Effect of wind field below unmanned helicopter on droplet deposition distribution of aerial spraying

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Abstract: Wind field is one of the important factors affecting the distribution characteristics of aerial spraying droplet deposition. In order to reveal the impact mechanism of droplet deposition distribution by the wind field below agricultural unmanned helicopter rotor, in this study, the wind field distribution below uniaxial single-rotor electric unmanned helicopter rotor was measured by using a wireless wind speed sensor network measurement system for unmanned helicopter. The effects of wind field in three directions (*X*, *Y*, *Z*) below the rotor on droplet deposition distribution were analyzed with the condition of aerial spraying droplet deposition in rice canopy, and the regression model was established via variance and regression analyses of experiment results. The results showed that, the wind field in *Y* direction had a significant effect on droplet deposition in effective spray area, the wind field in *Z* direction had an extremely significant effect on droplet deposition in effective spray area, and the corresponding significance (sig.) values were 0.011 and 0.000. Furthermore, the wind field in *Z* direction had a significant effect on the penetrability and uniformity of droplet deposition in effective spray area, the corresponding sig. values were 0.025 and 0.011 respectively. The wind speed in *Y* direction at the edge of effective spray area had a significant effect on droplet drift, the sig. value was 0.021. In addition, the correlation coefficient *R* of the regression model was 0.869 between droplet deposition in effective spray area and the wind speed in *Y* and *Z* directions, and 0.915 between the uniformity of droplet deposition in effective spray area and the maximum wind speed in *Z* direction. The result revealed the influencing mechanism of the wind field below the rotor of uniaxial single-rotor electric unmanned helicopter on the distribution of aerial spraying droplet deposition. The results can provide guidance for the actual production application of aerial spraying to reduce liquid drift and improve the utilization rate of pesticide.

Keywords: uniaxial single-rotor electric unmanned helicopter, aerial spraying, wind field, droplet deposition

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1 Introduction

Rice is the major food crop in China, the planting area of which is over 3.0×10^7 hm^2, and more than 60% of total population live on it[1,2]. Rice production takes an important role in the process of agricultural production. However, 15%-40% of the crop is lost to the pest outbreak each year in China[3]. So strengthening the protection of plant has an important significance for

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ensuring grain safety of China during the rice production.

In current production process of rice and other crops, the traditional manual and semi-mechanical operations continue to be the main way of plant protections[4,5], but the traditional operations are labor-intensive, low-efficiency and time-consuming. What's worse, the sprayers are monotonous, and the atomization qualities of which are poor, so it is extremely easy to cause excessive pesticide residues and workers' poisoning, etc.[6,7] As a new type of plant protection in recent years, the low-altitude and low-volume spraying technology of agricultural unmanned aerial vehicle (UAV) improved the disadvantages of above traditional plant protection methods. Because of high efficiency, low cost, good spraying effect and the ground machinery unable working in the field during the growth of rice, the applications of agricultural UAV are gradually becoming the preferred methods of plant protection operations[8-10].

With the rapid development and application of agricultural UAV for plant protection in China, the low-altitude and low-volume spraying technology has become a research hotspot. And a series of explorations have been made by researchers on the quality of its operation and the effect of droplet deposition distribution. Xue et al.[1] performed a series of field trials about UAV spraying to evaluate various techniques (flew at a height of 5 m, a speed of 3 m/s, and the wind speed of 3 m/s) for measuring spray deposition and aerial drift during spray application to paddy field. Chen et al.[11] studied the effect of different spray operation parameters on the droplet deposition distribution of aerial spraying in the hybrid rice canopy by the single-rotor unmanned helicopter HY-B-10L. Zhu et al.[12] developed a PWM controller for a UAV precision sprayer for agriculture which was shown to have potential as a precision spray system allowing for variable rate applications. Qin et al.[13] demonstrated the influence of spray parameters, such as (Droplets of 480 g/L chlorpyrifos·(Regent EC) (at a dose of 432 g a.i./hm^2, spray volume rate of approximately 15 L/hm^2), the flight height of 0.8 m and 1.5 m, the flight velocity of 3 m/s and 5 m/s) of the UAV on spray deposition in a rice canopy for control of plant hoppers showing that low volume applications of concentrated spray solution enhanced the efficacy duration.

