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Experimental Study of the Droplet Deposition Characteristics on an Unmanned Aerial Vehicle Platform under Wind Tunnel Conditions

Yuxuan Jiao, Xinyu Xue *, Suming Ding, Qingqing Zhou, Wei Kong, Yong Tian and Xiaoming Liu

Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China
* Correspondence: xuexinyu@caas.cn; Tel.: +86-25-8434-6243

Abstract: Unmanned aerial vehicles (UAVs) are widely used in field pesticide spray operations due to their wide applicability and high operational efficiency. However, their high spray height and fine pesticide droplets lead to a greater risk of drift and likely different droplet deposition outcomes compared to the expectation. So far, most of the previous studies have used direct field methods on UAVs' droplet deposition characteristics and there have been few carried out in wind tunnels. Thus, in this paper, a simulated UAV platform equipped with TeeJet 80-015 VP fan nozzles was utilized to study the droplet deposition characteristics in a wind tunnel. The droplet deposition amount and drift potential reduction percentage (*DPRP)* under different spray parameters were obtained. The results showed that when the rotor was open, the deposition amount in the target area increased by 2.6 times and the drift deposition amount decreased by 7.3 times when spraying tap water at 3 m/s wind speed and 3 bar pressure. Faster wind speeds led to greater drift deposition amounts and a lower *DPRP*, but higher pressures resulted in greater drift deposition amounts and a larger *DPRP*. The 30 g/L PEG-20000 solution has a higher droplet size and smaller relative droplet spectrum width R_s, resulting in the deposition amount in the target area increasing by 9.13% on average and the drift amount decreasing by 24.7% on average, and it can be used as an anti-drift additive when needed. The research results can provide reference and technical support for UAV wind tunnel tests and field operation specifications.

Keywords: unmanned aerial vehicles; wind tunnel; droplet deposition characteristics; drift potential reduction percentage

Citation: Jiao, Y.; Xue, X.; Ding, S.; Zhou, Q.; Kong, W.; Tian, Y.; Liu, X. Experimental Study of the Droplet Deposition Characteristics on an Unmanned Aerial Vehicle Platform under Wind Tunnel Conditions. *Agronomy* **2022**, *12*, 3066. https://doi.org/10.3390/agronomy12123066

Academic Editors: Paul Kwan and Yanbo Huang

Received: 1 November 2022
Accepted: 1 December 2022
Published: 3 December 2022

1. Introduction

Plant protection UAVs have gradually become the preferred plant protection machine for pesticide application operations due to the advantages of high operation efficiency, low cost, and freedom from terrain restrictions [1–3]. Aerial pesticide spraying application technology has also become a research hotspot [4–6]. In an ideal situation, all pesticide droplets should effectively deposit in the target area. However, in the actual operation, some pesticide droplets will drift to the non-target area due to the airflow [7,8], resulting in low pesticide utilization rates and environmental pollution [9,10]. Droplets sprayed by plant protection UAVs are more prone to drift due to the high spray height and small droplet size. Fish poisoning deaths in ponds, adjacent crops withered by pesticide damage, and other problems due to pesticide drift have occurred frequently over the past few decades. The above pesticide accidents have caused a lot of economic disputes and human health problems [11,12].

In order to reduce drift, researchers have conducted a variety of studies on factors that influence droplet deposition. The test methods of droplet deposition mainly include field tests and wind tunnel tests. Field tests can obtain the actual droplet deposition characteristics under typical conditions [13]. Chen et al. [14] studied the droplet deposition distribution of a four-rotor UAV in different growth stages of rice and found the droplet deposition density and coverage rate of small-size nozzles were high. Xiao et al. [15] found that adding aerial spray adjuvant can substantially increase the UAV's droplet deposition and reduce the drift when spraying cotton defoliant. Compared with field tests, wind tunnel tests were especially convenient for the initial acquisition of droplet deposition characteristics [16]. Zhang et al. [17] established a multivariate nonlinear droplet drift characteristic model including sampling distance, wind speed, nozzle type, and pesticide type in a wind tunnel. Ding et al. [18] found adjusting the spray angle can reduce the droplet drift through wind tunnel experiments. Although it is obvious that the field test is more in line with the actual operation situation, the meteorological conditions are very unstable and uncontrollable, which greatly affect the repeatability and operability of the measurement [19]. Spray parameters can be precisely controlled, and pesticides can be safely discharged without causing soil contamination in the wind tunnel [20–22].

During the process of droplet deposition, the ambient airflow will carry droplets to deposit in the non-target area while the downwash airflow, as an important feature of the UAV, generated by the rotors can help droplets to deposit quickly to some extent [23,24]. So, the impact of airflows in the research of droplet deposition characteristics of aerial spray must be combined [25–27]. There have been a lot of studies on droplet deposition characteristics in field experiments, but few have been reported under the action of downwash airflow in wind tunnels. This study explored the influencing factors of UAV spray deposition characteristics in a wind tunnel. An UAV spray device with rotors was installed at the end of the wind tunnel to generate downwash airflow, and the airflow from the wind tunnel was regarded as the crosswind. The effect of the droplet size and crosswind speed on the deposition were tested. The results were expected to provide guidance for spray deposition experiments in wind tunnels and the field operation procedures of plant protection UAVs.

2. Materials and Methods

In December 2020, the test was carried out in the NJS-1 wind tunnel [28] of the Sino–US Joint Spraying Center of the Nanjing Institute of Agricultural Mechanization of the Ministry of Agriculture and Rural Affairs. At that time, the room temperature was 14 ± 2 °C, the ambient wind speed was 0.6 ± 0.2 m/s, and the relative humidity of the air was 60–65%. The technical parameters of the wind tunnel are stable and can be continuously adjusted within the limited range. The operation section is 1.2 m wide, 1.8 m high, and 10.0 m long. The wind tunnel controls the rotational speed of the axial fan by changing the frequency of the frequency converter, thereby generating uniform airflow with airflow speed ranging from 0.5 m/s to 10.0 m/s.

2.1. Nozzle and Spray Medium

The wind tunnel test should be as consistent as possible with the actual field operation, so that the results are more reliable and comparable. Due to the unique spray method of UAVs, low-flow and fine droplet nozzles are commonly used for aerial spray. Generally, fine droplets have high drift risks and long drift distances, so it would be more obvious and practical to study their deposition and drift. Therefore, the 80-015 VP fan nozzle (TeeJet Technologies Co. Ltd., Ningbo, China, Figure 1) was selected.

The use of pesticide solutions to evaluate droplet deposition is the most reliable method. However, the widespread use of pesticide solutions, waste disposal, and frequent repetition of experiments can pose hazards to the health of the experimenters. Considering the extensive use of additives in plant protection operations at present, in addition to tap water from the laboratory, the commonly used surfactant polyethylene glycol 20000 (PEG-20000) (Xilong Science Co., Ltd., Shantou, China, Figure 2) was selected as the spray medium to mix with water at a concentration of 30 g/L. Moreover, a safe, water-soluble and economical fluorescent tracer BSF was added to the solution at a concentration of 0.3 g/L for the spray to facilitate the measurement of droplet deposition. The spray solution was reconstituted every day before the start of the tests.

