Droplet deposition characteristics of plant protection UAV spraying at night

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Abstract: The spraying technology of plant protection UAVs is developing rapidly. Although they can spray autonomously at night, the application performance under meteorological conditions at night still needs to be evaluated. In this research, the droplet deposition characteristics of nighttime and daytime spray of a P20 UAV with different operating parameters were compared. Specifically, the number of droplets deposited in different parts of the plant was evaluated. The results showed that under the same operating parameters the application time had a significant effect on the number of droplets deposited and coverage rate, the droplets number and coverage rate for the nighttime application were 43.47% and 37.21% higher than that by the daytime application. In terms of the droplets deposition in different parts of cotton plants, for the nighttime application, the proportions of the droplets on the upper, middle and lower layer to the total droplet number in the vertical direction of the plant were 41.24%, 35.71% and 23.05%, respectively and those were 43.09%, 33.99% and 22.91% for the daytime application. There were more droplets deposited on the middle and lower layer of the plants when spraying at night than those in the day. Additionally, the deposited droplets on the backside of the leaf account for 21.92% of the total droplets on a leaf for the nighttime application on average, while it was 20.23% for the daytime application, this proportion did not exceed 25% within all treatments. In the daytime, the droplet deposition effect was better at the flight speed of 3.0~3.5 m/s and flight height of 1.5~2.0 m, while for the nighttime application the best parameters were the flight speed of 3.0~4.5 m/s and the flight height of 2 m. The deposition amount and penetration of droplets of the nighttime application were better than that during the daytime, and the optimal operating speed at night is also faster, so spray at night can help to improve UAV operating efficiency.

Keywords: plant protection UAV, spraying at night, droplet distribution, parameters optimization
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1 Introduction

It is needed to be sprayed within a short time to contain the spread of crop diseases and pests. To improve spray efficiency, growers are increasingly inclined to work continuously at night[1]. However, most pesticide application equipment needs to be operated manually, working at night not only increases the operator's workload but also is easy to cause repeated spray and missed spray due to poor night vision.

Plant protection UAV technology has developed rapidly in recent years[2-5] and made breakthroughs in route planning[6], autonomous obstacle avoidance[7], terrain-following[8], variable rate pesticide application[9], etc. They are widely used in the prevention of diseases and pests of wheat, rice, and cotton[10-13]. Some UAVs can spray autonomously at night, which breaks the working time limitation[14]. Autonomous working at night for the plant protection UAV has become possible, however, scientific research on nighttime applications is limited and a big knowledge gap exists in this field. There are few studies available to provide UAV users with objective information to make an informed choice and determine if nighttime applications could be used as practical alternatives to the daytime application. In existing researches, spraying in the morning and evening by manned fixed-wing aircraft has been only reported. Fritz B K suggested that aerial spray should avoid the temperature inversion when using a fixed-wing aircraft. Because this meteorological condition without air convection near the ground will cause droplets to float in the air[15]. Temperature inversion appears mainly at night[16], which is theoretically favorable for pesticide application by small rotor drones. Because (i) stable atmosphere will mitigate the droplets drift, (ii) the lower temperatures and higher relative humidity at night will not cause much droplets evaporation, and (iii) strong downwash generated by UAV rotors could provide the kinetic energy that droplets required for dropping[17], so they would not float in the air.

To explore the advantages and distribution characteristics of droplets at night, a P20 plant protection UAV (Guangzhou Ji Fei Technology Co., Ltd.) was adopted to conduct spray tests in cotton fields during the day and night in this paper. The effects of different application times and operating parameters on droplet deposition were analyzed, specifically, the number of droplets on different parts of cotton plants was evaluated.

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2 Material and methods

2.1 Materials and devices

The test was conducted at the Korla Test Base of the Institute of Plant Protection of the Chinese Academy of Agricultural Sciences (41°45'06.5"N, 85°48'27.1"E). The experimental area was a total of 3 hm^2, which was divided into 22 small test fields for different parameters setting, and each field was 15 m×130 m (Figure 1). To avoid test errors caused by repeated and missed spray at the adjacent edge of two test fields, a rectangular area with a size of 6 m×10 m was taken in the center of each field, and the long side is consistent with the flight direction of the UAV. The distance between neighboring sampling rectangle was 9 m, so there had no independent buffer area to be set up between two treatments. As shown in Figure 2, five sampling points were taken on the diagonal of the rectangle.

