Droplet deposition and efficiency of fungicides sprayed with small UAV against wheat powdery mildew

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Abstract: Small unmanned aerial vehicle (UAV), a timely and effective pesticide sprayer, can be used to spray pesticide in a high efficiency without harming the crop, and is especially suitable for spraying for small farms and hills in Asian countries. In recent years, it has been chosen as a key and new technique for pesticide application. This paper studied the impact of UAV (UAV N-3) spraying parameters (different working height and different spraying concentrations) on the deposition of droplets on the wheat canopy and the prevention of powdery mildew. Water sensitive paper was used as the sampler to collect the pesticide droplets and image processing software Deposit Scan was used to compute the coverage rate of droplets on the wheat top layer to acquire the proportional distribution of droplets on the wheat lower layer. The experimental results showed the impact of spraying height on the distribution of droplets on the wheat upper layer was quite significant, when the spraying height was 5.0 m and the spraying speed was 4 m/s, the coverage rate of droplets on the wheat lower layer was the largest, as it was 45.6% of that on the upper layer, the droplets distribution was the most uniform, and the coefficient of variation was 33.13%. 450 g/hm^2 (dosage registered) of triadimefon SC (44%) was sprayed by the UAV, the control efficiency reached 55.1% after applying which was better than 20% and 40% of dosage decreased for each hectare, and the applying effect (35.6%) of 20% dosage decreased for each hectare had no significant difference from the applying effect (34.6%) applied by a knapsack-type electric sprayer. At 10 d after applying, the prevention effect realized by UAV was lower than that realized by a knapsack-type electric sprayer, and it may be correlated to the meteorological condition and water amount in the pesticide sprayed. Thus, when UAV spraying was chosen to prevent wheat powdery mildew under a serious disease situation, an auxiliary agent for spraying could be added to prolong the retention of pesticide on the plant surface to extend the pesticide effect. This study can provide a reference for the optimized design, performance upgrade and reasonable application of small UAV sprayers.

Keywords: unmanned aerial vehicle (UAV), spraying pesticide, parameters optimization, fungicide deposition, wheat powdery mildew, control effect
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1 Introduction

Wheat powdery mildew caused by the biotrophic fungi *Blumeria graminis* (DC) Speer f. sp. *tritici* Emend. E.J. Marshcl, is one of the most important wheat diseases worldwide, which occurs in regions with maritime and semi-continental climates and causes severe yield losses, including in Gansu, Jiangsu Province, China[1]. Especially during the wheat heading stage when powdery mildew becomes serious below the top layer, leaves in the wheat top layers are interlaced, ground machines can be hardly used effectively, and the crop will be seriously damaged because of machine rolling. Moreover, pesticide can be hardly applied into the middle and lower layers by manual spraying, as a result, the conidia of wheat powdery mildew breaks out, conidiophores spread[2], and the stable and high wheat yield is decreased. In the late growing stage, manual spraying is involved with difficult walking, high labor intensity, distinct waste of pesticide, and harm to the biological environment and the operators[3]. Emergency prevention against any fulminant plant disease or insect pest can be hardly realized by manual spraying, and thus there will be a great loss because of the failure in timely treatment. Therefore, it is urgent to improve the mechanization of wheat disease and pest insect control in China, enhance the capacity to prevent and control fulminant and large-scale plant diseases and insect pests, and satisfy the demand for labor force in rural areas[4].

Aerial application, commonly called crop dusting, involves spraying crops with fertilizers, pesticides, fungicides, and other crop protection materials from agricultural aircraft[5]. In Japan and South Korea where there are a lot of hills but small tillable field for each farmer, manned planes of fixed wings are not suitable, and thus mini unmanned helicopters are mainly used there in agricultural aviation. Comparing with large agricultural planes, mini unmanned helicopters are integrated with unique advantages as no special airport is necessary but the maneuverability is highly favorable[6], and they have a high adaptivity to landforms and a