Figure 1. TeeJet 80-015 VP fan nozzle.

Figure 2. Polyethylene glycol 20000.

2.2. Atomization Characteristic Test

Without considering any external factors, the droplet size is one of the most vital factors affecting the droplet deposition characteristics. The droplet size of the nozzle at three common working pressures (2, 3, and 4 bar) were measured. The atomization characteristic test device was arranged in the wind tunnel, and it consisted of a DP-02 laser particle size analyzer (Zhuhai Omega Instrument Co., Ltd., Zhuhai, China, measure range 0.1~1500 μm), 3WZ-25 triplex plunger pump (Physical Agriculture and Forestry Machinery Technology Co., Ltd., Suzhou, China), pressure gauge (Shanghai Automation Instrument Co., Ltd., Shanghai, China), linear guide, pressure regulating valve and nozzle, and other components. The research of Fritz et al. [29] showed that a test droplet size at low air velocities will result in the large bias in oversampling the smallest drop diameter portion of the spray. When the wind speed is ≥6.7 m/s and the distance between the nozzle and the laser is 30.5 cm, the spatial deviation of the particle size results can be controlled within 5%, so this setting was adopted for the measurement of droplet size. The spray surface of the nozzle was parallel to the airflow of the wind tunnel, as shown in Figure 3.

There are numerous indicators of droplet size in agricultural sprays and the most typical ones are D_{V10}, D_{V50}, and D_{V90}. It is usually dominated by the volume median diameter D_{V50} [30], which indicates the volume of droplet size smaller than D_{V50} accounts for 50% of the total volume. The droplet size uniformity was indexed by the relative droplet spectrum width R_S [31], which represents the span of the droplet diameter relative to the volume median diameter; see Equation (1). The smaller the R_S value, the narrower the droplet spectrum width and the better the uniformity of the droplet size.

$$R_S = \frac{D_{V90} - D_{V10}}{D_{V50}} \quad (1)$$

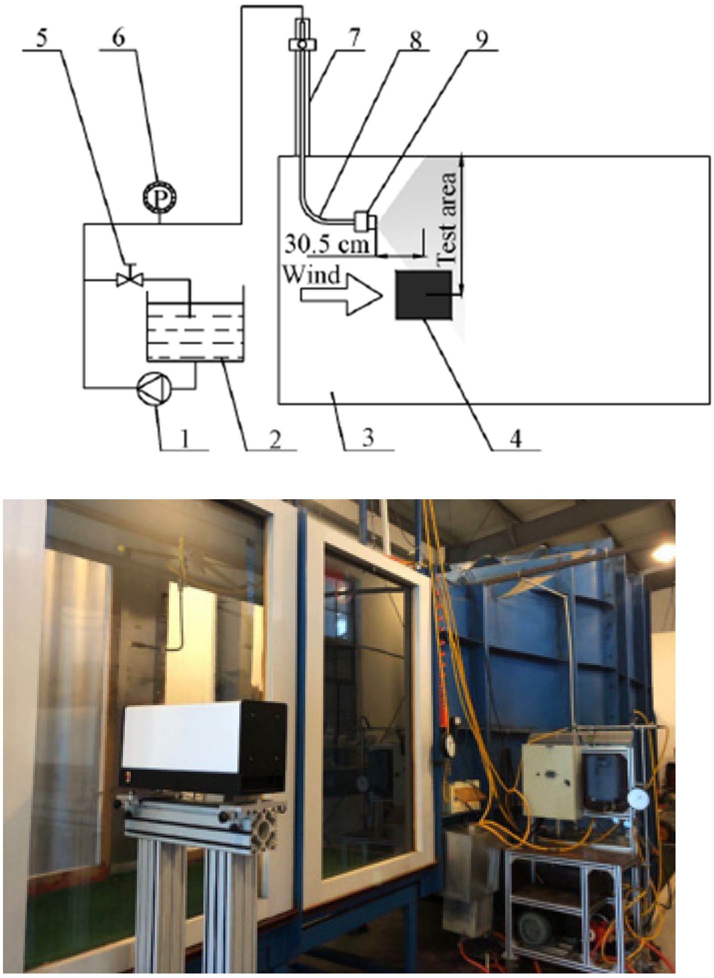


Figure 3. Atomization characteristics test device. 1—pump, 2—medicine box, 3—wind tunnel, 4—DP-02 laser particle size analyzer, 5—pressure regulating valve, 6—pressure gauge, 7—lifting guide rail, 8—spout, and 9—nozzle.

2.3. Droplet Deposition Test

In order to study the spray deposition characteristics of UAVs, considering the safety of the test process, it was planned for a simulated UAV platform to be placed at the end of the wind tunnel. The platform consisted of rotors (Shanghai TopXGun Robotics Co., Ltd., Shanghai, China), motors, and spray systems. The rotor's diameter was 0.56 m, co-axial with the nozzle, and the working speed can be adjusted in the range from 500 r/min to 3000 r/min. In order to guarantee the accuracy of the test results, it was necessary to collect complete droplets under the action of the non-destructive downwash airflow as much as possible. The use of symmetrically placed double nozzles would cause the spray range to exceed the width of the wind tunnel and droplets in the edge region would not be affected by the wind tunnel airflow. Therefore, only one nozzle was rotated and placed on the central axis of the broadside of the wind tunnel, as shown in Figure 4. In this way, the real deposition characteristics of a single nozzle under a single rotor can be obtained, which lays a foundation for the subsequent research on the interaction of multiple nozzles under the action of multiple rotors and makes a comparison.

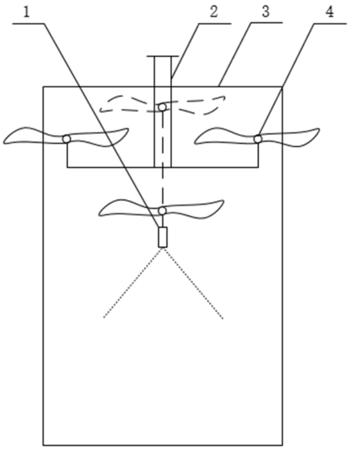


Figure 4. Rotor platform. 1—nozzle, 2—lifting rod, 3—wind tunnel outlet, and 4—rotor.