At present, the domestic research on the application of agricultural UAV has mainly focused on the effects of operation parameters of aerial spraying on the characteristics of droplet deposition distribution. In fact, the main factor that affects the droplet deposition distribution of aerial spraying is the wind field below the unmanned helicopter rotor, which is made up of wind field generated by rotating rotor and wind field of external environment. The study of droplet deposition regularity of aerial spraying needs to be taken into account the effect of wind field fundamentally[14-17]. A lot of researchers have simulated the effects of wind field generated by rotating rotor on droplet deposition in aerial spraying application by using computer models[18-20]. However, there is a big difference in droplet deposition results between the computer model and the actual field operation due to external environment interference. So far, there were few studies about effect of the wind field below the rotor on the droplet distribution of aerial spraying for the actual production application. Therefore, this paper took an uniaxial single-rotor electric unmanned helicopter as an example to study the characteristics of droplet deposition distribution of aerial spraying in the wind field of *X*, *Y*, *Z* directions below rotor which measured by using a wireless wind speed sensor network measurement system for unmanned helicopter, and combined with the deposition condition of droplet in rice canopy. It is hoped that the experimental results would revealed the mechanism of droplet deposition of aerial spraying by uniaxial single-rotor electric unmanned helicopter, and provide a theoretical guidance and data support for optimization of spray operating parameters and reduction of the liquid drift of aerial spraying.

2 Materials and methods

2.1 Experimental site

The experiments were carried out in the hybrid rice seed production base of Hunan Longping Seed Industry Co., Ltd. in Wugang City, Hunan Province. Crop growing stage was the jointing booting stage, the average height of 80 cm. Rice was transplanted by machinery with the row spacing between rice plants of 17 cm× 14.5 cm.

2.2 Materials and devices

As shown in Figure 1, the model of UAV used in this spraying test was HY-B-15L uniaxial single-rotor electric unmanned helicopter provided by Shenzhen Hi-tech New Agriculture Technologies Co., Ltd. The main performance index was shown in Table 1.

Figure 1 HY-B-15L UAV used in the spraying test

Table 1 Main performance index of UAV

Main parameter	Norms and numerical
Type	HY-B-15L uniaxial single rotor electric UAV
Size/mm×mm×mm	1760×580×750
Main/Tail rotor diameter/mm	2080/350
Maximum load/L	15
Flight speed/m·s^{-1}	0-8
Flight height/m	0.5-3
Spraying width/m	4-6

The spray system consists of U-type liquid tank, water-pump, spray bar, water-pipe, spray nozzle and other components. The spray nozzle is fan-shaped, and five nozzles distribute equidistantly along spray bar and perpendicular to the aircraft axis, spacing 450 mm. The nozzle orientation is downward and with a total flow of 2.4 L/min.

The Beidou Satellites Navigation Positioning System (BDS) for UAV is consisted of UB351 Beidou system with RTK differential positioning technology and bidirectional wireless radio station, with the plane accuracy of $(10+5\times D\times10^{-7})$ mm, and the vertical accuracy of $(20+1\times D\times10^{-6})$ mm, in which D is the actual measuring distance (km). The mobile station of system carried by UAV draw the trajectory of operation and positioning the sampling points of wind speed and droplets. Then we observed the relationship between the actual route of operation and the sampling point, and obtained the flight parameters of agricultural UAV through the trajectory of operation.

The wind field measurement system is a Wireless Wind Speed Sensor Network measurement system (WWSSN) for unmanned helicopter[21]. The system includes the impeller type of wind speed sensor and the wireless measurement node for wind speed sensors. The impeller type of wind speed sensor measured 3-dimensional wind velocity which produced by UAV operating at each sampling point, with the measuring range of 0-45 m/s and the accuracy of ±3%. The wireless measurement node for wind speed sensors consists of 490 MHz wireless data transmission module, microcontroller and power supply module, realizing the function that transfer wind speed data to the computer's intelligent control focus node.

Environmental monitoring system includes portable anemometer and digital temperature and humidity meter. Anemometer is used to monitor and record the wind velocity and direction of test environment, and temperature and humidity meter is used to measure the temperature and humidity of test environment.

Sample collection instruments included tripods, a scanner, clamps, rubber gloves, sealed bags and round paper clips.

2.3 Experimental method

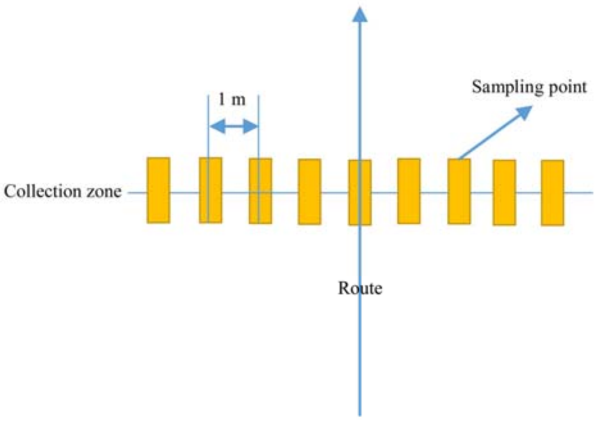
2.3.1 Wind field measurement system Arrangement