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high capacity for low altitude spraying[7-10]. In recent years, aerial machines, especially mini agricultural UAV (Unmanned aerial vehicle) for plant protection develop fast in China[11]. In respect of the current situation of UAV in China, a lot of exploration of farm spraying experiment has been made by scholars. For example, Qiu et al.[12] studied the distributing rule of fog drops applied by UAV CD-10 at different flying heights and flying speeds, and created a model for the relationship between deposition concentration and uniformity and flying speed and height and for the interaction between the two factors. Qin et al.[13] studied the impact of pesticide application by UAV on the droplets distribution on the corn top layer, and figured that when the working height was 5 m, the total deposition of droplets on the target was the least and the dispersion degree was the largest; when the working height was 7 m, the total droplets deposition on the target was larger than that when the working height was 5 m or 9 m, the dispersion degree of droplets deposition was the least, and the droplets distribution was the most uniform. For plant disease and insect pest control, Xue et al.[14] studied the effect of rice plant hopper and rice leaf roller control by UAV and figured that comparing with traditional manual pesticide application, the working efficiency of UAV could be improved by 60 times, the effective component in the pesticide solution sprayed could be reduced by 20%-30%, the labor intensity could be highly lowered, and it provided a working platform for effectively controlling any fulminant plant disease or insect pest and upgrading the plant protecting technique for large area paddy fields; Qin et al.[15] studied the impact of different working heights and working speeds of UAV HyB-15L on the droplets distribution and the controlling effect against paddy rice plant hopper. But few researches on the impact of different pesticide spraying parameters and pesticide application modes of small unmanned aerial vehicle on the droplets distribution uniformity and plant disease and insect pest control efficiency were reported.

Therefore, this paper intends to study the droplets distribution uniformity and the prevention against wheat powdery mildew in different pesticide spraying heights and different pesticide solution concentrations. The commonly used single-rotor UAV N-3 was chosen to spray the pesticide, the prevention effect of the routine knapsack-type electric fog sprayer was chosen as the control.

2 Materials and methods

2.1 Materials

The pesticide for experiment was triadimefon SC (44%) from Jiangsu Sword Agrochemicals Co., Ltd.; the wheat for experiment was Yannong 19, the growing stage was the heading stage and the flowering stage, plants were 0.8-1.0 m in height and spaced by 10 cm×20 cm, the LAI (leaf area index) was 5 m^2/m^2, and the target to prevent was powdery mildew.

2.2 Spraying platform and spraying system

The aerial platform was a pesticide spraying unmanned aerial vehicle N-3, and the prevention effect control test machine was a traditional Chinese knapsack-type fog sprayer with following parameters:

The type of aviation platform was the N-3 UAV, which was equipped with a spraying platform. The UAV was positioned by RTK differential GPS, the accuracy of flying height is controlled within ±0.3 m. The ground sprayer was a Shunpai Knapsack-type Electric Fog Sprayer 3WBD-16L (from Taizhou Jiaojiang Lüfeng Fog Sprayer Factory). The main parameters of the UAV and ground sprayer are presented in Table 1.

Table 1 Characteristic parameters of N-3 UAV and knapsack-type electric fog sprayer

	N-3 UAV	Knapsack-type electric fog sprayer 3WBD-16L
Rotor	Single rotor (Φ3.2 m)	
Nozzle type	Rotary atomizer	Fan-type nozzle
VMD/μm	230	300
Spraying type	centrifugal atomization (6000 r·min^{-1})	Pressure atomization (0.3 MPa)
Spraying angle	0°(vertically down)	0°(vertically down)
Single width/m	7	2
Nozzle numbers	2	1
Flowrate (one nozzle)/mL·min^{-1}	850	1000
Working height/m	5.0	0.5
Driving speed/m·s^{-1}	4	0.8-1
Spray volume/L·hm^{-2}	15	300
Tank capacity/L	25	20
Spraying pattern	Low volume and high concentration	High volume and low concentration

2.3 Environment monitoring

The air temperature and humidity at 1.5 m and 2.0 m above the plants were recorded by a digital temperature and humidity gauge (from Shenzhen Wanyitong Instrument Company) every 5 min; the wind speed at 1.5 m and 2 m above the plants were recorded by an anemoscope 8901 (from Shenzhen Wanyitong Instrument Company) every 60 s. The meteorological data, including the daily highest temperature, lower temperature, humidity and rainfall, were provided by the local plant protection bureau in Hongze County at Jiangsu Province in China.