Referring to the research on the optimal working height of plant protection UAVs [32–34], the field operation height of plant protection UAVs was generally 1.5~2 m and the droplet deposition characteristics were relatively good in this range. In this study, the height of the nozzle from the collector was set to be 1.5 m, and the spray direction of the nozzle was vertically downward. According to the standard ISO 22856 [35], the droplet deposition was collected by a polyethylene line with a diameter of 2 mm and a length of 1.1 m to ensure that the polyethylene line was within the range of the wind tunnel airflow. At the position 2 m away from the nozzle in the downwind direction, five collection lines were placed from 0.1 to 0.5 m above the wind tunnel floor at 0.1 m intervals, which were used to collect droplets passing through the vertical plane of air, named V_1, V_2, V_3, V_4, and V_5; the horizontal collection lines were arranged at intervals of 1 m from directly below the nozzle to 7 m in the downwind direction, and they were used to detect the deposition in the target area of 0,1 m and the drift of 2–7 m, named H_1, H_2, H_3, H_4, H_5, H_6, H_7, and H_8 (where $V_1 = H_3$), as shown in Figure 5. Considering the saturation of the deposition amount on the collection lines, the flow of the nozzle was controlled by an electronic timer which controlled the opening and closing of the solenoid valve to ensure the spray time of each test was fixed at 10 s.

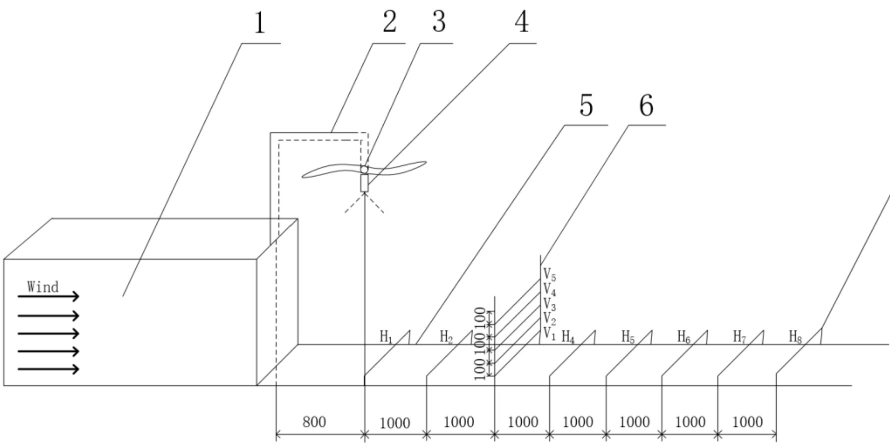


Figure 5. Droplet deposition distribution test device. 1—wind tunnel, 2—lifting rod, 3—rotor, 4—nozzle, 5—support frame, 6—vertical collection frame, and 7—horizontal collection frame.

In this study, spraying was carried out at three usual working pressures (0.2, 0.3, and 0.4 bar) and three wind tunnel speeds (1, 3, 5 m/s), and the rotor worked at a speed of 3000 r/min to simulate the operation state of the UAV in fields. The deposition results of spraying water at the wind speed of 3 m/s and 3 bar pressure when the rotor stopped were used as the reference spray. The purpose of fixing a reference spray is to make the results comparable for different crosswind speeds or pressures.

After each spray, it was necessary to wait for 10 min to ensure the droplets on the polyethylene lines were solidified, then tweezers were used to remove lines from the collection rack and they were placed into U-shaped tubes filled with 30 mL distilled water, fully shaken, and washed with an ultrasonic cleaner. After washing, the eluate was poured into the prepared test tube, and the concentration of the fluorescent agent was determined by a calibrated fluorescence spectrophotometer (ThermoFisher Scientific Co., Ltd., Shanghai, China). At the same time, in order to ensure the consistency of the test, at the beginning and the end of each test, calibration should be carried out under the conditions of 3 bar spray pressure and 3 m/s wind speed. If the results of both tests were within the 90% confidence interval, the results were considered acceptable, otherwise the test parameters were recalibrated. If the results were all within the 90% confidence interval, each treatment was repeated three times and the average was taken as the final data.

2.4. Calculation of Potential Drift Performance

In order to better illustrate the drift performance of the nozzle under different spray conditions, the drift potential (*DP)* in this paper represents the relative value of the drift deposition compared with the spray volume of the nozzle. The calculation method of numerical integration was used to study the drift potential (*DP)* in the vertical and horizontal directions, respectively DP_V and DP_H.

The DP_V calculation method on the vertical plane 2 m downwind from the nozzle is shown in Equations (2) and (3). This method was proposed by Miller et al. [36], and Herbst et al. [37] also used this method for statistical analysis.

$$DP_V = \sum_{i=1}^{5} P_{Vi} \times \Delta h_i \tag{2}$$

$$P_{Vi} = (\frac{A_{Vi} \times W \times 10^{-3}}{K} \times 6 \times 10^6) / Q \tag{3}$$

Among them, DP_V represents the spatial drift potential performance based on numerical integration of the plane at a distance of 2 m from the nozzle, μL/mL; P_{Vi} is the relative drift deposition amount on the i-th vertical collection line for every 1 L of solution sprayed by the nozzle, μL/L; $\triangle h_i$ is the height interval corresponding to each collection line, from V_1 to V_5 they are 0.05, 0.1, 0.1, 0.1, and 0.05 m, respectively; A_{Vi} is the drift deposition amount on the i-th vertical collection line, mg/L; W is the elution water volume, 30 mL; K *is* the tracer concentration, 300 mg/L; and Q *is* the nozzle flow, L/min.

The DP_H calculation method of the nozzle on the horizontal settlement surface is shown in Equations (4) and (5). Nilars [38] used this method for statistical analysis.

$$DP_H = \sum_{i=1}^{6} P_{Hi} \times \Delta x_i \tag{4}$$

$$P_{Hi} = (\frac{A_{Hi} \times W \times 10^{-3}}{K} \times 6 \times 10^6) / Q \tag{5}$$

Among them, DP_H represents the ground drift potential performance based on numerical integration, μL/mL; P_{Hi} *is* the relative drift deposition amount on the i-th horizontal collection line for every 1 L of solution sprayed by the nozzle, μL/L; A_{Hi} *is* the drift deposition amount on the i-th horizontal collection line, mg/L; and $\triangle h_i$ *is* the distance interval corresponding to each collection line, from H_3 to H_8 they are 0.5, 1, 1, 1, 1, and 0.5 m, respectively.

Based on the above calculation, all other spray conditions are compared with the reference spray to calculate the drift potential reduction percentages (*DPRP)*, as shown in Equation (6):

$$DPRP = \frac{(DP^{rs} - DP^{os})}{DP^{rs}} \times 100\% \tag{6}$$

Among them, *DPRP* represents the percentage of drift potential reduction, %; DP^{rs} represents the drift potential under the reference spray, μL/mL; and DP^{os} represents the drift potential under other spray conditions, μL/mL.

