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Characteristics on the Spatial Distribution of Droplet Size and Velocity with Difference Adjuvant in Nozzle Spraying

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Abstract: The spatial distribution of droplet size and velocity affects the deposition and distribution on the target. In order to investigate the influence of different adjuvant and pressures on the spatial distribution of droplet size and velocity in atomization area of different nozzles, air induction flat fan nozzle IDK120-03, multi-range flat fan nozzle LU120-03 and anti-drift flat fan nozzle AD120-03 were selected. Phase Doppler Interferometer (PDI) was used to analyze and compare the distribution of droplet size and velocity in the atomization area of three nozzles when four typical adjuvant Maisi, Maidao, Adsee AB-600 and Surun sprayed at different pressures. The results show that the volume median diameter of droplet size has no obvious change along the vertical direction of the nozzle center and increases with distance in the horizontal direction, the droplet size decreases with increasing pressure at the same position, the adjuvant all increases the droplet size (about 12%, 12%, 10% and 9% for Maisi, Maidao, Surun and Adsee AB-600, respectively), IDK120-03 nozzle droplet size is the largest and LU120-03 nozzle is the smallest in the same position. For droplet velocity distribution, droplet velocity decrease in distance along the vertical and horizontal direction, respectively, the droplet velocity increases with increasing pressure at the same position, compared with water, the droplet velocity increased by about 13%, 9%, 8%, and 4% for Maisi, Maidao, Surun, and Adsee AB-600, respectively, the velocity of AD nozzle is the largest and IDK nozzle is the smallest at the same position. The experiment can provide a basis for the selection of adjuvants and nozzles in pesticide application, and provide a data base for studying the distribution of droplets on the target.

Keywords: droplet size and velocity; Phase Doppler Interferometer; adjuvant affect; spatial distribution

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Citation: Li, X.; Chen, L.; Tang, Q.; Li, L.; Cheng, W.; Hu, P.; Zhang, R. Characteristics on the Spatial Distribution of Droplet Size and Velocity with Difference Adjuvant in Nozzle Spraying. *Agronomy* **2022**, *12*, 1960. https://doi.org/10.3390/agronomy12081960

Academic Editors: Xinyu Xue, Yubin Lan and Songchao Zhang

Received: 20 June 2022
Accepted: 18 August 2022
Published: 19 August 2022

1. Introduction

In the process of agricultural production, pesticide control can protect the growth environment of crops and is an effective method to quickly control the outbreak and spread of diseases and insect pests [1,2]. Agricultural pesticide application is dispersed to crops in the form of droplets formed by pesticide atomization, to realize large-scale contact between pesticide solution and crops [3,4]. Agricultural nozzles atomizes pesticides into droplets, and transfers liquid to crops under force. The atomization quality of pesticides directly affects the application quality. The droplet size distribution and droplet velocity distribution directly affect the movement state of droplets during transmission, which further affects droplet drift and droplet deposition rate [5]. Studying the distribution of droplet size and velocity in the nozzle spray flow field under different liquids is of great significance to study the droplet distribution on the target and reduce the droplet drift.

To improve the quality of agricultural pesticide application, the effective measurement of droplet parameters is particularly critical when appropriate droplet parameters are selected according to different crops [6]. The droplet size measurement methods include the mechanical measurement method of freezing or cooling droplets into solid particles for measurement, the electronic measurement method of measuring the electronic pulse signal generated by droplets, and the optical measurement method based on the physical properties of droplets (light intensity, phase difference, fluorescence and polarization) [7]. The droplet velocity measurement methods include laser doppler anemometry, particle image velocimetry technology (PIV) and high-speed camera [8]. To improve the effective utilization rate and application quality of pesticides, in addition to the use of new technologies, new atomization components and devices and the improvement of application methods, the atomization characteristics is improved by adding adjuvants to change the properties of the liquid [9–15]. Pesticide adjuvants are commonly used to improve atomization characteristics by changing physical properties such as surface tension, density and viscosity of the liquid [16,17]. The nozzle selection also plays an important role in atomization characteristics [18,19]. In the study that adjuvants can improve atomization characteristics and improve pesticide use efficiency in agriculture, Wang et al. [20] compared the droplet size distribution of anti-evaporation adjuvant and anti-floating adjuvant under different solubility liquids. Zhang et al. [16] studied the atomization characteristics of adjuvant Breakthru S240 on water dispersible granules and emulsifiable concentrate under two types of nozzles to study the influence of liquid properties on nozzle atomization. Zhang Ruirui et al. [21] explored the effects of adjuvant and their concentrations on the atomization effect of nozzle, and analyzed the differences of droplet volume diameter and droplet distribution relative span when IDK120-025 and LU120-015 nozzles were sprayed with different concentrations of typical adjuvants Yiou, reducing dosage and increasing production adjuvant Jijian and Urea. Tian Zhihui et al. [22] and Liu Yongqiang et al. [23] studied whether adjuvants could reduce pesticide use and enhance pesticide efficiency. In the study of nozzle atomization characteristics, Xiecheng et al. [24] used droplet size analyzer to conduct experimental research and visual graphic analysis on the atomization process of flat fan nozzle (ST) and anti-drift nozzle (IDK). The droplet size of IDK nozzle was larger than that of ST nozzle. Tang Qing et al. [25] explored the atomization characteristics of flat fan nozzle and air induction nozzle under high-speed airflow, the pressure change has a great influence on the droplet volume diameter of flat fan nozzle, and has little influence on the air induction nozzle. Zhang et al. [26] used phase Doppler Particle Instrument to test the droplet velocity in the atomization area of flat fan nozzle, and confirmed the velocity distribution of droplets. Li et al. [27] measured the atomization characteristics of flat fan nozzle and established the droplet size and droplet velocity models. Chen et al. [28] studied the spray atomization characteristics of small angle flat fan nozzle, measured the droplet size in the atomization field by Laser Particle Size Analyzer, and calculated the droplet uniformity under different parameters. Vallet et al. [29] studied the spatial distribution of droplet size and droplet velocity of flat fan nozzle and double-nozzle flat fan nozzle with Phase Doppler Particle Analyzer (PDPA). The droplet size and droplet velocity of double-nozzle were larger than those of single-nozzle. The above researchers studied the influence of adjuvants on the atomization characteristics and the atomization characteristics of different nozzles under different pressures, while the research on the spatial distribution trend of droplet velocity and droplet size in the atomization area of pressure nozzle by adjuvants has not been found in the literature.

The spatial distribution of droplet size and velocity affects the deposition and distribution on the target. In order to investigate the influence of different adjuvant and pressures on the spatial distribution of droplet size and velocity in atomization area of different nozzles, the study was conducted to explore the spatial distribution of droplet size and velocity in the atomization area of flat fan nozzle based on the spray pressure, flat fan nozzle and spray adjuvants. According to the spatial distribution of droplet size and velocity, it is easy for workers to obtain the desired atomization effect by adjusting the spray pressure, spray adjuvants and the nozzle type, thereby improving the utilization rate of pesticides. It also serves as a resource for subsequent research on droplet rebounding and deposition while hitting a given target.