2.4 Droplets distribution

In the single spraying amplitude droplets penetration test, the working height of UAV was 3.5 m and 5.0 m, the flying speed was 4 m/s, the area selected to spray on was fixed with water sensitive paper (25 mm×75 mm) (Figure 2) to the top (the second leaf) and bottom (25 cm above ground) on the crop by paper clips according to Figure 1. Transversal: 7 spots were sampled continuously and spaced by 0.5 cm each; longitudinal: repeated for three times and spaced by 5 m. A knapsack-type electric fog sprayer was used as the control.

After field work, naturally dried water sensitive paper was removed, sealed in a plastic bag and taken back to the lab, the fog drop coverage on the wheat canopy and droplets distribution uniformity were computed by the image processing software Deposit Scan[16].

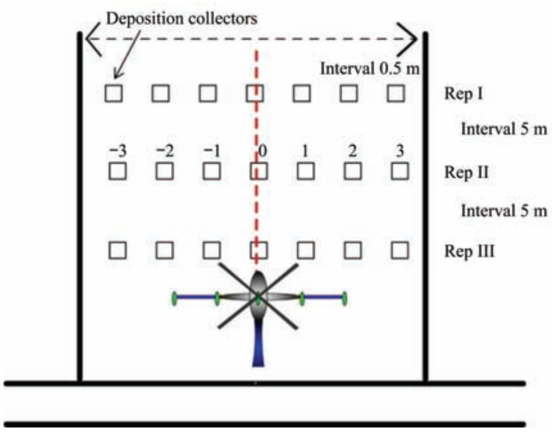

Figure 1 Layout of droplets sampling cards (Top view)

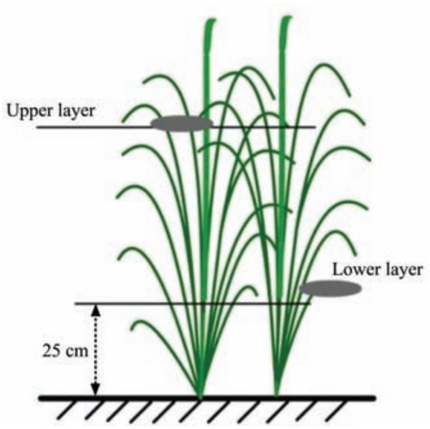

Figure 2 Sketches of sampling collectors on the wheat

2.5 Arrangement of the control zone

This experiment was taken in the wheat farm of Hongze Lake Farm, Sihong County, Jiangsu Province during the wheat powdery mildew prevention period in 2015, pesticide was sprayed for the first time on April 29th, and for the second time on May 4th. The experimental farm was divided into 3 areas, namely Area A, B and C. Each area was divided into 5 plots; the experiment was made in 5 processes, and each plot corresponded to a process. According to the farm pesticide effect experimental design, areas and plots were arranged randomly as shown in the Table 2. Numbers 1-4 in the figure were plots 1-4 corresponded to pesticide processes 1-4, and 5 was the control plot.

Table 2 Design of random areas

Section number	Area code				
A	1	4	2	3	5
B	2	5	4	1	3
C	4	3	1	5	2

Process 1 was: dosage 270 g/hm^2 sprayed by UAV N-3; Process 2 was: dosage 360 g/hm^2 sprayed by UAV N-3; Process 3 was: dosage 450 g/hm^2 sprayed by UAV N-3; Process 4 was: dosage 450 g/hm^2 sprayed by knapsack-type electric fog sprayer; and Process 5 was: blank control. During spraying, the pesticide sprayed by UAV N-3 was 15 L/hm^2, and the solution was sprayed down vertically from the height of 5.0 m above the crop (see the Figure 3); the pesticide sprayed by knapsack-type electric fog sprayer was 300 L/hm^2, and the solution was sprayed down vertically from the height of 0.5 m above the crop, as shown in Figure 4.