3. Results

3.1. Atomization Characteristics

Table 1 shows the atomization characteristics of the nozzle under different spray parameters. The D_{V50} under three pressures was 113.21~139.09 μm when spraying tap water and 166.75~204.02 μm when spraying 30 g/L PEG-20000 solution, which increased by 46.7% compared with water. There were significant differences in D_{V50} under different spray parameters. As the pressure increased, the relative droplet spectrum width R_S increased when spraying tap water and decreased when spraying 30 g/L PEG-20000 solution. The uniformity of droplet size when spraying 30 g/L PEG-20000 solution was better than that of tap water.

When the droplet size is less than 150 μm, the anti-drift performance will be poor [39]. $\Phi_{Vol<150\mu m}$ indicates the cumulative ratio of the droplet size less than 150 μm. Compared with water, the $\Phi_{Vol<150\mu m}$ decreased by 47.3% when spraying 30 g/L PEG-20000 solution.

It was found that spraying 30 g/L PEG-20000 solution can increase the droplet size, decrease the proportion of fine droplets, and improve the uniformity of atomization, which can effectively improve the anti-drift performance of the droplets.

Table 1. Atomization characteristics of the nozzle under different spray parameters.

Spraying Medium	Pressure/bar	D_{V10}/μm	D_{V50}/μm	D_{V90}/μm	$\Phi_{Vol<150\mu m}$/%	Droplet Spectrum Width R_S/%
Tap water	2	84.76	139.09 (±2.42) a	234.36	53.92 (±0.95)	1.08 (±0.06) a
	3	77.43	126.51 (±4.54) b	221.83	59.28 (±2.18)	1.14 (±0.02) b
	4	71.37	113.21 (±1.50) c	205.15	66.25 (±0.87)	1.18 (±0.02) b
30 g/LPEG-20000	2	134.51	204.02 (±3.50) d	354.54	20.76 (±0.14)	1.08 (±0.06) a
	3	129.26	184.90 (±2.32) e	308.80	30.56 (±0.46)	0.97 (±0.02) c
	4	125.28	166.75 (±4.13) f	279.99	44.98 (±0.34)	0.93 (±0.04) c

Note: The same letter after the data in the same column indicates that there was no significant difference within the 95% confidence interval.

3.2. Droplet Deposition Amount

The droplet deposition amount in the vertical and horizontal directions of each collection line are shown in Tables 2 and 3. It can be evidently seen that under the action of the rotor downwash airflow, the overall trend was that the deposition amount was the largest in the target area of 0,1 m, and the drift deposition amount of 2–7 m in the horizontal direction decreased with the increasing distance from the nozzle. The drift deposition amount in the vertical direction increased with the increase in the distance from the nozzle.

The effect of wind speed on the droplet deposition amount was of great importance. At 1 m/s wind speed, the total drift deposition amount in the horizontal and vertical directions accounted for 3.61% of the deposition amount in the target area when spraying water and accounted for 1.77% when spraying 30 g/L PEG-20000 solution. In the horizontal direction, the droplets mainly deposited directly below the nozzle when spraying with water and 30 g/L PEG-20000 solution; in the vertical direction, only a small number of droplets deposited at 0.1 m above the ground. The main reason for the situation was that the downward pressure of the rotor downwash airflow on the droplets was much greater than the coercing effect of the low-speed airflow on the droplets, so that most of the droplets deposited directly below the nozzle. When the wind speed increased to 3 m/s, the total drift deposition amount accounted for 28.33% of the deposition amount in the target area when spraying tap water and accounted for 23.8% when spraying 30 g/L PEG-20000 solution. In the horizontal direction, the droplet deposition amount below the nozzle was greatly reduced, and more droplets deposited at 1 m away from the nozzle. Under the combined action of the rotor downwash airflow and the high-speed wind tunnel airflow, the droplet deposition direction began to change from the vertical downward direction to the rear. Droplets began to deposit from 0.2 to 0.5 m in the vertical direction because the airflow had an enhanced ability to carry the droplets and fine droplets were subjected to the backward action of the wind tunnel airflow at the moment of leaving the nozzle. The smaller the droplet size, the faster the backward flying speed and the higher the horizontal and vertical distance of the drift. When the wind speed increased to 5 m/s, the droplet drift deposition in both the horizontal and vertical directions increased significantly. The total drift deposition amount accounted for 199% of the deposition amount in the target area when spraying tap water and accounted for 142.1% when spraying 30 g/L PEG-20000 solution. In the horizontal direction, only a small number of droplets deposited below the nozzle and the droplets mainly deposited at distances of 1,2 m away from the nozzle.

The deposition and drift amount were proportional to the pressure in both the horizontal and vertical directions. The effect of pressure was more obvious with the increase in wind speeds. Under the same spray parameter, compared with the tap water, the deposition amount in the target area increased by 9.13% and the drift deposition amount decreased by 24.7% on average when spraying 30 g/L PEG-20000 solution, which confirmed that 30 g/L PEG-20000 solution could effectively improve the anti-drift performance of the droplets.

Except the fact that the drift deposition in the vertical direction was more than that of the reference spray when the wind speed was 5 m/s and the pressure was 4 bar, the drift deposition in the horizontal and vertical directions under other spray parameters was less than that of the reference spray. Moreover, the droplet deposition in the target area under the reference spray was far less than that of other sprays. Under the effect of the downwash airflow, the deposition amount in the target area is 3.56 times and the total drift deposition amount is 0.12 times of the reference spray when spraying tap water at 3 m/s wind speed and 3 bar pressure. More intuitively, the deposition amount in the target area and total drift deposition amount at 5 m/s wind speed and 3 bar pressure is 2.86 times and 0.63 times that of the reference spray. The downwash airflow significantly increased the droplet deposition in the target area while suppressing the drift of a large number of droplets.

Table 2. The relative deposition amount on the vertical collection line P_{Vi}.

Spraying Medium	Wind Speed/m·s^{-1}	Pressure/bar	Droplet Deposition Amount/μL·L^{-1}					Total Drift Deposition (V_1+…V_5)/μL·L^{-1}
			V_5	V_4	V_3	V_2	V_1	
Tap water	1	2	0.00 (±0.00)	0.00 (±0.00)	0.00 (±0.00)	0.00 (±0.00)	32.30 (±0.66)	32.3
		3	0.00 (±0.00)	0.00 (±0.00)	4.52 (±0.76)	1.21 (±0.13)	29.05 (±3.40)	34.78
		4	0.00 (±0.00)	0.00 (±0.00)	0.00 (±0.00)	0.00 (±0.00)	35.64 (±0.66)	35.64