2. Materials and Methods

2.1. Experimental Materials

2.1.1. Nozzle and Adjuvants

The experiment was carried out in the Aviation Spraying Technology Laboratory of National Agricultural Intelligent Equipment Engineering Technology Research Center. The spray adjuvant parameter information is shown in Table 1. The liquid ratio refers to the recommended dosage configuration of the adjuvant. The ratio was 1:1000. The experimental nozzles were the air induction flat fan nozzle IDK120-003, multirange flat fan nozzle LU120-03 and anti-drift flat fan nozzle AD120-03 from LECHLER, Germany. Spray angles are all 120°. The nozzle structure is shown in Figure 1.

Table 1. Characteristics of different spray adjuvants.

Adjuvants	Type	Manufacturer
Surun	Agricultural silicone synergist	Qingdao Hairunhe Biotechnology Co., Ltd., Qingdao, China
Adsee AB-600	Mixed water-based and cationic surfactants	Akzo Nobel N. V, Amsterdam, The Netherlands
Maidao	Improved mixture of vegetable oil and emulsifier	China National Chemical Corporation, Beijing, China
Maisi	Improved mixing of mineral oil and emulsifier	China National Chemical Corporation, Beijing, China

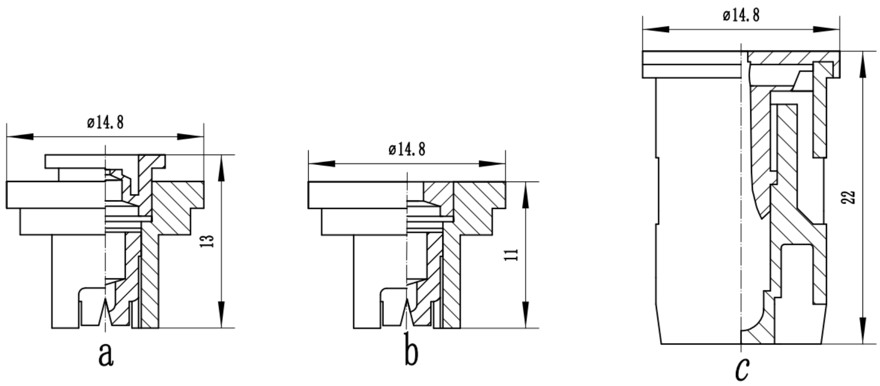
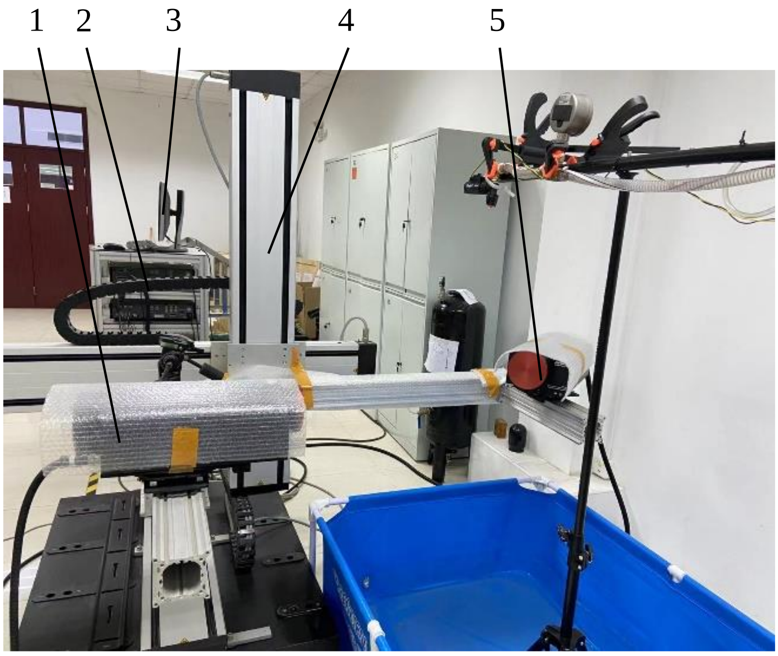


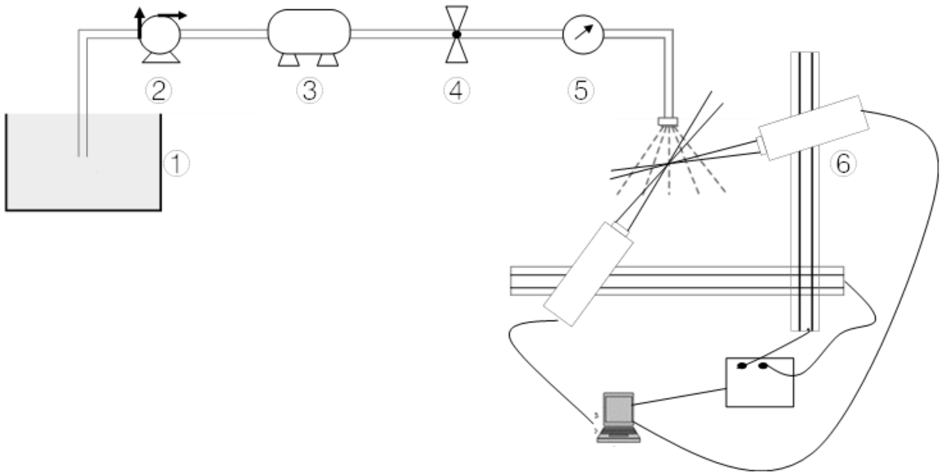
Figure 1. Diagram of nozzle structure ((**a**) LU120-03, (**b**) AD120-03, (**c**) IDK120-03).

2.1.2. Experimental Equipment

The nozzle droplet parameter measurement system is shown in Figure 2, which is composed of a three-dimensional positioning device, spray system and droplet parameter measurement device. The three-dimensional positioning device is used to move the Phase Doppler Interferometer (PDI) on the transport device to measure the droplet characteristics of the fixed point. The spray system is a SCS spray control system independently designed by Beijing Agricultural Intelligent Equipment Technology Research Center. The system consists of a water storage tank, a water pump, a pressure stabilizing tank, a pressure regulating valve, a pressure gauge and a nozzle. By adjusting the outlet pressure of the pressure valve, the spray pressure can be accurately controlled and recorded in real time. The measuring device adopts Phase Doppler Interferometer (PDI), which includes signal transmitter, signal receiver, ASA signal processor, data management computer and AIMS system software. PDI launch interference fringes generated by two coherent laser beams intersected from the transmitter through the spraying area. The velocity information is obtained by the frequency difference between the scattered light and the irradiated light of the moving particle, and the particle size is determined by analyzing the phase shift generated by the reflected or refracted scattered light of the spherical particle passing through the laser measuring body. Technical specifications for PDI are shown in Table 2.



(**a**)



(**b**)

Figure 2. (**a**) Instrumentation used in the experiment. 1. Three-dimensional Positioning Device 2. equipped with AIMS software computer 3. ASA Signal Processor 4. Signal Receiver 5. Signal Transmitter. (**b**) Measurement system of droplet parameters with PDI. 1. Water Storage Tank 2. water Pump 3. Pressure Stabilizing Tank 4. Pressure Regulating Valve 5. Pressure Gauge 6. PDI.

Table 2. Phase Doppler Interferometer (PDI) technical specifications.