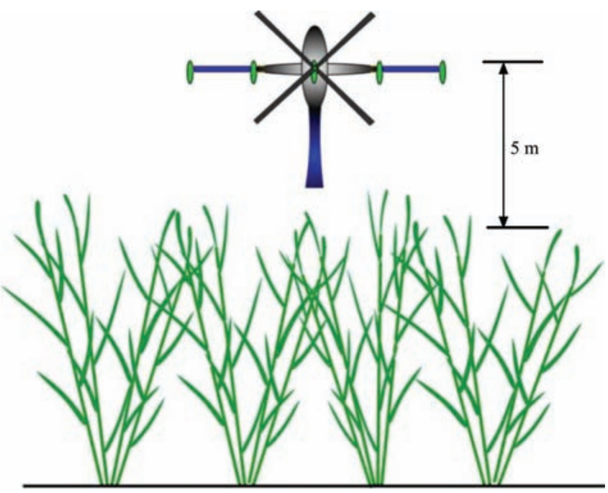

Figure 3 N-3 UAV sprays sampling in wheat fields

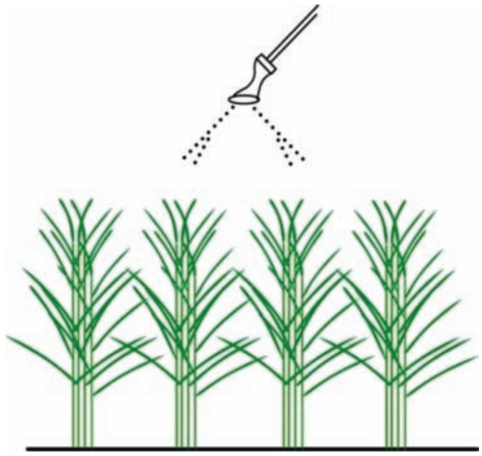
Figure 4 Knapsack powered sprayer sprays sampling in wheat fields

2.6 Disease investigating and pesticide effect calculating method

2.6.1 Investigating method

The prevention effect was firstly investigated on the 7th day (May 11th) after the secondary pesticide application, and the second prevention effect was secondly investigated on the 10th day (May 14th). The disease on each plot was investigated by the improved "Level 0-9" method (as shown in the Table 3), plants were divided into 9 equal sections from bottom to top, and levels were determined by the severity of disease on leaves or ears at different heights. Each plot was sampled at 5 points, 20 plants were investigated at each spot, disease levels were recorded, and *DI* (Disease Index) was calculated as per the equation below:

$$DI = \frac{0 \times n_0 + 1 \times n_1 + ... + 9 \times n_9}{9 \times (n_0 + n_1 + ... + n_9)} \times 100 \quad (1)$$

where, n_0, $n_1 \ldots n_9$ are numbers of plants in different disease levels.

Table 3 Wheat powdery mildew classification standard

Disease Class	Description
0	No disease on the whole plant
1	A few of disease spots on leaves at 1st section (disease spots below 2% of leaf area)
2	A few of disease spots on leaves at 2nd section and light disease on leaves at 1st section (disease spots in 3%-10% of leaf area)
3	Light disease on leaves at 3rd section, medium disease on leaves at 2nd section (disease spots in 11%-25% of leaf area), and serious disease on leaves at 1st section
4	Light disease on leaves at 4th section, and medium or serious disease on leaves at 3rd section and below
5	Light disease on leaves at 5th section, and medium or serious disease on leaves at 4th section and below
6	Light disease on leaves at 6th section, and medium or serious disease on leaves at 5th section and below
7	Light disease on leaves at 7th section, medium or serious disease on leaves at 6th section and below, and a few of disease spots on the flag leaf
8	Light or medium disease on the flag leaf, and medium or serious disease on the flag leaf and below
9	Serious disease on all leaves, different classes of disease on ears, and ear disease indicated by percentage

$$DI = \frac{\sum (x \times f)}{n \times \sum f} \times 100\% \quad (2)$$

where, *DI* is the disease index; *x* is the gradient level; *n* is the highest gradient level (*n*=9); and *f* is the number of leaves at each gradient.