Arrangement of the WWSSN in the field was based on the 3-line wind field measurement method introduced by Wang et al.[22] The node of WWSS were arranged at intervals of 1 m along a line perpendicular to the UAV route, numbered 1# to 10#. The 10# node was used to measure the environmental wind speed synchronously, placed at a distance of about 15 m from the 9# node. The agricultural UAV implemented the spraying operations along the route above 5# node. As shown in Figure 2, three wind speed sensors were arranged on each node, and the installation directions of wind speed sensor axis were X direction (parallel to the flight direction), Y direction (perpendicular to the flight direction), Z direction (perpendicular to the ground direction), respectively.

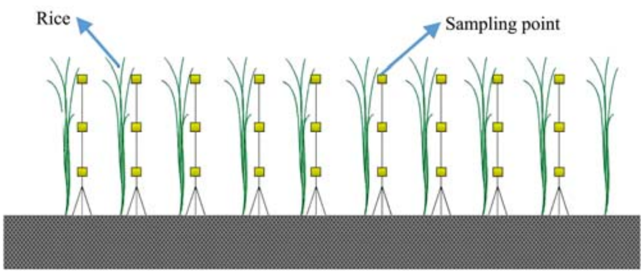
Figure 2 Layout of wind field measurement system

2.3.2 Droplet sampling point Arrangement

As shown in Figures 3a and 3b, the droplet collecting belt and the wind field measuring belt were the same sampling belt, and each droplet sampling point were set at the same position of each node. The number of droplet sampling points was 9 in each layer, which was the same as the number of node, and with the intervals of 1 m. In the vertical direction of rice plants, the droplet sampling points were arranged in the upper, middle and lower layer. The spacing between the upper layer and middle layer, the middle layer and the lower layer were about 25 cm, and the spacing between the lower layer and the ground was about 20 cm.



a. Plane layout



b. Three-dimensional layout

Figure 3 Sample point layout

2.3.3 Experimental design

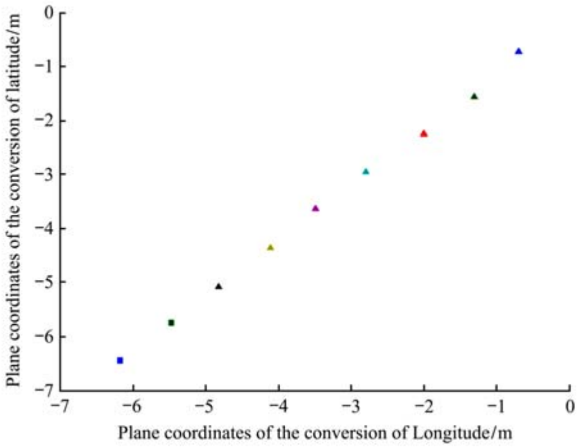
Water was sprayed instead of liquid pesticide in this experiment, and the liquid volume of each test was 5 L. The water-sensitive paper (Syngenta) was used as a collection card to collect droplets, the size of 26 mm × 76 mm.

To ensure the validity and comparability of test data, the experiment was repeated 6 times. And the flight speed was selected in the range of 2.5-5.0 m/s, the flight height was about 1.5 m, according to the experience and suggestions of the manipulator.

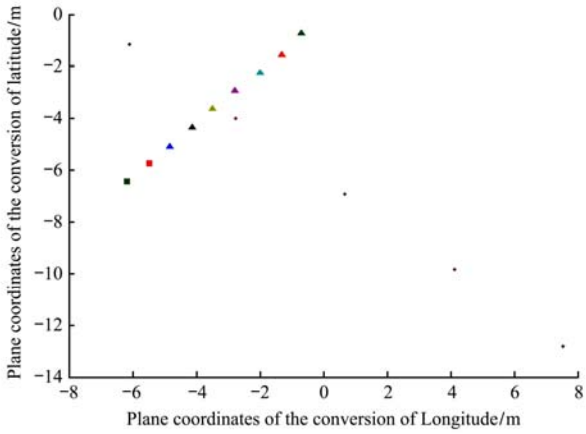
2.4 Data processing

2.4.1 Operating parameters and trajectory processing

Figure 4a was depicted by geographic data, which was acquired by the location of each collection point collecting from the Beidou System UB351. Figure 4b shows the UAV flight trajectory of the first spray operation, which acquired by the Beidou System UB351 for agricultural UAV. And the trajectory positioning frequency of the Beidou System UB351 in the spraying operation was 1 Hz.



a. Collection point position



b. The first test trajectory

Figure 4 Droplet collection point and flight trajectory

Table 2 shows the UAV operating parameters obtained from the Beidou System UB351 (average flight altitude and average flight speed). The experiments were carried out between 16:00-18:00 in the afternoon, with the environmental temperature of about 30°C and the environmental humidity of about 67%.