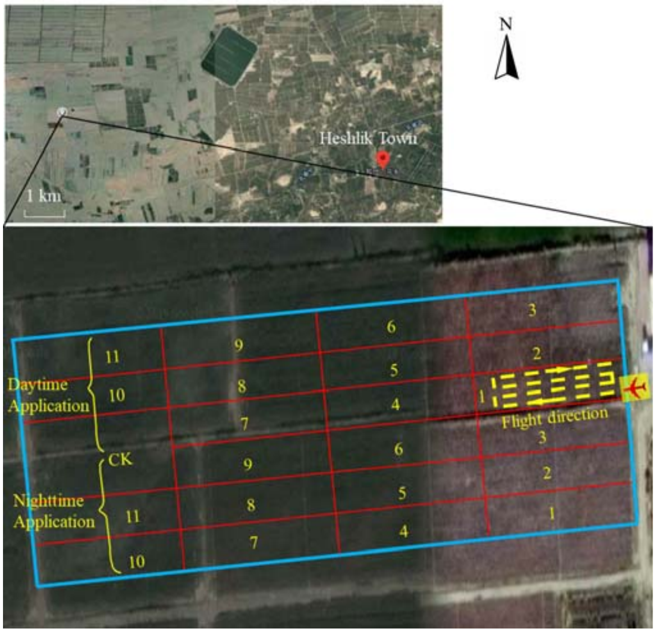


Figure 1 Experimental fields division (1-11 are treatment No.)

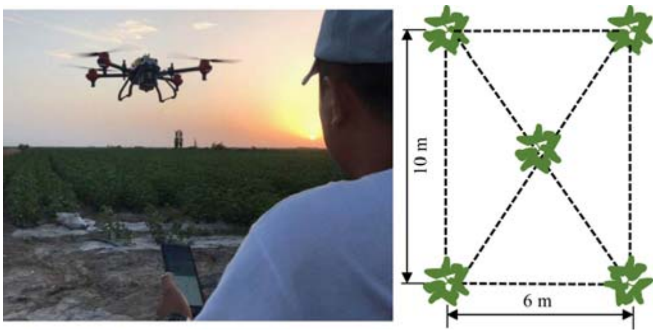


Figure 2 Test scene and sampling points distribution

The cotton species was Xinluzhong #41. The plant was sowed on April 20, 2018, and the plant density was from 211,000 to 225,000 plants per hectare. A drip irrigation system under plastic films was applied for watering. Under each film, 3 drip tapes were employed along the row. The distance between the adjacent drip holes on a drip tape was 0.3 m. The drip hole flow rate was 2.4 $L\cdot h^{-1}$ with a working pressure of 50 kPa. Groundwater was used as a source of water. The test was conducted during the day and night on July 10, 2018. At this time, the cotton plant was in the bud stage, the average plant height was 65 cm, and the rate of cotton plant with aphid reached 100%. Before the test, two spray operations were performed in the test fields by boom sprayer on June 2 and June 14, 2018, to control cotton aphids.

The P20 electric quad-rotor plant protection UAV can spray at night autonomously. The effective spray width was 3 m. Four centrifugal nozzles were mounted under each rotor, and the spray volume can be set from 0 to 15 $L\cdot ha^{-1}$ with a load capacity of 10 kg. The RTK provides high-precision positioning and navigation with an accuracy of a centimeter. Refer to the normal operating parameters of the UAV and current cotton plant height, different flight heights (1.5 m, 2.0 m, 2.5 m) and flight speeds (3 m/s, 4 m/s, 5 m/s) were tested. The spray volume (7.5 $L\cdot hm^{-1}$, 11.3 $L\cdot hm^{-1}$, and 15 $L\cdot hm^{-1}$) was configured based on the recommendation from a well-trained UAV operator.

It is necessary to control cotton aphids while collecting droplet deposition information. Therefore, the pesticides and additives were used in applications, they were 22% Sulfoxaflor at a dose of 300 $mL\cdot ha^{-1}$ (American Dow AgroScience Co., Ltd.), 5% Acetamiprid microemulsion at a dose of 45 $g\cdot ha^{-1}$ (Dongguan Ruidefeng Biotechnology Co., Ltd.), Etoxazole at a dose of 300 $mL\cdot ha^{-1}$ (Sumitomo Chemical Co., Ltd., Japan), and Gelangdi at a dose of 300 $mL\cdot ha^{-1}$ (Glenada Chemical Company, USA) to prevent droplets from drifting.

2.2 Experimental method

The Latin Hypercube (LH) was adopted for the experimental design. Compared with the traditional method, LH can effectively improve sampling efficiency as the sampling number is reduced significantly without the loss of accuracy. The procedure for LH is defined as follows: $X_1, X_2, \cdots X_M$ is the M input random variables. Each random variable obeys a certain probability distribution:

$$Y_m=F_m(X_m)$$

Where Y_m is the probability of X_m and is scaled from 0 to 1, and F_m is the probability cumulative function of X_m. Then the nth sample value of the mth random variable x_{mn} is calculated by the inverse function of F_m:

$$X_{mn}=F_m^{-1}\left(\frac{n-a}{N}\right)$$

Where a is an internal variable that meets the 0-1 distribution. All the sample values of the input variables construct a $N\times M$ sampling matrix. Finally, each column of the sampling matrix should be shuffled randomly, and each row constitutes a random scenario[18].