	3	2	40.50 (±1.66)	66.21 (±2.92)	70.68 (±2.79)	54.66 (±1.00)	53.04 (±2.13)	285.09
		3	28.19 (±1.93)	46.80 (±2.33)	42.40 (±0.28)	62.80 (±0.72)	150.40 (±7.21)	330.59
		4	21.42 (±2.46)	40.00 (±2.05)	35.82 (±1.83)	73.78 (±0.24)	166.10 (±4.45)	337.12
	5	2	72.30 (±2.23)	85.47 (±1.68)	231.40 (±9.24)	396.00 (±11.14)	764.86 (±10.34)	1549.97
		3	53.57 (±2.80)	119.80 (±0.90)	301.70 (±3.37)	500.20 (±12.12)	833.20 (±5.37)	1808.47
		4	115.80 (±5.47)	223.80 (±6.85)	404.4 (±10.73)	902.20 (±30.72)	1099.5 (±12.58)	2745.2
30 g/L PEG-20000	1	2	0.00 (±0.00)	0.00 (±0.00)	0.00 (±0.00)	0.00 (±0.00)	10.81 (±0.46)	10.81
		3	0.00 (±0.00)	0.00 (±0.00)	0.00 (±0.00)	0.00 (±0.00)	20.10 (±0.47)	20.1
		4	0.00 (±0.00)	0.00 (±0.00)	0.00 (±0.00)	0.00 (±0.00)	19.73 (±0.79)	19.73
	3	2	3.73 (±0.16)	0.00 (±0.00)	5.34 (±0.26)	56.27 (±1.32)	119.30 (±3.55)	184.64
		3	31.56 (±0.80)	51.06 (±0.88)	62.11 (±2.52)	89.35 (±3.07)	101.10 (±5.85)	335.18
		4	76.98 (±3.31)	79.29 (±1.51)	80.00 (±0.50)	98.31 (±3.47)	137.31 (±4.25)	471.89
	5	2	52.00 (±0.65)	93.40 (±0.94)	139.80 (±0.83)	328.20 (±7.36)	501.62 (±7.51)	1115.02
		3	66.03 (±0.94)	108.20 (±0.96)	164.90 (±1.65)	461.30 (±1.85)	594.53 (±10.32)	1394.96
		4	39.82 (±2.94)	88.36 (±1.94)	174.40 (±2.09)	550.06 (±8.73)	682.05 (±6.09)	1534.69
Reference Spray			12.85 (±0.08)	54.46 (±0.11)	206.2 (±5.16)	799.43 (±11.31)	1069.8 (±12.36)	2142.69

Table 3. The relative deposition amount on the vertical collection line P_{Hi}.

Spraying Medium	Wind Speed/m·s⁻¹	Pressure/bar	Droplet Deposition Amount/μL·L⁻¹								Target Area Deposition (H_1+H_2)/μL·L⁻¹	Total Drift Deposition $(H_3+…H_8)$/μL·L⁻¹
			H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8		
Tap water	1	2	2077.2 (±67.4)	97.1 (±6.4)	32.3 (±0.7)	12.4 (±1.1)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	2174.14	44.72
		3	2062.1 (±48.4)	227.5 (±8.6)	29.1 (±3.4)	16.7 (±0.5)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	2289.5	45.73
		4	2162.4 (±25.9)	238.5 (±11.3)	35.6 (±0.7)	18.9 (±1.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	2400.5	54.57
	3	2	1175.5 (±16.7)	434.2 (±7.0)	123.0 (±2.1)	22.6 (±0.5)	1.2 (±0.2)	1.7 (±0.2)	0.0 (±0.0)	0.0 (±0.0)	1609.1	148.63
		3	1267.2 (±4.2)	572.8 (±10.0)	150.4 (±7.2)	38.9 (±2.3)	8.2 (±0.4)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	1839.8	201.29
		4	1373.3 (±18.0)	581.7 (±9.5)	166.1 (±4.5)	14.6 (±0.9)	35.1 (±1.5)	9.1 (±0.6)	4.1 (±0.4)	0.1 (±0.0)	1954.7	229.02
	5	2	16.0 (±0.8)	1406.1 (±29.8)	764.9 (±10.3)	42.4 (±1.6)	22.6 (±0.5)	16.0 (±0.3)	9.4 (±0.3)	1.9 (±0.2)	1422.02	857.02
		3	20.9 (±1.7)	1456.3 (±35.9)	833.2 (±5.4)	19.1 (±0.5)	42.4 (±1.1)	11.4 (±0.9)	13.6 (±0.8)	6.3 (±0.2)	1476.9	926.01
		4	23.8 (±2.6)	1623.4 (±30.5)	1099.5 (±12.6)	122.4 (±3.8)	22.0 (±0.4)	6.3 (±0.3)	1.1 (±0.1)	0.0 (±0.0)	1646.82	1250.85
30 g/L PEG-20000	1	2	2202.1 (±15.8)	135.2 (±3.8)	10.8 (±0.5)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	2337.32	10.81
		3	2310.9 (±20.1)	260.5 (±6.0)	20.1 (±0.5)	10.4 (±0.2)	0.0 (±0.0)	0.9 (±0.1)	0.0 (±0.0)	0.0 (±0.0)	2571.42	31.35
		4	2530.2 (±30.0)	296.2 (±6.0)	19.7 (±0.8)	13.2 (±0.7)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	2826.42	32.89
	3	2	1216.2 (±19.7)	537.5 (±7.9)	99.3 (±3.6)	28.4 (±0.3)	9.8 (±0.1)	9.0 (±0.5)	9.6 (±0.4)	4.2 (±0.2)	1753.71	160.32
		3	1461.5 (±19.4)	706.2 (±5.0)	101.1 (±5.9)	36.9 (±1.8)	21.6 (±0.4)	8.0 (±0.3)	3.2 (±0.4)	0.0 (±0.0)	2167.75	170.84

		4	1650.2 (±33.0)	694.2 (±12.6)	137.3 (±4.3)	44.1 (±1.2)	12.0 (±0.5)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	2344.39	193.36
		2	143.7 (±3.9)	955.6 (±3.7)	501.6 (±7.5)	88.0 (±1.8)	69.2 (±2.1)	38.0 (±0.5)	11.5 (±0.3)	2.9 (±0.1)	1099.36	711.21
	5	3	41.8 (±0.7)	1714.1 (±24.8)	594.5 (±10.3)	90.4 (±0.9)	24.1 (±1.0)	12.1 (±0.7)	6.7 (±0.3)	3.1 (±0.2)	1755.88	730.84
		4	52.3 (±1.2)	1622.3 (±30.2)	682.1 (±6.1)	75.1 (±2.5)	11.6 (±0.6)	12.5 (±0.4)	8.3 (±0.3)	3.6 (±0.2)	1674.53	793.28
Reference spray			93.52	422.38	1069.75	591.76	272.70	146.13	83.25	26.13	515.90	2189.72

