects of spray quality. *Crop Prot.* **2001**, *20*, 333–343. [CrossRef]
13. Doruchowski, G.; Holownicki, R. Environmentally friendly spray techniques for tree crops. *Crop Prot.* **2000**, *19*, 617–622. [CrossRef]
14. Pezzi, F.; Rondelli, V. The performance of an air-assisted sprayer operating in vineyard. *J. Agric. Eng. Res.* **2000**, *76*, 331–340. [CrossRef]
15. Li, J.; Zhao, C.Q.; Li, S.J.; Chen, H.; Ding, S.F. Study on droplet deposition characteristics of orchard air blast sprayer based on CFD. *J. Huazhong Agric. Univ.* **2019**, *06*, 171–177.
16. Qiu, B.; Yan, R.; Ma, J.; Guan, X.; Ou, M. Research Progress Analysis of Variable Rate Sprayer Technology. *Trans. Chin. Soc. Agric. Mach.* **2015**, *46*, 59–72.
17. Zhai, C.; Sha, X.U.; Long, J.; Hanzhe, L.I.; Zhang, B.; Zhu, R. Optimization design of orchard air-assisted sprayer and mathematical model for spray height control. *J. Northwest A F Univ. (Nat. Sci. Ed.)* **2018**, *46*, 148–154.
18. Solanelles, F.; Escolà, A.; Planas, S.; Rosell-Polo, J.R.; Camp, F.; Gràcia, F. An electronic control system for pesticide application proportional to the canopy width of tree crops. *Biosyst. Eng.* **2006**, *95*, 473–481. [CrossRef]
19. Wang, L.; Zhang, S.; Ma, C.; Xu, Y.; Qi, J.; Wang, W. Design of variable spraying system based on ARM. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2010**, *26*, 113–118, (In Chinese with English abstract).

20. Gonzalez, R.; Pawlowski, A.; Rodriguez, C.; Guzman, J.L.; Sánchez-Hermosilla, J. Design and implementation of an automatic pressure-control system for a mobile sprayer for greenhouse applications. *Span. J. Agric. Res.* **2012**, *10*, 939–949. [CrossRef]
21. Huang, S.; Zhu, R.; Wang, Y.; Liu, W. Design and algorithm of constant pressure and variable flow control system of variable pesticide application machine. *J. Agric. Mech. Res.* **2011**, *2*, 19–22, (In Chinese with English abstract).
22. Berk, P.; Stajnko, D.; Lakota, M.; Belsak, A. Real time fuzzy logic system for continuous control solenoid valve in the process of applying the plant protection product. *J. Agric. Eng.* **2015**, *15*, 1–9.
23. Liu, Z.; Hong, T.; Zhang, W.; Fan, Z. Fuzzy control implementing and testing on electromechanical flow valve. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2010**, *26* (Suppl. S1), 22–26, (In Chinese with English abstract).
24. Song, L.; Dong, Z.; Xiang, L.; Xing, S. Variable universe adaptive fuzzy PID control of spray flow valve. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2010**, *26*, 114–118, (In Chinese with English abstract).
25. Chen, S.; Yin, D.; Wei, X.; Pei, W. Design and simulation of variable weed spraying controller based on adaptive neural fuzzy inference system. *J. Drain. Irrig. Mach. Eng.* **2011**, *29*, 272–276, (In Chinese with English abstract).
26. Na, G.; Jingtao, H. Design and experiment of variable rate spaying system on Smith-Fuzzy PID control. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2014**, *30*, 56–64, (In Chinese with English abstract).
27. Wei, D.; Xiongkui, H.; Weimin, D. Droplet size and spray pattern characteristics of PWM-based continuous variable spray. *Int. J. Agric. Biol. Eng.* **2009**, *2*, 8–18.
28. Huanyu, J.; Mingchuan, Z.; Junhua, T.; Yan, L. PWM variable spray control based on Kalman filter. *Trans. Chin. Soc. Agric. Mach.* **2014**, *5*, 60–65, (In Chinese with English abstract).
29. Zhai, C.Y.; Wang, X.; Liu, D.Y.; Ma, W.; Mao, Y.J. Nozzle flow model of highpressure variable-rate spraying based on PWM technology. *Adv. Mater. Res.* **2012**, *422*, 208–217. [CrossRef]
30. Li, L.; He, X.; Song, J.; Zhong, C. Spray characteristics on pulse-width modulation variable application based on high frequency electromagnetic valve. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2016**, *32*, 97–103, (In Chinese with English abstract).
31. Huanyu, J.; Lijun, Z.; Guangyuan, L.; Weinan, S.H.I. Experiment on dynamic spray deposition uniformity for PWM variable spray of single nozzle. *Trans. Chin. Soc. Agric. Mach.* **2017**, *48*, 41–46, (In Chinese with English abstract).