Specification	Parameter
Drop size measurement range	0.3 to >8000 μm (spherical or near-spherical particles)
Size dynamic range	50:1
Estimated size accuracy	±0.5 μm or 0.5% of full size range
Estimated size resolution	±0.5 μm or 0.5% of full size range
Velocity measurement range	−600 to 1000 m/s
Velocity accuracy	±0.1%
Volume flux accuracy	±10%
Laser type	Diode pumped solid state (DPSS)
Wavelength	491 nm, 532 nm, 561 nm, 660 nm

2.2. Test Method

The experiment was carried out in the room without wind, stable temperature and humidity, and the evaporation of droplets was ignored. Considering the influence of gravity, the nozzle was arranged in the downward direction as shown in Figure 3, and the X-axis and Z-axis coordinate systems were established with the nozzle outlet center as the coordinate origin. Five horizontal spray sections were selected along the Z-axis of 10–50 cm and 10 cm interval. The interval of 5 cm was selected as the measurement point to collect data on the horizontal X axis, and the pressure values were 150, 200, 250, 300 and 350 kPa, respectively. Each sampling coordinate was sampled for 20 s, and each measuring point was repeated for three times. The average value of three repeated times was used as the droplet size and velocity of the measuring position.

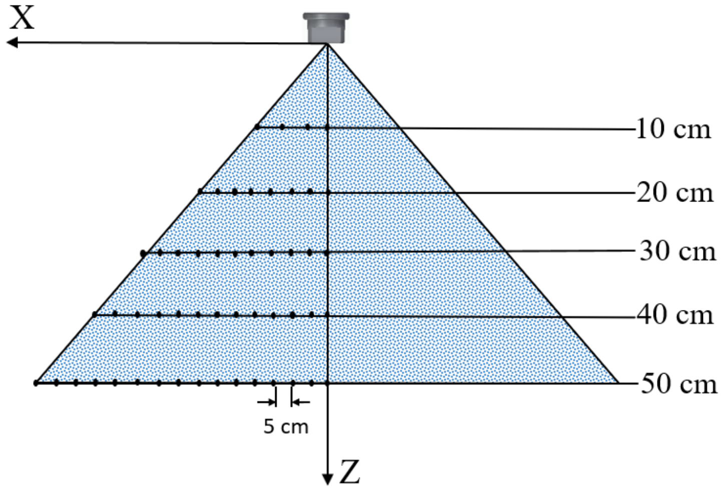


Figure 3. Sample point diagram of spray surface (black point as measuring point).

2.3. Basic Theory

The particle size of spray droplets is generally represented by the characteristic points of the droplet diameter distribution curve, which is called the characteristic diameter of droplets. It represents the percentage of the volume of all droplets below a certain diameter in the total volume of all droplets. The characteristic diameters include $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$. $D_{v0.5}$ represents the volume fraction particle size with a cumulative distribution of 50%, which is called the droplet volume median diameter. It refers to the accumulation of the volume of the sampled droplets from small to large, and the cumulative value is the droplet diameter corresponding to 50% of the total volume of the sampled droplets, that is, the volume content of particles less than this particle size accounts for 50% of all particles [30]. $D_{v0.5}$ is also called Volume Median Diameter (VMD) of droplets. The average speed of droplets in the atomization area is selected, and the definition of the average speed of droplets is as follows:

$$v = \frac{\int_{v_{\min}}^{v_{\max}} v dn}{\int_{v_{\min}}^{v_{\max}} dn} \quad (1)$$

the average droplet velocity V is used as the spatial distribution parameter of droplet velocity, and $D_{v0.5}$ is used as the spatial distribution parameter of droplet size. V_X and V_Z represent the average velocity of droplets on horizontal X axis and vertical Z axis, respectively. D_Z and D_X represent the median diameter of droplet volume $D_{v0.5}$ on horizontal X axis and vertical Z axis, respectively.

3. Results and Discussion

3.1. Droplet Size Distribution of Droplets

3.1.1. Vertical Z-Axis Droplet Size D_Z Distribution

The distribution of droplet size D_Z along the Z axis in the vertical direction is shown in Figure 4. As can be seen from Figure 4a, in general, the droplet size D_Z has no significant change along the Z axis in the vertical direction at the center of the nozzle. Because the liquid sheet is not easy to mix and move along the original trajectory after breaking into droplets, a stable droplet is formed. Therefore, considering the relationship between pressure and droplet size, it can be seen from Figure 4b that the droplet size decreases gradually with the increase of spray pressure. According to the Bernoulli equation:

$$\mathrm{p} = \frac{1}{2}\rho v^2 + \rho g h = C \tag{2}$$

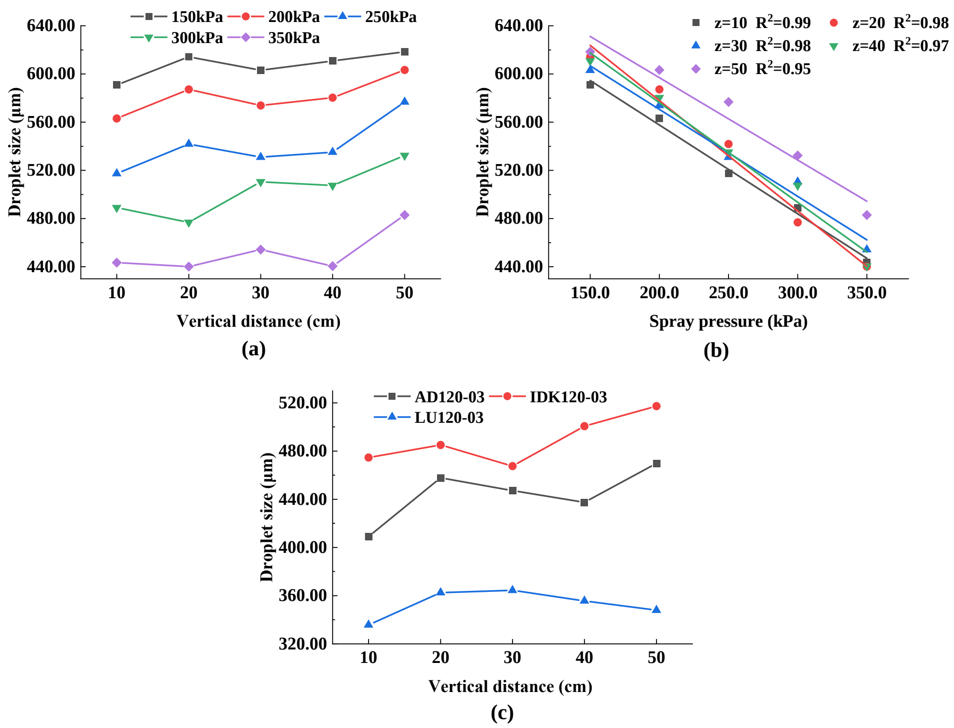


Figure 4. Distribution of droplet size on Z axis. (**a**) different pressures (**b**) relationship between pressure and droplet size (**c**) different nozzles.