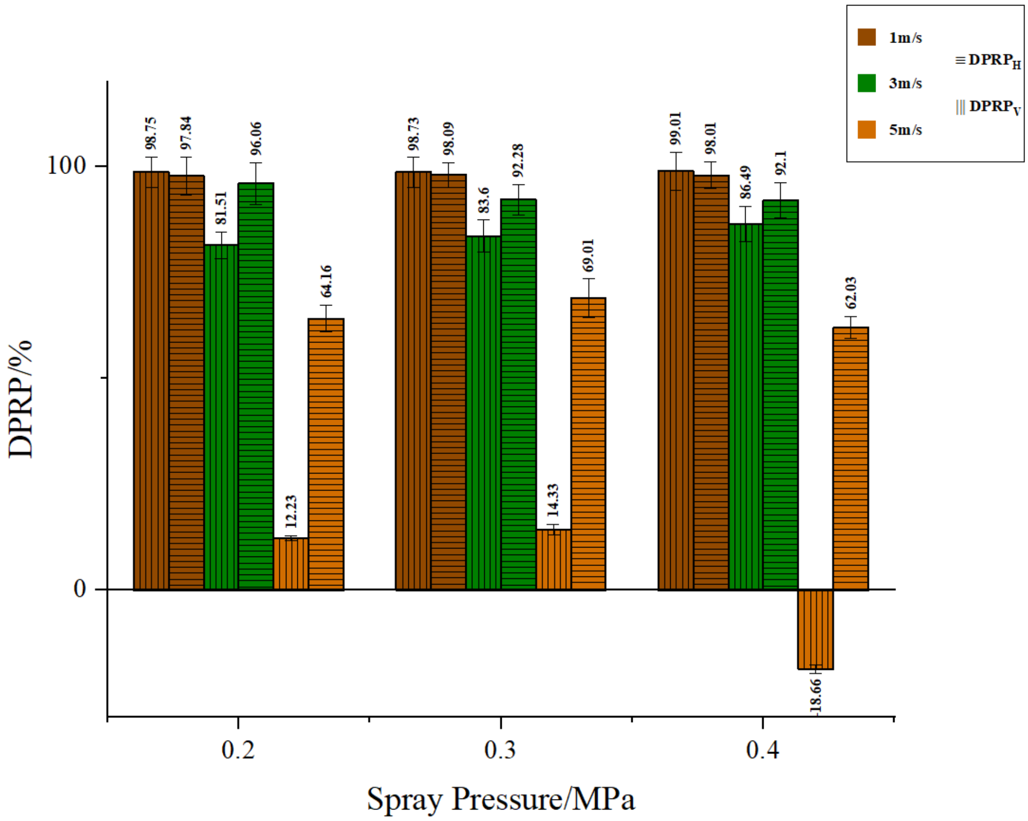
3.3. Drift Potential Reduction Percentage

From Table 4, it can be seen that the *DP* in the vertical direction was more than that of the reference spray only when spraying tap water at a wind speed of 5 m/s and a pressure of 4 bar, and the *DP* in the horizontal and vertical directions under other spray parameters were all less than those of the reference spray, which was consistent with the trend of drift deposition amount. As can be seen from Figure 6, compared with the effect of pressure on the drift deposition amount, the effect of pressure on the *DPRP* was small, and there was a situation whereby *DPRP* increased with the increase in pressure. However, it has been concluded above that, the pressure was proportional to the drift deposition amount. The reason for this situation was that the increase in pressure led to an increase in the flow rate of the nozzle, and the ratio of the drift deposition amount to the flow rate of the nozzle was likely to decrease, so *DP* decreased and *DPRP* increased. From Figure 7, the effect of wind speed on *DPRP* was highly noteworthy, especially in the vertical direction. Under the wind speed of 1 m/s, the average $DPRP_H$ of the spraying water and 30 g/L PEG-20000 solution was 98.5%, and the average $DPRP_V$ was 99.15%; under 3 m/s wind speed, the $DPRP_H$ decreased to 92.84% and the $DPRP_V$ decreased to 85.82%; while under 5 m/s wind speed, the $DPRP_H$ decreased to 67.01% and the $DPRP_V$ decreased to 18.49%. Under the same spray parameters, the $DPRP_H$ and $DPRP_V$ of spraying 30 g/L PEG-20000 were higher than those of the tap water.

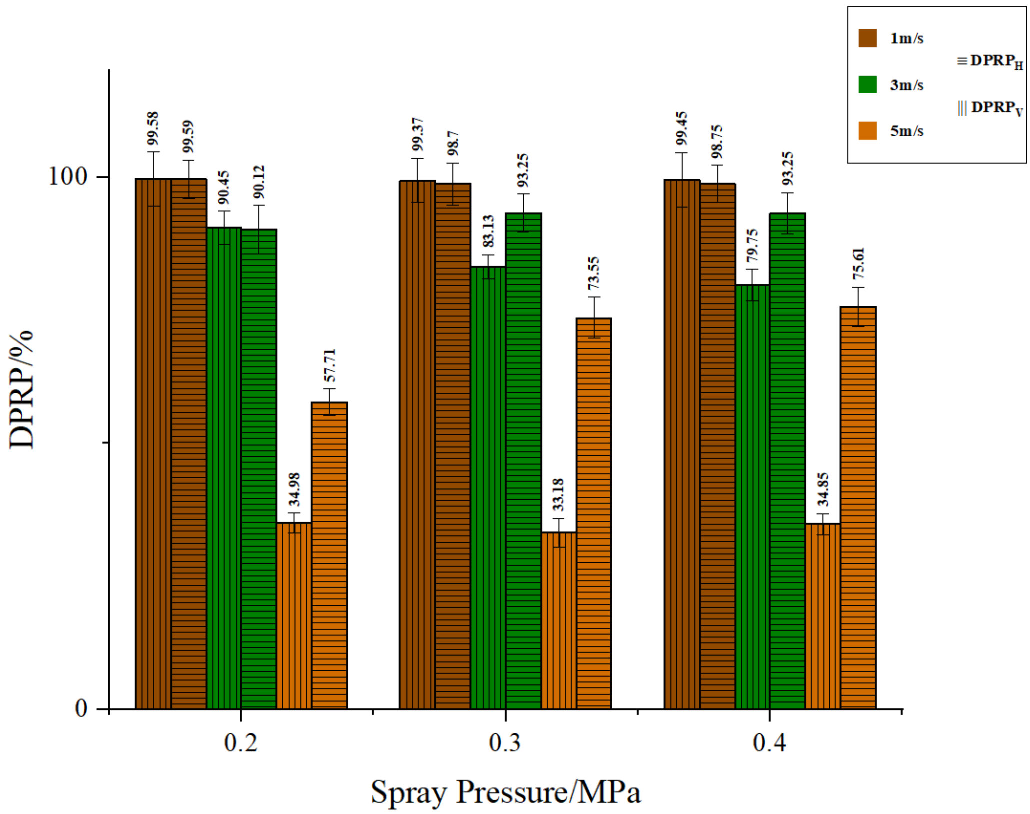
Table 4. Drift potential and drift potential reduction percentage in vertical and horizontal directions.