2.6.2 Pesticide effect calculating method

The control efficiency of the disease of processing area compared with the blank control area after applying fungicide. The formula is:

$$E=\left(1-\frac{I_{CB}I_{PA}}{I_{CA}I_{PB}}\right)\times 100\% \qquad (3)$$

where, E is the disease control efficiency; I_{CB} is the disease index of blank control before pesticide application; I_{PA} is the disease index of process plot after pesticide application; I_{CA} is the disease index of blank control after pesticide application; and I_{PB} is the disease index of process plot before pesticide application.

3 Results and discussion

3.1 Environment condition

The experimental research shows the occurrence of wheat powdery mildew is highly correlated to the change of meteorological condition[17]. In the daily temperature change, the longtime suitable temperature (15°C-18°C) is the most advantageous for the germination and infection of wheat powdery mildew spores while long time day temperature above 25°C will distinctly inhibit the pathogenic bacteria[18].

Figure 5 shows that from April 20th to 24th, the daily mean temperature gradually rose from 12.8°C-20.3°C, and the relative humidity changed within 50%-90%. The temperature dropped on 25th and then rose again. On 28th, the temperature dropped after rain, the daily mean temperature was about 16°C, and the daily mean relative humidity reached 90% on the raining day. On May 2nd when it rained again, the daily mean temperature was about 18°C, the relative humidity exceeded 90%, and it promoted the occurrence of powdery mildew and the infection and spread of pathogenic spores. Pesticide was sprayed for the first time on April 29th and for the second time on May 4th, and each time was on the first day after rain. On May 11th, 7 d after pesticide application, when the disease was investigated for the first time, the daily mean temperature was 18°C-20°C, and the daily mean humidity gradually dropped to 50%. On May 14th, 10 d after pesticide application, when the disease was investigated for the second time, the daily mean temperature and daily mean humidity gradually rose. On May 15th when it rained, the daily mean temperature dropped to 10°C approximately while the daily mean relative humidity rose to 85%, and the powdery mildew was probably aggravated.