Table 2 Test parameters

Operating parameters	First test	Second test	Third test	Fourth test	Fifth test	Sixth test
Flight speed/m·s^{-1}	4.48	4.96	3.53	2.50	3.20	4.12
Flight height/m	1.04	1.17	1.44	0.88	0.98	1.25

2.4.2 Acquiring and processing of droplet data

When each test was finished, the water-sensitive papers placed in the sampling area were quickly gathered in sealed bags one by one until the droplets have dried, and 600 dpi digital images were acquired using a scanner in the laboratory. Then, an image processing software called "DepositScan" was utilized to extract droplet deposits and spray parameters such as coverage rate, deposition rate and density of droplet spots[23].

In order to evaluate the uniformity of droplet deposition in each sampling points and the penetrability of droplet in rice plants in the test, coefficient of variation (CV) were used to show the uniformity and the penetrability of droplet deposition in this paper[24], the coefficient of variation (CV) is,

$$CV = \frac{S}{\bar{X}} \times 100\% \tag{1}$$

$$S = \sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2 / (n-1)} \tag{2}$$

where, S is the standard deviation of the samples in the same test group; X_i is the deposition rate in each sampling points, μL/cm^2; $\bar{X}$ is the mean value of deposition rate in each test group, μL/cm^2; n is the number of sampling points in each test group.

The wind speed in X, Y, Z directions which acquired by Wireless Wind Speed Sensor Network measurement system (WWSSN) for unmanned helicopter, selecting the maximum value of wind speed to represent the wind field intensity below unmanned helicopter rotor[21,22].

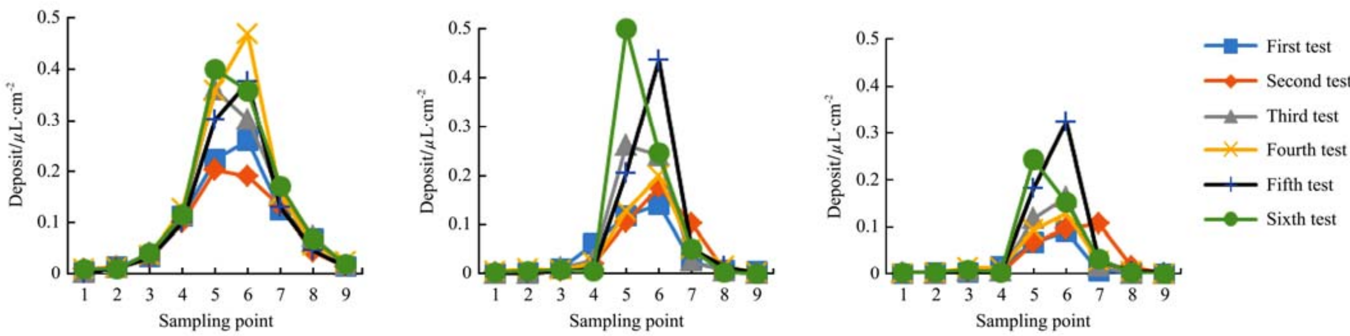
In order to further show the effect of the wind field below uniaxial single-rotor electric unmanned helicopter rotor on droplet deposition distribution above rice canopy, and to revealed the relationship between droplet deposition distribution and 3-demensional wind field distribution below the rotor, the stepwise regression method was carried out for variance analysis and regression analysis of all test results (the results of droplet deposition and wind field distribution) by using SPSS 16.0 software, establishing regression equation between droplet deposition distribution and wind field distribution, and testing its significance (significant level p<0.05)[25].