Spraying Medium	Wind Speed/m·s $^{-1}$	Pressure/bar	DP_V	DP_H	$DPRP_V$/%	$DPRP_H$/%
Tap water	1	2	2.01	35.49	98.75 (±3.50)	97.84 (±4.51)
		3	2.04	31.36	98.73 (±3.41)	98.09 (±2.90)
		4	1.58	32.67	99.01 (±4.39)	98.01 (±3.15)
	3	2	29.60	64.73	81.51 (±3.19)	96.06 (±4.99)
		3	26.26	126.72	83.60 (±3.80)	92.28 (±3.58)
		4	21.63	129.72	86.49 (±4.15)	92.10 (±4.11)
	5	2	140.55	588.42	12.23 (±0.58)	64.16 (±3.12)
		3	137.19	508.79	14.33 (±1.20)	69.01 (±4.48)
		4	190.03	623.42	−18.66 (±0.95)	62.03 (±2.55)
30 g/L PEG-20000	1	2	0.67	6.71	99.58 (±5.10)	99.59 (±3.56)
		3	1.01	21.41	99.37 (±4.84)	98.70 (±3.90)
		4	0.88	20.47	99.45 (±5.16)	98.75 (±3.42)
	3	2	15.30	162.19	90.45 (±3.12)	90.12 (±4.53)
		3	27.02	110.84	83.13 (±2.23)	93.25 (±3.55)
		4	32.42	110.85	79.75 (±2.88)	93.25 (±3.81)
	5	2	104.13	694.38	34.98 (±1.89)	57.71 (±2.50)
		3	107.00	434.18	33.18 (±2.65)	73.55 (±3.85)
		4	104.33	400.40	34.85 (±1.95)	75.61 (±3.66)

Reference spray	160.14	1641.78	0	0

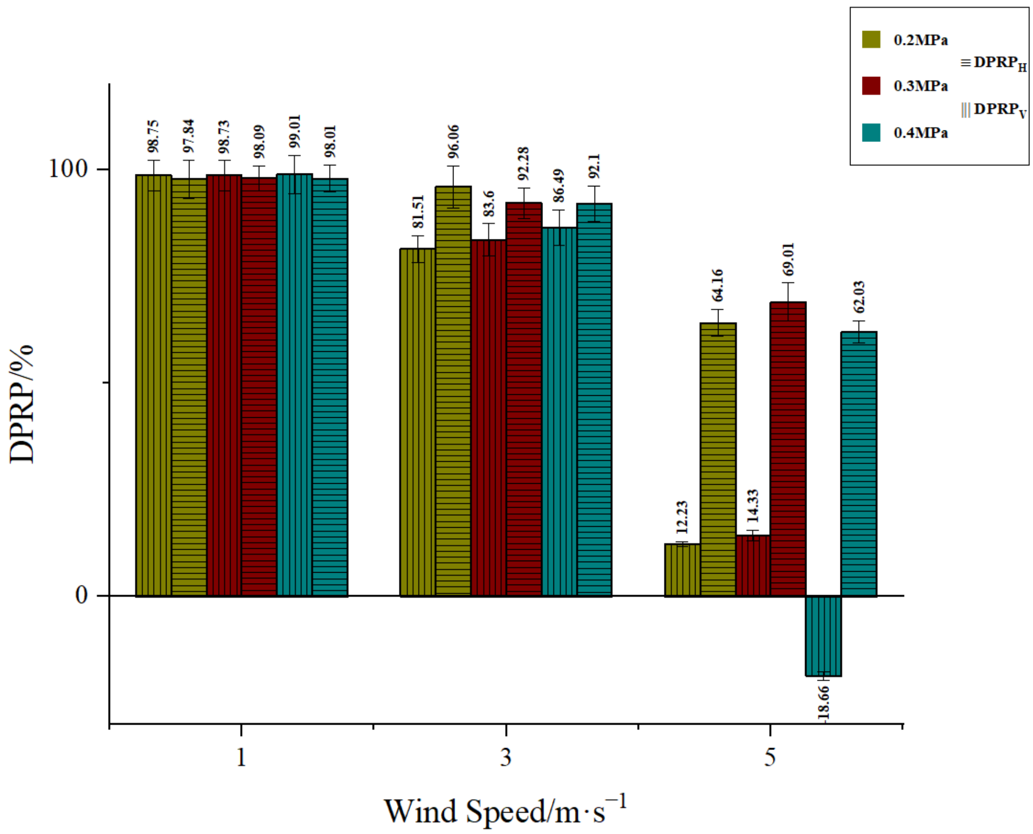


(**a**) Tap water.

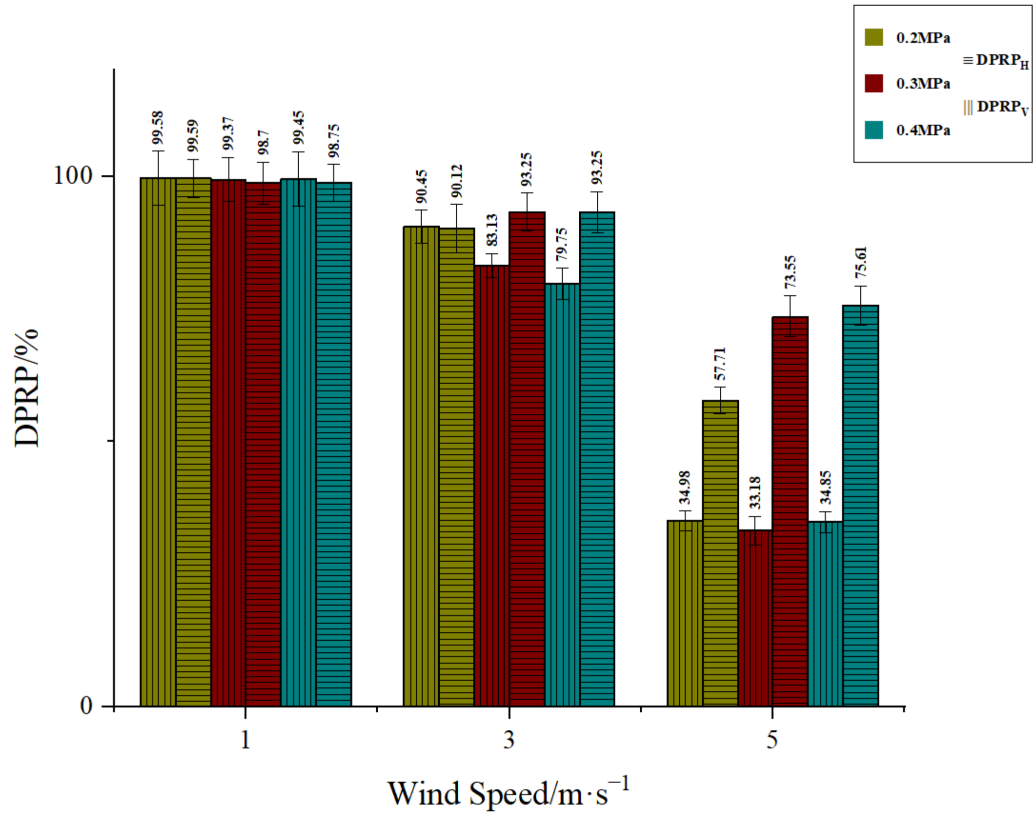


(**b**) 30 g/L PEG-20000.