There is a pressure difference between the outside and the inside of the nozzle exit. The pressure difference between the outside and inside of the nozzle exit makes the liquid sheet rupture more thoroughly and produces smaller droplets. The fitting relationship between droplet size D_Z at different distances on Z axis and spray pressure P is shown in Table 3. Figure 4c is the droplet size distribution of different nozzle structure, under the same conditions, IDK120-03 nozzle droplet volume diameter $D_{v0.5}$ maximum, LU120-03 minimum. Since the spacing between the slit plates of the LU nozzle is narrower than that of the IDK and AD nozzles, the liquid film is broken to produce smaller droplets.

Table 3. Fitting relationship between droplet size D_Z and spray pressure p at measure positions.

Measure Position	Fitting Relationship	R^2
Z = 10 cm	$D_Z = -0.74p + 705.23$	0.99
Z = 20 cm	$D_Z = -0.92p + 761.31$	0.98
Z = 30 cm	$D_Z = -0.72p + 715.12$	0.98
Z = 40 cm	$D_Z = -0.83p + 741.57$	0.97
Z = 50 cm	$D_Z = -0.68p + 733.74$	0.95

The distribution of droplet size D_Z on Z axis by the adjuvants is shown in Table 4. It can be seen that compared with water, the droplet volume median diameter $D_{v0.5}$ of the four adjuvants was increased. Maidao and Maisi can increase the average percentage of increase in droplet volume median diameter by about 12%, followed by 10% for Surun and 9% for the smallest Adsee AB-600. According to reference [31], Due to the stable emulsion droplets formed by oil adjuvants, the penetration ability is weaker than that of silicone and cationic surfactants. Under the same conditions, the droplet size increases when the droplets are broken.

Table 4. Droplet size distribution at different adjuvants.

Adjuvant Types	Parameter	Vertical Distance (cm)				
		10	20	30	40	50
Water	Volume Median Diameter (VMD)/μm	387.7	409.2	426.8	426.8	410.5
Maisi	Volume Median Diameter (VMD)/μm	456.1	478.6	484.2	459.1	449.3
	Rate of change relative to tap water/%	17.64	16.96	13.08	7.57	9.45
Surun	Volume Median Diameter (VMD)/μm	447.9	474.2	464.5	447.4	440.6
	Rate of change relative to tap water/%	15.53	15.88	8.48	4.83	7.33
Adsee AB-600	Volume Median Diameter (VMD)/μm	437.1	470.1	462.0	444.4	453.1
	Rate of change relative to tap water/%	12.74	14.88	7.89	4.12	10.38
Maidao	Volume Median Diameter (VMD)/μm	466.6	474.6	476.7	448.6	459.1
	Rate of change relative to tap water/%	20.35	15.98	11.33	5.11	11.84

3.1.2. Horizontal *X*-Axis Droplet Size D_X Distribution

The droplet size D_X distribution on the horizontal X axis is shown in Figure 5. In each horizontal direction, the larger the pressure at the same position is, the smaller the droplet volume median diameter $D_{v0.5}$ is. The larger the pressure is, the greater the liquid disturbance is, and the droplet breakage is more complete. At the same level, far away from the center position, the larger the droplet size is, the larger the droplet size is at the edge. Because the distance between the center position and the edge of the spray is the farthest, the collision probability of the droplet at the center position is large, resulting in the secondary atomization of the droplet. The droplet size is smaller than the edge, and the large droplet is easier to move to the edge.

The distribution of droplet size D_X on the X axis of the adjuvants is shown in Figure 6. It can be seen from the figure that, compared with water, Maisi, Surun, AdseeAB-600 and Maidao adjuvants have an increasing trend on droplet size. At the same position of the horizontal section, the droplet size of the Maisi is the largest in the horizontal direction, and the droplet size of Adsee AB-600 and the Maidao are close, and the smallest is the Surun.

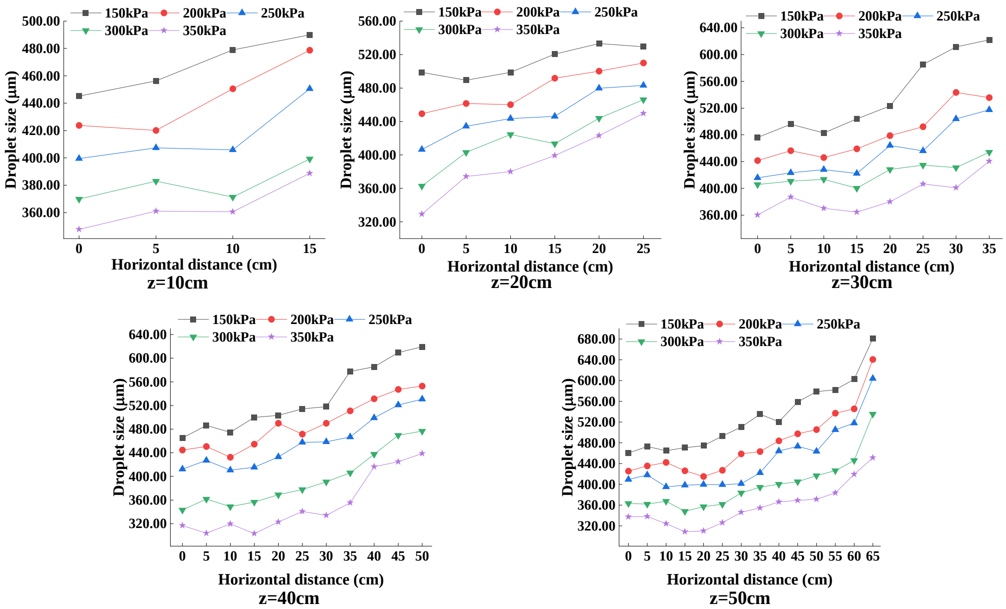


Figure 5. Horizontal direction droplet size D_X distribution in different pressure.

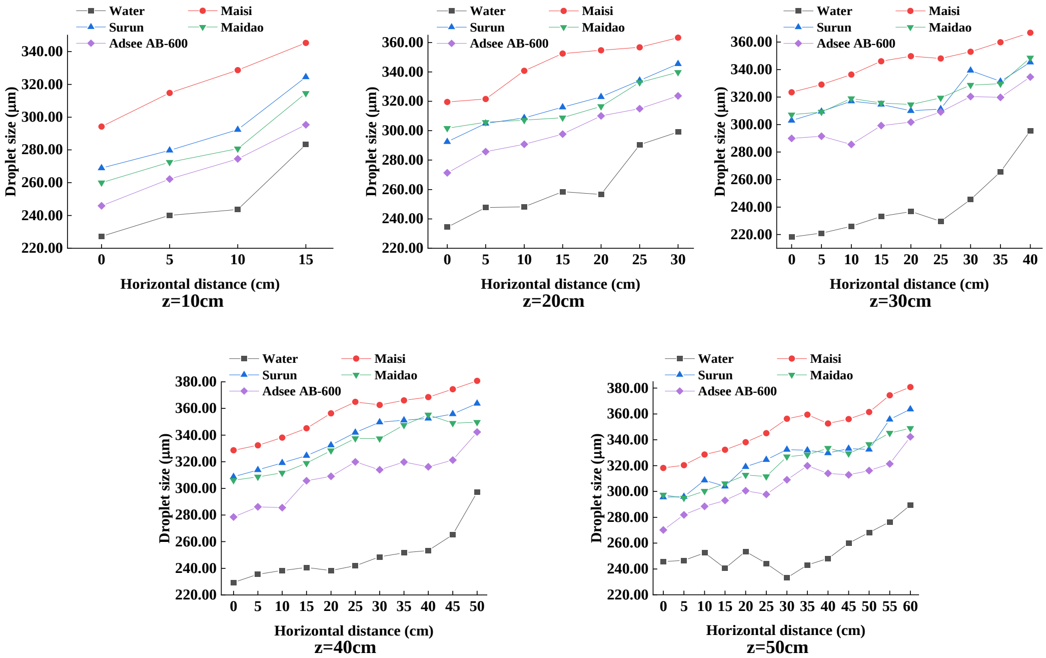


Figure 6. Horizontal direction droplet size D_X distribution in different adjuvants.