32. Liu, H.; Zhu, H.; Shen, Y.; Chen, Y.; Ozkan, H.E. Development of digital flow control system for copy multi-channel variable-rate sprayers. *Trans. ASABE* **2014**, *57*, 273–281.
33. Xu, Y.; Bao, J.; Fu, D.; Zhu, C. Design and experiment of variable spraying system based on multiple combined nozzles. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2016**, *32*, 47–54, (In Chinese with English abstract).
34. Dekeyser, D.; Duga, A.T.; Verboven, P.; Endalew, A.M.; Hendrickx, N.; Nuyttens, D. Assessment of orchard sprayers using laboratory experiments and computational fluid dynamics modelling. *Biosyst. Eng.* **2013**, *114*, 157–169. [CrossRef]
35. Shen, Y.; Zhu, H. Embedded computer-controlled premixing inline injection system for air-assisted variable-rate sprayers. *Trans. ASABE* **2015**, *58*, 39–46.
36. Zhang, W.; Liu, Z. Experiment on variable rate spray with real-time mixing pesticide of 3WY-A3 sprayer. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2011**, *27*, 130–133, (In Chinese with English abstract).
37. Hu, K.; Zhou, Z.; Qi, L.; Wang, X.; Ji, R. Spraying performance of the direct injection variable-rate sprayer. *Trans. Chin. Soc. Agric. Mach.* **2010**, *41*, 70–74, 102, (In Chinese with English abstract).
38. Yang, Z.; Niu, M.; Li, J.; Xu, X.; Xu, J.; Chen, Z. Design and experiment of an electrostatic sprayer with on-line mixing system for orchard. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2015**, *31*, 60–67, (In Chinese with English abstract).
39. Cai, X.; Walgenbach, M.; Doerpmund, M.; Lammers, P.S.; Sun, Y. Direct nozzle injection sprayer based on electromagnetic-force valve. *Trans. Chin. Soc. Agric. Mach.* **2013**, *44*, 69–72, (In Chinese with English abstract).
40. Jens, K.W.; Tanja, P.; Katrin, A. Assessment of Different Parameters Influencing the Quality of Spray Distribution on Orchard Sprayers. *Gesunde Pflanz.* **2019**, *71*, S9–S15.
41. Qiu, W.; Gu, J.; Ding, W.; Sun, C.; Li, Y.; Zhao, S. The droplet deposition distribution in fruit canopy using air-assisted sprayer. *J. Yangzhou Univ. (Agric. Life Sci. Ed.)* **2015**, *36*, 68–72.
42. Farooq, M.; Landers, A.J. Interactive Effects of Air, Liquid and Canopies on Spray Patterns of Axial-flow Sprayer. In Proceedings of the Annual Meeting of the ASAE, "Dynamic Partnerships for an Environmentally Safe and Healthy World", Ottawa, ON, Canada, 1–4 August 2004.
43. He, X.K.; Zeng, A.; He, J. Effect of Wind Velocity from Orchard Sprayer on Droplet Deposit and Distribution. *Trans. Chin. Soc. Agric. Eng.* **2002**, *4*, 75–77.
44. Lü, X.L.; Fu, X.; Wu, P.; Ding, S.; Zhou, L.; Yan, H. Influence of Spray Operating Parameters on Droplet Deposition. *Trans. Chin. Soc. Agric. Mach.* **2011**, *42*, 70–75.
45. Reichard, D.L.; Zhu, H.; Downer, R.A.; Fox, R.D.; Brazee, R.D.; Ozkan, H.E.; Hall, F.R. A laboratory system to evaluate effects of shear on spray drift retardants. *Trans. ASAE* **1996**, *39*, 1993–1999. [CrossRef]
46. Fox, R.D.; Brazee, R.D.; Reichard, D.L.; Hall, F.R. Power in an Air Sprayer Jet. *Trans. ASAE Am. Soc. Agric. Eng.* **1982**, *25*, 1181–1184. [CrossRef]
47. Fox, R.D.; Brazee, R.D.; Svensson, S.A.; Reichard, D.L. Air Jet Velocities from a Cross-flow Fan Sprayer. *Trans. ASAE* **1992**, *35*, 1381–1384. [CrossRef]
48. Pergher, G.; Gubiani, R.; Tonetto, G. Foliar deposition and pesticide losses from three air-assisted sprayers in a hedgerow vineyard. *Crop Prot.* **1997**, *16*, 25–33. [CrossRef]

49. Svensson, S.A.; Brazee, R.D.; Fox, R.D.; Williams, K.A. Air jet velocities in and beyond apple trees from a two-fan cross-flow sprayer. *Trans. ASAE* **2003**, *46*, 611–621. [CrossRef]
50. Svensson, S.A.; Fox, R.D.; Hansson, P.A. Forces on apple trees sprayed with a cross-flow fan air jet. *Trans. ASAE* **2002**, *45*, 889–895. [CrossRef]