Figure 6. The drift potential reduction percentage under different pressures.



(**a**) Tap water.



(**b**) 30 g/L PEG-20000.

Figure 7. The drift potential reduction percentage under different wind speeds.

4. Discussion

The method of using wind tunnels to assess droplet deposition and drift has been recognized by most scholars and research institutions, and relevant ISO standards have also been established. Previous studies have discussed drift without rotors or using small UAV devices. Zhang et al. [17] studied the drift of the nozzle without the effect of rotors in a wind tunnel and found that the drift deposition trend of the nozzle was similar to this paper: the drift in the vertical direction increased with the increase in the distance from the nozzle to the ground and the drift in the horizontal direction decreased with the increase in the horizontal distance to the nozzle. Zhang also found that the physical properties of different types of pesticides and water were different, so it was meaningful to use PEG-20000 as the spray medium in this paper. Jiao et al. [40] studied the effects of different concentrations of polyethylene glycol on droplet size and drift deposition and found that the D_{V50} increased by 37.43% and the $\Phi_{Vol<150\mu m}$ decreased by 63.67% when spraying 30 g/L PEG-20000 compared to tap water. Bruno et al. [41] added polyethylene glycol to the water and also found that the size of D_{V50} nearly doubled. The results of this paper are similar to those of the above studies. The D_{V50} increased by 46.7% compared with water and the $\Phi_{Vol<150\mu m}$ decreased by 47.3% when spraying 30 g/L PEG-20000 solution. The reason for this is the fact that the viscosity of the solution increased after the addition of polyethylene glycol, resulting in an increase in droplet size and a decrease in the proportion of small droplets [42,43]. Medet et al. [44] evaluated the drift reduction performance of additives in a wind tunnel and found that the drift deposition of the spraying water increased by about one and two times when the wind speed increased from 2 m/s to 3.5 m/s and 5 m/s, respectively. The situation was improved by the addition of certain additives. When the wind speed increased from 2 m/s to 3.5 m/s and 5 m/s, the drift deposition increased by about 0.75 times and 1.5 times, respectively, or even lower. Although the results are different due to the differences in the types of additives, nozzles, and spray parameters, the trend of change in this paper is the same as that in the above study. Our results also showed that under the same spray parameters, compared with tap water, the deposition amount in the target area when spraying 30 g/L PEG-20000 solution increased by 9.13% on average, and the drift deposition amount decreased by 24.7% on average. Therefore, PEG-20000 may be appropriately used as an anti-drift additive and the research on special pesticides for plant protection UAVs is an essential direction in the future. Wang et al. [45] installed a spray device with a UAV rotor in a wind tunnel and studied its drift characteristics. They equally found the downward pressure of the downwash airflow generated by the UAV rotor on the droplets will be immensely weakened at higher wind tunnel airflow speeds. Our results showed that the $DPRP_V$ and $DPRP_H$ of droplets at a wind speed of 5 m/s reduced by about 80% and 30%, respectively, compared with those at a wind speed of 1 m/s. In the various pieces of research on spray drift in wind tunnels, few people have mentioned the droplet deposition trend in the target area. This paper specifically focused on the deposition in the target area of a 0,1 m distance from the nozzle. The deposition amount in the target area increased with the increase in pressure and decreased with the increase in wind speed. Taking tap water as an example, the deposition amount in the target area ranged from 2770% of the drift deposition amount under the wind speed of 1 m/s to 350% under the wind speed of 3 m/s and finally to 50% under the 5 m/s wind speed. Even under the action of the rotor downwash airflow, the deposition amount in the target area still decreased sharply with the increase in the wind speed. Moreover, the deposition amount in the target area is 3.56 times and the total drift deposition amount is 0.12 times the reference spray when spraying tap water at 3 m/s wind speed and 3 bar pressure. It can be seen that the rotor downwash airflow significantly increased the deposition amount in the target area while suppressing a large amount of drift. The shortcoming of this study was that the droplet deposition and drift under different rotor speeds were not considered. Tang et al. [46] studied the effect of rotor speed on droplet movement and deposition and found that the spray angle of the nozzle increased with the increase in the downwash air velocity. The droplet movement was gradually inclined towards the rotor direction. This phenomenon will become more obvious with the increase in rotor speeds. Whether increasing the rotor speed can offset part of the weakening effect of the wind tunnel airflow on the downwash airflow needs to be further studied.

In summary, the downwash airflow has a great influence on the droplet deposition and drift. The research will become extra complex if the crosswind from different directions is also combined. At the same time, realizing the "reproduction" of actual field operations was a task of great significance and challenge because uncontrollable and irregular test conditions will have a great impact on drift and different types of rotary-wing UAVs have different machine parameters. Whether the wind tunnel test and the field test can establish high-precision models and so on are all directions to be studied in the future, so we still have a long way to go.

5. Conclusions

This paper studied the deposition and drift of the TeeJet 80-015 VP nozzle at three pressures (2, 3, and 4 bar) and three wind speeds (1, 3, and 5 m/s) using polyethylene lines and a BSF fluorescent tracer. The rotor downwash airflow significantly promoted the deposition in the target area while suppressing the drift of a large number of droplets in both horizontal and vertical directions. Faster wind speeds and higher pressures will result in a higher drift deposition amount. However, faster wind speeds will result in a lower *DPRP* and higher pressures may result in a larger *DPRP*. Adding 30 g/L PEG-20000 to the spray medium can effectively improve the anti-drift performance of the droplets. In the follow-up, the interaction between multiple airflows, different rotors, nozzle types, rotor speeds, and other factors on the deposition in the target area and drift will be further studied, and climate conditions such as ambient temperature and humidity will be considered as much as possible, in order to establish a more complete and accurate model, which will help to improve the reliability of UAV wind tunnel test results and provide greater reference values for field operations.

Author Contributions: Data curation, Y.J.; formal analysis, Y.J.; investigation, Y.J., Q.Z., Y.T. and X.L.; methodology, X.X., S.D. and W.K.; supervision, X.X. and S.D.; writing—original draft, Y.J.; writing—review and editing, Y.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (Grant No. 2017YFD0701000); the Guangdong Key Area R&D Program (Grant No.2019B20221001) and the Jiangsu Province and Education Ministry Co-sponsored Synergistic Innovation Center of Modern Agricultural Equipment Project (grant No. XTCX1004).

Data Availability Statement: Not applicable.

Acknowledgments: The authors were very grateful to their tutors Xue Xinyu and Ding Suming, and for the help of their colleague Xu Yang and classmates Wang Shan and Si Bowen during the experiments.

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

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