The distribution of droplet size D_X on the X-axis by nozzle type is shown in Figure 7. Overall, the droplet size increases with the increase of horizontal distance. When comparing the three types of nozzles, the droplet size of LU120-03 nozzle is smaller than that of the other two types of nozzles, and the droplet size of IDK120-03 nozzle is the largest. According to the reference [32], IDK120-03, the air-induced nozzle adopts the Venturi suction structure and operates according to the Venturi Law. In the place where a high-speed liquid flow is produced in the front nozzle, the air is inhaled through the side hole to form a large droplet with special air and liquid mixed aeration. The droplet size is larger than that of other nozzles.

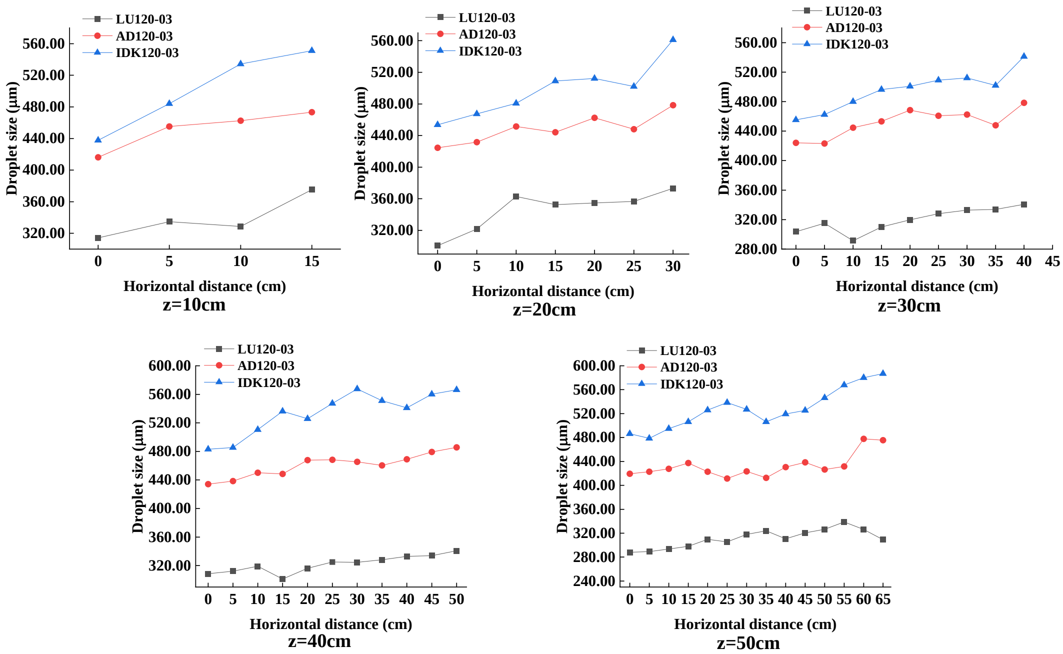


Figure 7. Horizontal direction droplet size D_X distribution in different nozzles.

3.2. *Droplet Velocity Distribution of Droplets*

3.2.1. Vertical *Z*-Axis Droplet Velocity V_Z Distribution

The droplet velocity V_Z distribution on the vertical *Z*-axis is shown in Figure 8. As can be seen from Figure 8a, at the same position, the droplet velocity increases with the increase of pressure. When the pressure increases 50 kPa, the velocity increases about 1.1m/s. Under the same pressure, the droplet velocity decreases with the increase of the vertical *Z*-axis distance. Droplets break down, resulting in lower speed due to the presence of air assist. The fitting relationship between droplet velocity V_Z and vertical distance z under different pressure is shown in Table 5. As can be seen from Figure 8b, the droplet velocity V_Z of all nozzles decreases with the distance of Z axis in the vertical direction. Under the same conditions, the droplet velocity V_Z of AD120-03 is the largest, and the whole stage velocity is also the largest. LU120-03 has the fastest drop speed and IDK120-03 has the slowest drop speed. According to the fluid aerodynamic resistance equation:

$$\mathrm{F}_D = C_D \frac{\rho_g \left| v - v_p \right| \left(v - v_p \right)}{2} \cdot \frac{\pi d_p^2}{4} \tag{3}$$

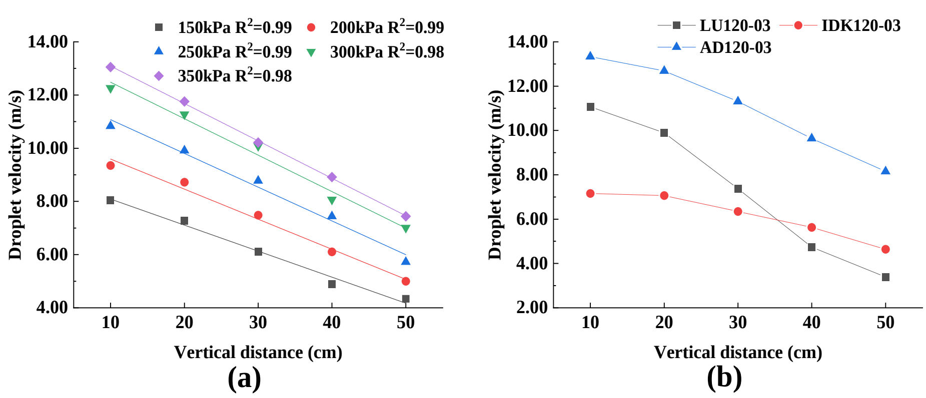


Figure 8. Distribution of droplet velocity V_Z on Z axis. (**a**) different pressure (**b**) different nozzles.

Table 5. The fitting relationship between droplet velocity V_Z and vertical distance Z at spray pressure.

Spray Pressure	Fitting Relationship	R^2
150 kPa	$V_Z = -0.09\ Z + 9.07$	0.99
200 kPa	$V_Z = -0.11\ Z + 10.73$	0.99
250 kPa	$V_Z = -0.12\ Z + 12.34$	0.99
300 kPa	$V_Z = -0.13\ Z + 13.85$	0.98
350 kPa	$V_Z = -0.14\ Z + 14.50$	0.98

Large droplets are more aerodynamically assisted than small droplets, resulting in a smaller total acceleration than small droplets. The droplets decelerate due to air resistance, and due to the blocking effect of air, small droplets decelerate faster than large droplets.