3 Results and analysis

3.1 Data processing results

3.1.1 Droplet deposition data

Figure 5 shows the distribution of droplet deposition in upper, middle and lower layers of rice plants by using the agricultural unmanned helicopter for 6 times spraying test respectively.



a. Droplet deposition in the upper layer of plants b. Droplet deposition in the middle layer of plants c. Droplet deposition in the lower layer of plants

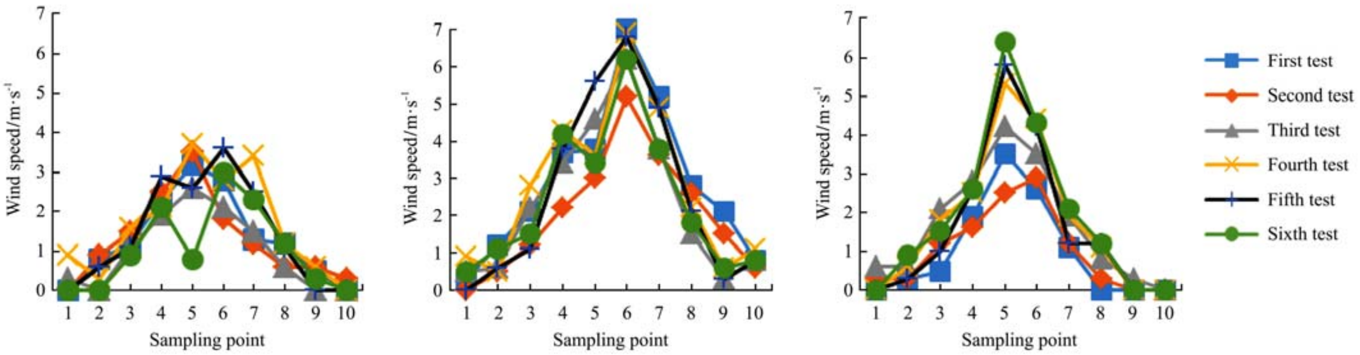
Figure 5 Droplet deposition

It can be seen from the droplet distribution in each layer of rice plants, the droplet deposition trend of aerial spraying in each layer of plants were basically the same, the amount of droplet deposition decreased from upper to lower layer, the amount of droplet deposition in upper layer were much higher than that in middle layer, and the amount of droplet deposition in middle layer is slightly higher than that in lower layer. Droplet mainly deposited in the sampling points of 4#, 5#, 6#, 7# in upper layer of rice plant and the sampling points of 6#, 7#

in middle and lower layer. According to the evaluation method of droplet density for evaluating effective spraying width of agricultural UAV, droplet density of the sampling point of 4#, 5#, 6# and 7# in upper layer could meet the evaluation requirement[26]. Therefore, the sampling points of 4#-7# in droplet collecting area could be used as the sampling points in effective spraying width area of agricultural unmanned helicopter in this spraying test.

3.1.2 Wind field distributing data

Figure 6 shows the wind field distribution in *X*, *Y*, *Z* direction above rice canopy which measured by wind field measurement system for 6 times spraying test respectively.



a. Wind field distribution in *X* direction b. Wind field distribution in *Y* direction c. Wind field distribution in *Z* direction

Figure 6 Wind field distribution

It can be seen from the wind field distribution in *X*, *Y*, *Z* directions above rice canopy, because of the different flight parameters of spraying operation, there was also a difference in wind field distribution for each test, but the wind velocity showed a trend of *Y*>*Z*>*X* directions in general; And due to the influence of environmental wind field, the wind field in *X*, *Y* directions were slightly offset along the direction of environmental wind field in horizontal direction.

3.2 Effect of wind field on droplet deposition in effective spray area

The droplet deposition distribution in the effective spray area was shown in Table 3.

Table 4 shows the results of variance analysis and regression analysis of the effect of the 3-dimensional wind field below single-rotor electric unmanned helicopter rotor on droplet deposition in effective spray area with using the stepwise regression method. From the results of variance analysis, the value of significance level of factor of the wind speed in Y direction was less than 0.05, which indicated that the wind speed in *Y* direction had a significant effect on the droplet deposition in the effective spray area; the value of significance level of the factor of wind speed in *Z* direction was less than 0.01, which indicated that the wind speed in *Z* direction had an extremely significant effect on the droplet deposition in the effective spray area. And the probability of significance test of regression equation is 0.011, less than 0.05. Therefore, the linear relationship between explained variable and explanatory variable was significant, and a linear equation can be established.

Table 3 Droplet deposition in effective spray area

Test number	Collection position	Average deposition /μL·cm^{-2}	Penetrability /%	Uniformity /%
First test	4#	0.064	60.95	45.33
	5#	0.136	47.54	
	6#	0.164	42.59	
	7#	0.053	98.47	
Second test	4#	0.042	101.03	38.05
	5#	0.125	46.23	
	6#	0.155	27.62	
	7#	0.114	10.41	
Third test	4#	0.049	97.60	61.72
	5#	0.247	40.49	
	6#	0.236	24.31	
	7#	0.066	97.51	
Fourth test	4#	0.055	95.15	58.07
	5#	0.193	60.70	
	6#	0.266	55.01	
	7#	0.078	71.22	
Fifth test	4#	0.037	122.81	76.45
	5#	0.230	22.64	
	6#	0.379	12.09	
	7#	0.069	62.34	
Sixth test	4#	0.041	127.75	71.65
	5#	0.386	28.37	
	6#	0.252	33.42	
	7#	0.086	71.35	