Table 1 shows the treatment design in the test. The daytime application was conducted from 5:00~7:00 pm and the nighttime application from 10:00~12:00 pm. Before the UAV takes off the water-sensitive papers (WSPs) were fixed on cotton leaves at each sampling plant (Figure 3). Sampling cotton plants were divided into the upper, middle, and lower layer. One WSP was fixed on the upper and the other on the backside of the leaf at each sampling layer. UAV took off by the test fields. When each test field has been sprayed and droplets have dried, WSPs have been collected into a sealable plastic bag with relative label, then they were taken back to the laboratory and scanned into an image with a resolution of at least 600 dpi, finally, these images were analyzed by ImageJ software (National Institutes of Health, USA) to obtain droplet deposition information including the number per unit area, coverage rate and size of deposited droplets. This software is based on image technology. In addition to rotating, graying, and smoothing an image, it can also analyze a series of features of the object in the selected area such as number, length, angle, circumference, area. The droplet coverage rate is the ratio of the area covered by the droplets to the total area of the WSP.

Meteorological data was recorded during the test by a Kestrel 4500 Environmental Meter (Nielsen-Kellerman, USA). The air temperature was 28.4~32.6°C, the relative humidity was 41.3%~ 55.3%, and the wind speed was 0.4~2.4 m·s^{-1} with the direction of the northeast during the daytime application while they were 24.8~28.2°C, 54.1%~69.5%, and 0~1.9 m·s^{-1} during the nighttime application. The wind speed at night was slower than that in the day, but their direction was the same, which was basically parallel to the UAV flight route. During the nighttime application, the average air temperature was 5.9°C lower than the daytime, and the relative humidity was 13.1% higher than that during the day.

Table 1 The treatments design

Application time	No.	Flight speed /m·s^{-1}	Flight height /m	Spray volume /L·hm^{-2}
Day/Night	1	5	1.5	7.5
	2	4	2.5	15
	3	3	1.5	11.3
	4	3	2.5	7.5
	5	3	1.5	15
	6	4	2	11.3
	7	5	2.5	7.5
	8	3	2	15
	9	5	2	11.3
	10	4	1.5	7.5
	11	4	2	15

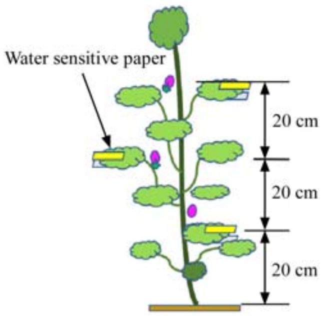
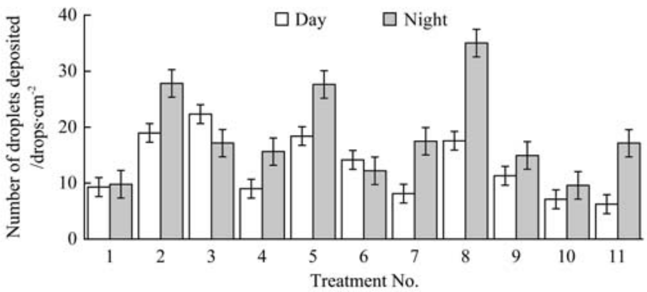