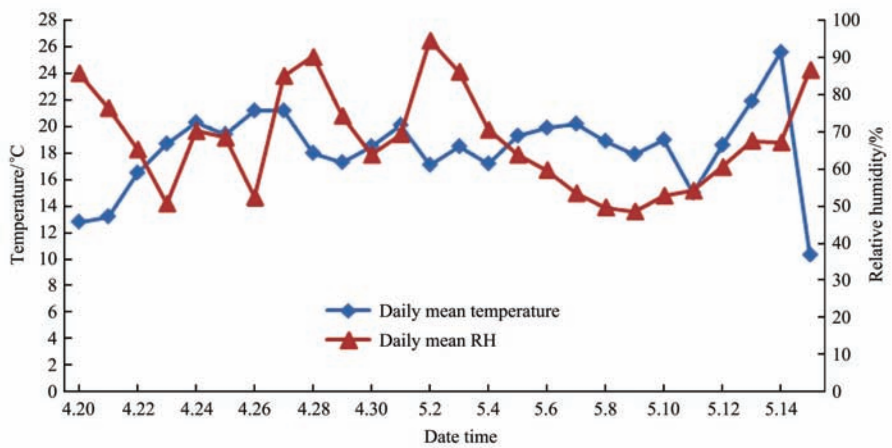

Figure 5 Daily mean temperature and relative humidity during test

3.2 Analysis of deposition effect

It is significantly important to optimize the working parameter of UAV so as to enlarge the fog drop penetration, improve the uniformity of deposition distribution, control the deviation and further improve the pesticide solution deposition rate. Table 4 shows that when the flying speed was fixed (at 4 m/s) but the flying height was improved from 3.5 m to 5.0 m, the droplets coverage rate on wheat canopy was increased from 2.67% to 3.66%, and on the lower layer was increased from 0.91% to 1.67%. When the flying height was 3.5 m, the ratio of droplets coverage on the lower layer to that on the canopy was 34.1%, the variation coefficient of droplets distribution was 40% on wheat canopy and 40.44% on the lower layer; when the flying height was 5.0 m, the ratio of droplets coverage on the lower layer to that on the canopy was 45.6%, the variation coefficient of droplets distribution was 33.13% on wheat canopy and 36.84% on the lower layer. When sprayed by a knapsack-type electric fog sprayer, the droplets coverage rate on the wheat canopy was 14.9% and 4.3% on the lower layer, the ratio of droplets coverage on the lower layer to that on the canopy was 28.9%, and the variation coefficient of droplets distribution was 31.48% on wheat canopy and 43.34% on the lower layer. As influenced by wheat canopy, the ratio of droplets coverage on the lower layer to that on the canopy for knapsack-type electric fog sprayer was distinctly lower than that for UAV spraying at 5.0 m. When sprayed by UAV in a light natural wind, wheat branches and leaves the airflow below the rotors will move, and thus the deposition of droplets on the lower layer is enlarged.

Table 4 Droplets deposit and spraying uniformity

Spray machines	Nozzles working Height/m	Sampling site	Coverage /%	Spraying uniformity/%
UAV	3.5	Upper layer	2.67 ± 1.0	40.00
		Lower layer	0.91 ± 0.4	40.44
	5.0	Upper layer	3.66 ± 1.2	33.13
		Lower layer	1.67 ± 0.7	36.84
Knapsack powered sprayer	0.5	Upper layer	14.9 ± 4.6	31.48
		Lower layer	4.3 ± 1.8	43.34

The effect of droplets deposition in the wheat canopy is very obvious with unmanned aerial vehicle, especially at later growth stage of wheat, maximum LAI. Droplets coverage with conventional ground machine spraying was obviously lower than the UAV's droplets coverage at the bottom of the wheat. The downward air flow from the rotor wing could actuate the movement of wheat leaves, thus augmenting the droplet deposition in the bottom layer of wheat. As most of the research with UAVs is still in its initial stages, there are a number of open questions that need solving, like route planning[19] and the function law of pesticide droplets acted by rotor downwash flow[20], among others.