Table 4 Results of deposition rate variance analysis and regression analysis

Source difference	Regression coefficient	Standard deviation	Sig.-value	Significance	R	R^2
Constant	–0.386	0.130	0.007	**		
Y direction	0.075	0.027	0.011	*	0.869	0.755
Z direction	0.159	0.024	0.000	**		

Note: This article took the significance level α=0.05, "--" in the table represents factors have no significant impact on test result.

Regression coefficients of the regression equation were –0.386, 0.075, 0.159 respectively according to regression analysis, and the regression model was,

$$y_1 = 0.075V_Y + 0.159V_Z - 0.386 \quad (3)$$

where, y_1 is the deposition rate in the effective spray area; V_Y and V_Z represent the wind speed value in Y and Z direction, respectively. In addition, R of the regression model is 0.869.

It can be seen from the regression model that the coefficients values of the wind speed in Y and Z direction were positive number, indicated that there was a positive correlation between the deposition rate in the effective spray area and the wind speed in Y and Z direction below the rotor. And the greater value of wind speed in Y and Z direction below the rotor, the more deposition rate in the effective spray area, which was consistent with the actual spraying operation.

3.3 Effect of wind field on the penetrability of droplet deposition in effective spraying area

Table 5 shows the results of variance analysis and regression analysis of the effect of the 3-dimensional wind field below single-rotor electric unmanned helicopter rotor on the penetrability of droplet in effective spray area with using the stepwise regression method. From the results of variance analysis, the value of significance level of factor of the wind speed in Z direction is less than 0.05, which indicated that the wind speed in Z direction had a significant effect on the penetrability of droplet in the effective spray area. And the probability of significance test of regression equation is 0.025, less than 0.05. Therefore, the linear relationship between explained variable and explanatory variable is significant, and a linear equation can be established.

Regression coefficients of the regression equation were 0.934, –0.107 respectively according to regression analysis, and the regression model is:

$$y_2 = -0.107V_Z + 0.934 \quad (4)$$

where, y_2 is the penetrability of droplet in effective spray area; V_Z is the wind speed value in Z direction. In addition, R of the regression model is 0.456.

Table 5 Results of deposition penetrability variance analysis and regression analysis

Source difference	Regression coefficient	Standard deviation	Sig.-value	Significance	R	R^2
Constant	0.934	0.150	0.000	**	0.456	0.208
Z direction	−0.107	0.045	0.025	*		

3.4 Effect of wind field on the uniformity of droplet deposition in effective spraying area

In order to showed the effect of wind field under the agricultural unmanned helicopter rotor on the uniformity of droplet deposition in effective spraying area, using the peak value of wind speed in X, Y, Z direction under the rotor in each test to study the relationship between wind field in three directions and the uniformity of droplet deposition[27,28]. Table 6 shows the results of variance analysis and regression analysis of the effect of the 3-dimensional wind field below single-rotor electric unmanned helicopter rotor on the uniformity of droplet deposition in effective spray area with using the stepwise regression method. From the results of variance analysis, the value of significance level of factor of the wind speed in Z direction was less than 0.05, which indicated that the wind speed in Z direction had a significant effect on the uniformity of droplet deposition in the effective spray area. And the probability of significance test of regression equation is 0.011, less than 0.05. Therefore, the linear relationship between explained variable and explanatory variable is significant, and a linear equation can be established.

Regression coefficients of the regression equation were 0.122, 0.099 respectively according to regression analysis, and the regression model was,

$$y_3 = 0.099\mathrm{V}_{Z\text{-max}} + 0.122$$

where, y_3 is the uniformity of droplet deposition in effective spray area; $V_{Z\text{-max}}$ is the peak value of wind speed in Z direction. In addition, R of the regression model is 0.915.

Table 6 Results of deposition uniformity variance analysis and regression analysis

Source difference	Regression coefficient	Standard deviation	Sig.	Significance	R	R^2
Constant	0.122	0.106	0.031	*	0.915	0.837
Z direction	0.099	0.022	0.011	*		

It can be seen from the regression model that the coefficient value of the wind speed in Z direction was positive number, indicated that there was a positive correlation between the uniformity of droplet deposition in the effective spray area and the peak value of wind speed in Z direction below the rotor. The larger value of wind speed in Z direction can improve the uniformity of droplet deposition in effective spray area by weakening the effect of wind field in the horizontal direction on droplet deposition. Therefore, the model is consistent with the droplet deposition mechanism of aerial spraying.