The distribution of the droplet average velocity V_Z on the Z axis by the adjuvants is shown in Table 6. Under different vertical positions, the droplet velocity V_Z decreases along the Z axis. Among the adjuvants, the velocity of AdseeAB-600 adjuvant is the smallest, and that of the Maisi is the largest, followed by the Maidao and the Surun. Compared with water, the droplet velocity of Maisi, Maidao, Surun and Adsee AB-600 increased by about 13%, 9%, 8% and 4%, respectively.

Table 6. Droplet velocity distribution at different adjuvants.

Adjuvant Types	Parameter	Vertical Distance (cm)				
		10	20	30	40	50
Water	Droplet velocity/m·s^{-1}	5.727	5.578	5.271	4.500	4.029
Maisi	Droplet velocity/m·s^{-1}	6.643	6.215	5.793	5.127	4.584
	Rate of change relative to tap water/%	16.00	11.42	9.90	13.95	13.75
Surun	Droplet velocity/m·s^{-1}	6.617	5.951	5.607	4.887	4.309
	Rate of change relative to tap water/%	15.54	6.69	6.36	8.62	6.95
Adsee AB-600	Droplet velocity/m·s^{-1}	5.966	5.998	5.586	4.631	4.137
	Relative rate of change to tap water/%	4.18	7.53	5.97	2.90	2.69
Maidao	Droplet velocity/m·s^{-1}	6.501	5988	5.594	5.096	4.351
	Rate of change relative to tap water/%	13.51	7.36	6.12	13.26	7.99

3.2.2. Horizontal *X*-Axis Droplet Velocity V_X Distribution

The droplet velocity V_X distribution on the horizontal X axis is shown in Figure 9. It can be seen from the figure that the droplet velocity generally increases with the increase of pressure. The droplet velocity V_X decreases with the increase of *X*-axis distance in the horizontal direction. The center droplet velocity is the largest, and the edge droplet velocity is the smallest.

The distribution of droplet velocity V_X on the X axis of the adjuvants is shown in Figure 10, the droplet velocity V_X decreases with the increase of the horizontal distance. The velocity V_X of Maisi adjuvants is the largest in the horizontal direction, followed by the Surun and the Maidao, and the smallest is AdseeAB-600. Because Maisi is a vegetable oil adjuvant can produce stable emulsion droplets, reduce the concentration of surfactant on the oil-water interface, resulting in increased hydrophobicity, hydrophobic points form holes, compared with organic silicon and cationic surfactants, the penetration ability is weak, and the droplets are broken and fast. In the spray area, the droplets exchange energy with the surrounding air in the process of movement, and a part of the air is entrained to move in the same direction, forming a two-phase flow of gas-liquid mixture. The droplets near the center of the nozzle are concentrated. When the droplets move, the airflow forms vortex at the tail of the nozzle, and the droplet velocity decreases significantly under the influence of air power. Near the edge, the number of droplets is rare, and the conditions for reducing velocity change are few.

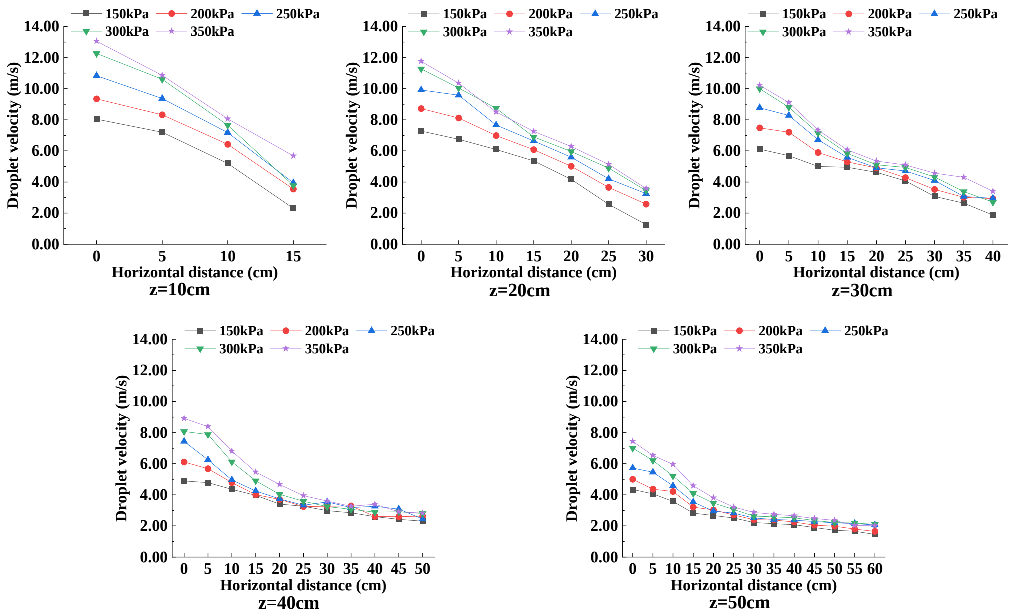


Figure 9. Horizontal direction droplet velocity V_X distribution in different pressure.

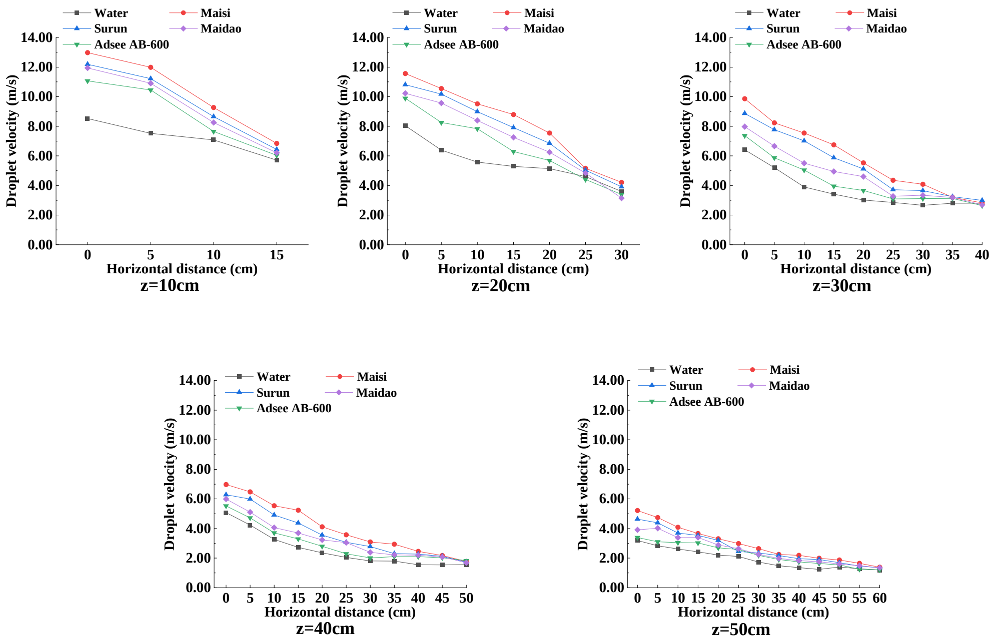


Figure 10. Distribution of droplets velocity V_X on X-axis with different adjuvants.

The distribution of droplet velocity V_X on the X-axis by nozzle type is shown in Figure 11. the droplet velocity V_X on X-axis of three nozzles decreases with the increase of X-axis distance in horizontal direction. AD120-03 nozzle droplet velocity is the largest, LU120-03 followed, IDK120-03 is the smallest.