3.3 Effects of UAV spraying on wheat powdery mildew control

To clarify the control efficiency of UAV on wheat powdery mildew, we compared the effect of low volume spraying by UAV to the effect of spraying by knapsack-type electric fog sprayer. As shown in Table 5, 7 d later after pesticide application, the control efficiency of dosage 270 g/hm^2 (40% less than the registered dosage) sprayed by UAV was 35.57%, distinctly lower than that of dosage 360 g/hm^2 (20% less than the registered dosage) and that of dosage 450 g/hm^2 (registered dosage), in which, the effect of dosage 270 g/hm^2 sprayed by UAV was not significantly different from that of dosage 450 g/hm^2 sprayed by electric powered sprayer; 10 d later after pesticide application, the control efficiency of 360 g/hm^2 and 450 g/hm^2 by UAV were 64.47% and 67.88% respectively, both higher than 52.31%, the effect of 270 g/hm^2; the effect of dosage 450 g/hm^2 sprayed by electric powered sprayer was 72.93%, higher than that of dosage 270 g/hm^2, 360 g/hm^2 or 450 g/hm^2 sprayed by UAV. Comparing the effect of 10 d later to the effect of 7 d later after pesticide application, all the control effects of different processes were improved, the effects of dosage 270 g/hm^2, 360 g/hm^2 and 450 g/hm^2 sprayed by UAV were improved by 16.74%, 17.83% and 12.75% respectively, and the effect of dosage 450 g/hm^2 sprayed by knapsack-type electric fog sprayer was distinctly improved by 38.32%. Seven days later after pesticide application, the control efficiency of process 3 (dosage 450 g/hm^2) sprayed by UAV was the best. A research has shown that the effective period of high concentration was longer than that of low concentration[21], applying pesticide by UAV belongs to low volume but high concentration spraying, and by the downward airflow below rotors, crops can be disturbed, droplets will penetrate the canopy and reach the bottom. Ten days later after pesticide application, the control efficiency realized by UAV spraying was lower than that realized by knapsack-type electric powered sprayer, and it was probably correlated to meteorological conditions and water content in the solution. Moreover, the air stream that was generated by rotor wings could perturb the wheat, and the droplets were prone to penetrating the canopy layer, reaching the bottom of the wheat. Lee[22] used mist and colored smoke as displaying carriers to determine the rules of the air stream of rotor wings on pesticide droplet action and successfully observed the wind field of the UAV and trajectory of pesticide droplets. However, the present description of downwash flow under the UAV on droplet disposition remains non-quantitative, especially for the vertical component of wind field, which needs to be further investigated. Ten days later after pesticide application, the daily mean relative humidity rose, and thus the powdery mildew was aggravated, as UAV spraying was low volume spraying, the pesticide effect was impacted by the excessively long retention of pesticide solution on crop surface. Therefore, when UAV is used to spraying pesticide solution against serious wheat powdery mildew, it is recommended that some auxiliary agent must be added to enlarge the retention period of pesticide solution on crop surface so that the pesticide effect can be prolonged, and the prevention effect against wheat powdery mildew can be improved. However, some further researches will be made in the future.

Table 5 Control efficiency for wheat powdery mildew in the heading stage

Treatment	Disease index before spraying	7 d after treatment		10 d after treatment	
		Disease index	Control efficiency	Disease index	Control efficiency
1	23.13	17.14	35.57±1.29c	14.8	52.31±1.14c
2	22.00	13.5	46.64±0.71b	10.49	64.47±0.76b
3	23.82	12.29	55.13±0.95a	10.27	67.88±0.72b
4	24.29	18.25	34.61±1.02c	8.83	72.93±2.19a
5	23.75	27.32		31.89	

Note: Data in the table are mean ±SD. Different letters in the same column indicate significant difference at $p<0.05$ level by Duncan test.

4 Conclusions

In this research during the wheat heading stage, agricultural UAV was firstly used for low altitude and low volume pesticide application against wheat powdery, the droplets distribution and control efficiency on different layers of wheat at different working height and different pesticide solution concentrations were studied and analyzed, the effect showed by routine knapsack-type electric powered sprayer was used as the control, and the experiment result showed:

(1) The impact of UAV spraying on the distribution of droplets on different layers of wheat was quite significant especially during the late growing stages when the leaf area index was the largest, the droplets coverage on the lower layer of wheat realized by routine ground sprayer was distinctly lower than that realized by UAV. It favorably indicated that the downward air stream below rotors could enlarge the droplets penetration when UAV was used for low volume spraying. At a fixed flying speed (4 m/s) when the flying height was 3.5 m, the droplets coverage rate on wheat canopy and the distribution uniformity were the best, the ratio of droplets coverage rate on the lower layer to that on the canopy was 45.6%, higher than that when the flying height was 5.0 m and that realized by knapsack-type electric powered sprayer.

(2) In the experiment for prevention against wheat powdery mildew, 7 days later after pesticide application, the effect realized by UAV was better than that by knapsack-type electric powered sprayer especially when the dosage was reduced by 20%. 10 d after pesticide application, the prevention effect realized by UAV spraying was lower than that realized by knapsack-type electric powered sprayer, and it was probably correlated to meteorological conditions and water content in the solution.

(3) When UAV is used to spraying pesticide solution against serious wheat powdery mildew, it is recommended that some auxiliary agent must be added to enlarge the retention period of pesticide solution on crop surface so that the pesticide effect can be prolonged, and the control efficiency against wheat powdery mildew can be improved. However, some further researches will be made in the future.

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