3.5 Effect of wind field on droplet drift

Table 7 shows droplet drift in the left and right drift area and wind speeds in X, Y, Z directions at the edge of effective spray area. It can be seen from the table that the amount of droplet drift in the right drift area was more than that in the left drift area. In addition, the wind speed in X and Z direction at the left edge of effective spray area (4# sampling point) were more than that at the right edge of effective spray area (7# sampling point), and the wind speed in Y direction at the left edge of effective spray area (4# sampling point) was less than that at the right edge of effective spray area (7# sampling point). It was consistent with the difference in the amount of droplet drift in the left and right drift area. More importantly, it also showed that droplet were prone to drift due to the influence of wind field in Y direction in the process of droplet deposition.

In order to revealed effect of the wind field below agricultural unmanned helicopter rotor on droplet drift more clearly, the wind speed in X, Y, Z direction below the rotor at the edge of effective spray area of each test were used to study the relationship between wind field and droplet drift. Table 8 shows the results of variance analysis and regression analysis of the effect of the 3-dimensional wind field below single-rotor electric unmanned helicopter rotor on droplet drift in drift area with using the stepwise regression method. From the results of variance analysis, the value of significance level of factor of the wind speed in Y direction was less than 0.05, which indicated that the wind speed in Y direction had a significant effect on droplet drift. And the probability of significance test of regression equation was 0.021, less than 0.05. Therefore, the linear relationship between explained variable and explanatory variable is significant, and a linear equation can be established.

Table 7 Droplets deposition in the left and right drift area and wind field distribution at the edge of effective spray area

Test number		Wind speed at the edge of the effective spray area/m·s^{-1}			Droplets drift /μL·cm^{-2}
		X direction	Y direction	Z direction	
1	Left	2.30	3.70	1.90	0.069
	Right	1.30	5.20	1.10	0.096
2	Left	2.50	2.20	1.60	0.064
	Right	1.20	3.60	1.20	0.081
3	Left	1.90	3.40	2.80	0.074
	Right	1.50	3.80	1.90	0.093
4	Left	2.10	4.30	2.50	0.094
	Right	3.40	4.90	1.90	0.102
5	Left	2.90	3.80	2.60	0.054
	Right	2.50	4.90	1.20	0.085
6	Left	2.10	4.20	2.60	0.088
	Right	2.30	3.80	2.10	0.093

Table 8 Results of droplet drift variance analysis and regression analysis

Source difference	Regression coefficient	Standard deviation	Sig.-value	Significance	R	R^2
Constant	0.035	0.018	0.043	*	0.655	0.429
Y direction	0.012	0.004	0.021	*		

Regression coefficients of the regression equation were 0.035, 0.012 respectively according to regression analysis, and the regression model is:

$$y_4 = 0.012V_Y + 0.035$$

where, y_4 is the amount of droplet drift in drift area; V_Y is the value of wind speed in Y direction at the edge of effective spray area. In addition, R of the regression model is 0.655.

4 Discussion

Wind field is one of the important factors affecting the droplet deposition distribution characteristics of aerial spraying. Revealing the effect mechanism of droplet deposition distribution of aerial spraying on the wind field below agricultural unmanned helicopter rotor, which has an important guiding significance to reduce aerial spraying liquid drift and improve the utilization of pesticides in the practical application. The wind field distribution below uniaxial single-rotor electric unmanned helicopter by using a wireless wind speed sensor network measurement system for unmanned helicopter was measured, the impact on the droplet deposition distribution by the wind field in *X*, *Y*, *Z* directions below the rotor combined with the condition of droplet deposition of aerial spraying in rice canopy was analyzed, the regression model via variance analysis and regression analysis of experiment results was established in this research.

It should be noted that, R^2 of the models of effect of the wind field below agricultural unmanned helicopter rotor on deposition rate and deposition uniformity of droplet in effective spray area were 0.755 and 0.837, respectively. And R^2 of the models of effect of the wind field below agricultural unmanned helicopter rotor on penetrability of droplet deposition in effective spray area and effect of the wind field at the edge of effective spray area on droplet drift were 0.208 and 0.429, respectively. The values of R^2 of former two models were greater than 0.7, which indicated that the established regression equation had a good significance for prediction and control in practice, and could provide guidance for actual production application[24]. However, the values of R^2 of latter two models were smaller than 0.5.