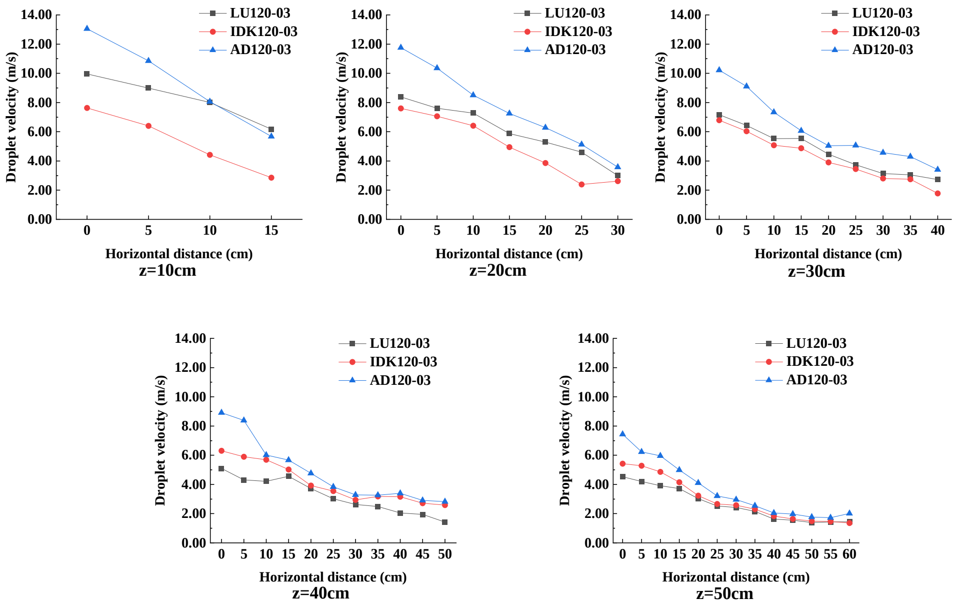


Figure 11. Horizontal direction droplet velocity V_X distribution in different nozzles.

4. Conclusions

In this paper, the effects of different adjuvants and pressures on the droplet size and velocity spatial distribution in different nozzle atomization area are comprehensively compared. The conclusions are as follows:

(1) In the spatial distribution of droplet volume median diameter $D_{v0.5}$, in the vertical direction of the nozzle center, the droplet size $D_{v0.5}$ has no significant change with the Z axis vertical distance. Compared with water, the distribution of the adjuvants on the droplet volume median diameter $D_{v0.5}$ was as follows: the average increase proportion of droplet volume median diameter was the largest by Maidao and Maisi, which increased by about 12%, followed by Surun by 10%, and the minimum was 9% of Adsee AB-600. Among the three nozzles, IDK120-03 nozzle produced the largest droplet volume median diameter $D_{v0.5}$ and the smallest droplet volume median diameter LU120-03. In the horizontal direction, the droplet volume median diameter $D_{v0.5}$ increases with the increase of horizontal distance, and the droplet size at the edge is the largest. The droplet size $D_{v0.5}$ increased with the increase of Maisi, Surun, AdseeAB-600 and Maidao adjuvants. The increase of droplet size $D_{v0.5}$ with Maisi adjuvants is the largest, while that with AdseeAB-600 and Maidao adjuvants was close to each other, and the smallest was the Surun adjuvants.

(2) In the droplet velocity spatial distribution, at the vertical direction of the nozzle center, the droplet velocity decreases with the increase of the vertical distance Z axis after the liquid is forced to atomize by the nozzle. The droplet velocity increases with pressure at the same position. In the four kinds of adjuvants solutions, the droplet velocity of Maisi, Maidao, Surun and AdseeAB-600 adjuvants increased by 13%, 9%, 8% and 4%, respectively, relative to water at the vertical direction of the nozzle center. In the three types of nozzles, the droplet velocity produced by the AD120-03 nozzle at the vertical direction of the nozzle center is greater than that of the IDK120-03 and LU120-03 nozzles. In the horizontal direction of atomization area, the droplet velocity decreases with the increase of horizontal distance of X axis. Compared with the droplet velocity distribution of the adjuvant solution, the droplet velocity of the Maisi is the largest in the horizontal direction, followed by the Surun, followed by the Maidao, and the smallest is the AdseeAB-600 adjuvant solution. Compared with the three types of nozzles, the droplet velocity V_Z of AD120-03 is the largest and the whole stage velocity is the largest in the horizontal direction. LU120-03 droplet velocity decreased most obviously, IDK120-03 droplet velocity decreased relatively slowly.

(3) Among the four types of adjuvants, it was found that the oil adjuvant Maisi could increase the droplet size and velocity, because the concentration of surfactant on the oil-water interface decreased with the stretching of the liquid sheet during the atomization of oil adjuvants, resulting in an increase in hydrophobicity. The hydrophobic oil droplets were easier to move to the gas-liquid interface to form holes, resulting in a large degree of droplet rupture. Due to the thick liquid sheet at the nozzle outlet, shift of emulsified droplet VMD to increasing VMD during breakage. When the droplet size needs to be increased, the oil-based silk adjuvants can be selected.

(4) Spraying different adjuvant solutions with different nozzles under different pressures can change the droplet size and velocity distribution, and the spatial distribution of droplet velocity and droplet size is different. The adjuvant in this paper can increase the droplet size, provide reference, and reduce the drift caused by small droplets to a certain extent, which has important research significance for improving the target rate and pesticide adhesion rate, and further improving the quality of pesticide application.

Author Contributions: Conceptualization, X.L. and R.Z.; methodology, R.Z. and Q.T.; software, X.L., W.C. and P.H.; validation, X.L., R.Z. and L.L.; formal analysis, X.L. and R.Z.; investigation, X.L. and W.C.; resources, Q.T., R.Z. and L.C.; data curation, X.L.; writing—original draft preparation, X.L.; writing—review and editing, X.L. and R.Z.; visualization, R.Z.; supervision, R.Z.; project administration, R.Z.; funding acquisition, R.Z. and L.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the National Key Research and Development Project of China [grant number 2019YFD1101102-3]; National Natural Science Foundation of China [grant number 32071907]; Outstanding Scientist Cultivation Project of Beijing Academy of Agriculture and Forestry Sciences (JKZX202205).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Faical, B.S.; Freitas, H.; Gomes, P.H.; Mano, L.Y.; Pessin, G.; de Carvalho, A.C.P.L.F.; Krishnamachari, B.; Ueyama, J. An adaptive approach for UAV-based pesticide spraying in dynamic environments. *J. Comput. Electron. Agric.* **2017**, *138*, 210–223. [CrossRef]
2. Focks, A.; ter Horst, M.; van den Berg, E.; Baveco, H.; van den Brink, P.J. Integrating chemical fate and population-level effect models for pesticides at landscape scale: New options for risk assessment. *J. Ecol. Model.* **2014**, *280*, 102–116. [CrossRef]
3. Spanoghe, P.; De, S.M.; Van, M.P.; Steurbaut, W. Influence of agricultural adjuvants on droplet spectra. *Pest Manag. Sci. Former. Pestic. Sci.* **2007**, *63*, 4–16. [CrossRef] [PubMed]
4. Yu, Y.; Zhu, H.; Ozkan, H.E.; Derksen, R.C.; Krause, C.R. Evaporation and deposition coverage area of droplets containing insecticides and spray additives on hydrophilic, hydrophobic, and crabapple leaf surfaces. *J. Trans. ASABE* **2009**, *52*, 39–49. [CrossRef]
5. Tuck, C.R.; Ellis, M.C.B.; Miller, P.C.H. Techniques for measurement of droplet size and velocity distributions in agricultural sprays. *J. Crop Prot.* **1997**, *16*, 619–628. [CrossRef]
6. Bozdogan, N.Y.; Bozdogan, A.M. Comparison of field and model percentage drift using different types of hydraulic nozzles in pesticide applications. *Int. J. Environ. Sci. Technol.* **2009**, *6*, 191–196. [CrossRef]
7. Cao, J. *Liquid Atomization*; Peking University Press: Beijing, China, 2013.
8. Huseyin, G.; Heping, Z.; Erdal, O.; Peter, L. Characterization of hydraulic nozzles for droplet size and spray coverage. *J. At. Sprays* **2012**, *22*, 627–645.
9. Emilia, H.; Arnoldus, W.P.V. Spray drift review: The extent to which a formulation can contribute to spray drift reduction. *J. Crop Prot.* **2013**, *44*, 75–83.
10. Bradley, K.; Fritz, W.; Clint, H.; Wale, B.; Greg, R.; Kruger, R.S.H. Measuring droplet size of agricultural spray nozzles—measurement distance and airspeed effects. *J. At. Sprays* **2014**, *24*, 747–760.
11. Zyl, S.; Brink, J.C.; Calitz, F.J.; Fourie, H.P. Effects of adjuvants on deposition efficiency of fenhexamid sprays applied to Chardonnay grapevine foliage. *J. Crop Prot.* **2010**, *29*, 843–852.
12. Wang, S.; Dorr, G.J.; Khashehchi, M.; Xiongkui, H. Performance of selected agricultural spray nozzles using particle image velocimetry. *J. Agric. Sci. Technol.* **2015**, *17*, 601–613.

13. Nita, M.; Ellis, M.A.; Wilson, L.L.; Madden, L.V. Evaluation of the curative and protectant activity of fungicides and fungicide–adjuvant mixtures on Phomopsis cane and leaf spot of grape: A controlled environment study. *J. Crop Prot.* **2007**, *26*, 1377–1384. [CrossRef]
14. Samuel, A.; Weidong, J.; Mingxiong, O.; Pei, W.; Eric, A.A. Analysis of potential impaction and phytotoxicity of surfactant-plant surface interaction in pesticide application. *Crop Prot.* **2020**, *127*, 104961.
15. Joseph, E.H.; Travis, W.G.; Robert, J.R.; Fred, H.Y.; Ramon, G.L. Coverage and drift potential associated with nozzle and speed selection for herbicide applications using an unmanned aerial sprayer. *J. Weed Technol.* **2020**, *34*, 235–240.
16. Zhang, W.; He, X.; Song, J.; Wang, C.; Herbst, A. Effect of additive S240 on atomization of water dispersible granule and emulsion medicine. *J. Trans. Chin. Soc. Agric. Eng.* **2014**, *30*, 61–67.
17. Zhao, H.; Song, J.; Zeng, A.; He, X. Relationship between dynamic surface tension of spray liquid and droplet size. *J. Trans. Chin. Soc. Agric. Mach.* **2009**, *40*, 74–79.
18. Robert, N.K.; Jeffrey, A.G. The effect of spray particle size and distribution on drift and efficacy of herbicides. *J. Asp. Appl. Biol. Int. Adv. Pestic. Appl.* **2004**, *71*, 44–51.
19. Ferguson, J.C.; O'Donnell, C.C.; Chauhan, B.S.; Adkins, S.W.; Kruger, G.R.; Wang, R.B.; Ferreira, P.H.U.; Hewitt, A.J. Determining the uniformity and consistency of droplet size across spray drift reducing nozzles in a wind tunnel. *J. Crop Prot.* **2015**, *76*, 1–6. [CrossRef]
20. Wang, X.; He, X.; Song, J.; Herbst, A. Effect of additives type and concentration on droplet drift of different nozzles. *J. Trans. Chin. Soc. Agric. Eng.* **2015**, *31*, 49–55.
21. Zhang, R.; Zhang, Z.; Xu, G.; Chen, L.; Hewitt, A.J. Effect of spray auxiliaries type and concentration on spray nozzle atomization effect. *J. Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 36–43.
22. Tian, Z.; Yuan, G.; Gao, P.; Shen, G. Study of effects of different spray fertilizer on rice paddy herbicide reduction. *J. Plant Prot.* **2020**, *46*, 297–302.
23. Liu, Y.; Zhang, G.; Zhou, C.; Wang, W.; Hu, Y.; Mu, W. Synergistic effects of cationic auxiliaries 1227 and $C_{(8\text{-}10)}$ and organosilicon auxiliaries Breakthru S240 on three insecticides. *J. Insects* **2011**, *54*, 902–909.
24. Xie, C.; He, X.; Song, J.; Herbst, A. Comparative study on atomization process of two types of fan fog heads. *J. Trans. Chin. Soc. Agric. Eng.* **2013**, *29*, 25–30.
25. Tang, Q.; Chen, L.; Zhang, R.; Zhang, B.; Yi, T.; Xu, M.; Xu, G. Atomization characteristics of standard fan nozzle and air induced nozzle under high speed airflow. *J. Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 121–128.
26. Zhang, J.; Song, J.; He, X.; Zeng, A.; Liu, Y. Droplet motion characteristics in the process of fan-shaped spray nozzle atomization. *J. Trans. Chin. Soc. Agric. Mach.* **2011**, *42*, 66–69.
27. Li, S.; Chen, C.; Wang, Y.; Kang, F.; Li, W. Study on the Atomization Characteristics of Flat Fan Nozzles for Pesticide Application at Low Pressures. *J. Agric.* **2021**, *11*, 309. [CrossRef]
28. Chen, C.; Li, S.; Wu, X.; Wang, Y.; Kang, F. Analysis of droplet size uniformity and selection of spray parameters based on the biological optimum particle size theory. *J. Environ. Res.* **2021**, *11*, 109. [CrossRef]
29. Vallet, A.; Tinet, C. Characteristics of droplets from single and twin jet air induction nozzles: A preliminary investigation. *J. Crop Prot.* **2013**, *48*, 63–68. [CrossRef]
30. *ASAE Standards S572*; Spray Nozzle Classification by Droplet Spectra. ASAE: St. Joseph, MI, USA, 2004.
31. Zhang, H.; Zhou, H.; Zheng, Z.; Liao, J.; Hewitt, A.J. Effects of pesticide auxiliaries on aerosol droplet size for airborne and ground control of forest pests. *J. Sci. Silvae Sin.* **2020**, *56*, 118–129.
32. Makhnenko, I.; Alonzi, E.R.; Fredericks, S.A.; Colby, C.M.; Dutcher, C.S. A review of liquid sheet breakup: Perspectives from agricultural sprays. *J. Aerosol Sci.* **2021**, *157*, 105805. [CrossRef]