Firstly, it can be seen from Figure 5 that droplet mainly deposited at the sampling points of 4#, 5#, 6# and 7# in the upper layer of plants and at the sampling points of 5# and 6# in the middle and lower layers of plants, and the deposition rate of droplet at both sides of the sampling points of 5# and 6# decreased sharply. This was probably caused by the main reason that the wind field below single-rotor electric unmanned helicopter rotor was too strong and causing rice plants in the central area of the flight route lodge to both sides. As a consequent, droplet couldn’t be acquired normally by the sampling points in the middle and lower layers of plants. This phenomenon is consistent with the practical application basically.

In addition, it was found that droplet deposition in the upper layer of more than 80% of the droplet collection points accounted for more than 50% of the sum of droplet deposition in the upper, middle and lower layer. That is, the amount of droplet deposition in the upper layer plays a major role in calculation of the average amount of droplet deposition in each collection points. As a result, the droplet deposition in the models of effect of wind field below rotor on the deposition rate and the deposition uniformity of droplet in effective spray area were mainly based on droplet deposition in the upper layer of rice plants in the process of model analyzing. It can be known that rice lodging had little effect on droplet deposition in the upper layer of plant, and these two models were less affected. While the droplet deposition in the models of effect of wind field below rotor on the penetrability of droplet deposition in effective spray area and effect of the wind field at the edge of effective spray area on droplet drift were mainly based on droplet deposition in the upper, middle and lower layers of rice plants in the process of model analyzing, and Table 3 shows the penetrability of droplet deposition at the sampling points of 5# and 6# in the vicinity of the flight route were better than that at the sampling points of 4# and 7# at the edge of effective spray area. Therefore, R^2 of these two models was smaller because the two models were obviously affected by rice plants lodging. It also provided a theoretical support for the effect of the wind field below the rotor on the droplet deposition distribution from the view of theory.

The research showed that effect of the wind field below agricultural uniaxial single-rotor electric unmanned helicopter rotor on droplet distribution of aerial spraying is a real problem. Therefore, further research about the droplet deposition regularity of aerial spraying need to study the mechanism of effect of the wind field below agricultural UAV on droplet distribution of aerial spraying, and the main research focus in the basic field of agricultural aviation spraying in the future should be the relationship between the distribution of wind field below rotor and the droplet deposition distribution of aerial spraying. What’s more, the wind field below rotor would cause the phenomenon of rice lodging at both sides of the flight route to decrease droplet deposition in the middle and lower layers of crop. Because of the diversity of agricultural UAVs, the variety of crops, the difference of lodging degree, the complex operating environment in China, the mechanism of effect of the wind field below agricultural UAV on droplet distribution of aerial spraying will have a great potential for research in the future. In order to improve the efficiency and benefit of spraying operations by selecting reasonable operating parameters, we should expand the range of droplet collection and increase the number of tests. The model about effect of wind field below rotor on the distribution of droplet deposition will be established based on abundant data, and the results will provide theoretical guidance and data support for optimizing the parameters of wind field generated by spraying operation and reducing pesticides drift of aerial spraying.

5 Conclusions

This paper took an uniaxial single-rotor electric unmanned helicopter as example to study the effect of the wind field in *X*, *Y*, *Z* directions below rotor which measured by using a wireless wind speed sensor network measurement system for unmanned helicopter on distribution of droplet deposition in rice canopy by aerial spraying. According to the results of variance analysis and regression analysis (significance level $p<0.05$), the following conclusions can be drawn:

1) The effect of the wind field in *Y* and *Z* direction on droplet deposition in effective spray area were significant and extremely significant respectively, and the correlation coefficient *R* of the regression model was 0.869 between droplet deposition in effective spray area and the wind speed in *Y* and *Z* directions, which indicated that the model could provide a guidance for the practical spray application.

2) Only the wind field in *Z* direction had a significant effect on the uniformity and penetrability of droplet deposition in effective spray area, and the correlation coefficient *R* of the regression model was 0.915 between the uniformity of droplet deposition in effective spray area and the maximum wind speed in *Z* direction, which indicated that the model could provide a guidance for the practical spray application.

3) The wind speed in *Y* direction at the edge of effective spray area had a significant effect on droplet drift, which indicated that the wind speed in *Y* direction below rotor had a significant effect on droplet drift.

4) In practical application of aerial spraying, wind field below UAV rotor have a positive effect on droplet deposition on crop canopy, and it should be noted that the phenomenon of crops lodging at both sides of the flight route caused by the wind field below rotor would decrease the droplet deposition in the middle and lower layer of crops simultaneously. Therefore, in order to ensure that droplet can be deposited at different locations of crops, suitable operating parameters should be selected reasonably to improve the efficiency and benefit of spraying operations.

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