Figure 3 Distribution of sampling points within a cotton plant

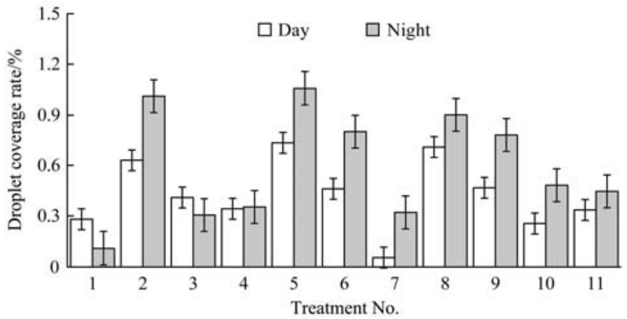
3 Results and analysis

3.1 Effect of meteorological conditions on droplet deposition

The number of deposited droplets and the coverage rate of the five sampling points were averaged to obtain the droplets distribution of the test field. Figure 4a compares the difference of droplets number between the daytime and nighttime application for each parameter setting. Under the same parameters, the deposited droplet number for the nighttime application (18.58 drops/cm^2) was 43.47% more than that by the daytime application (12.95 drops/cm^2). As shown in Figure 4b, the average droplet coverage rate was 0.59% for the nighttime application, which was 37.21% higher than the 0.43% for the daytime application. After droplets leave the nozzle, they are drifting, evaporating, and depositing on the ground or plant canopy. This process is not only affected by air temperature and humidity, but also by atmospheric pressure, atmospheric stability, wind speed and direction, so the droplet distribution is the result of these factors working together under the whole meteorological condition. The higher wind speed will increase the drift loss of droplets, while the lower wind speed will make the droplets floating in the air during spraying. But for the UAV spraying at night, downwash velocity near the crop canopy can reach 5~8 m·s^{-1}, which provides kinetic energy that droplets required for dropping, so spraying at night didn't cause a lot of droplets to float in the air. The temperature during the day was high and the relative humidity was significantly lower than that at night. The hot and dry conditions will increase the floating loss of pesticide, because the droplets will quickly evaporate and become smaller droplets, steam, or concentrated pesticide particles. From Figure 4 it can be known that the number of deposited droplets is inversely proportional to temperature but proportional to relative humidity, which was consistent with the research results of Fritz B K. Fritz B K et al[17] believed that the difference in droplet deposition caused by different temperature and relative humidity is mainly reflected in the amount of droplet evaporation loss. Meteorological conditions are one of the main factors affecting pesticide application quality, it is uncontrollable. Therefore, the best operating time needs to be selected for UAV applications to reduce droplet drift and evaporation loss. According to the test results, the meteorological condition at night was favorable for UAV spray.



a. Number of droplets deposited



b. Coverage rate of droplets

Figure 4 Comparison of droplet deposition characteristics for the daytime and nighttime applications

3.2 Effect of operating parameters on droplet distribution

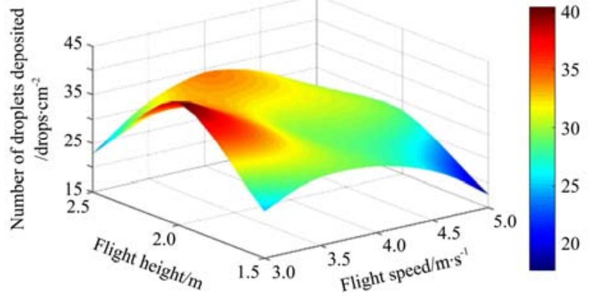
Operating parameters are another important factor to affect spraying quality. Figure 5 shows the effect of operating speeds and heights of the UAV on the droplet deposition number.

In fact, the optimal operating parameters for the daytime and nighttime applications were different. For the nighttime application (Figure 5a), as the flight height increased from 1.5 to 2.5 m, the number of deposited droplets increased first and then decreased, it reached a maximum with the flight height of 2 m. When UAV sprayed at a lower height, the spray width was shortened, along with the fact that cotton plants prevented droplets from spreading in the horizontal direction, there was an uneven droplet distribution. Conversely, spraying at a higher elevation will cause more droplets to drift. The farther the vertical distance from the nozzle to crop canopy, the longer time it takes for a droplet to deposit, which increases the chance of droplet loss. There was a good deposition when UAV spray with the flight speed of 3~4.5 m·s^{-1}. After that, the number of droplets decreased with the increase of speed. When UAV fly at a faster speed, the downwash was weakened seriously and become more disorganized, this was not conducive to promote droplets deposition. For the daytime application in figure 5b, when fly speed was 3~3.5 m·s^{-1}, the droplet deposition was better. Compared with the nighttime application, the daytime optimal flight speed was slower, because the stronger downwash was needed for droplets deposition during the daytime application. When the UAV flies at a high speed, the downwash in the vertical direction was weakened and the optimal aggregation position of the downwash from each rotor would be elevated[19,20], which had a little contribution on droplets dropping. Under high temperature and wind conditions during the daytime, droplets would be easier to be evaporated and drifted. In terms of operating height, the optimal one was 1.5~2 m, which was lower than that for the nighttime application, because spraying in the day needs to enhance downwash by lower flight height to resist natural wind and carry the droplets reaching crop canopy as soon as possible.

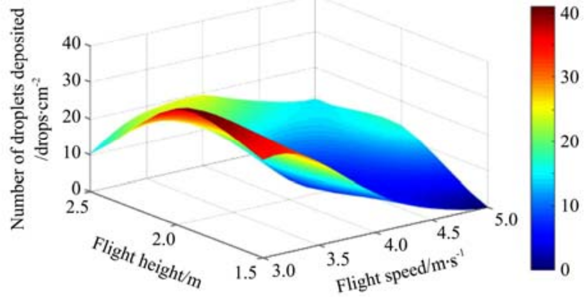
Additionally, as the spray volume of the UAV increased, the number of deposited droplets also increased. It can be seen from Figure 4 that no matter whether spray in the day or at night, the droplet deposition of treatment 2, 5, 8 was the better, because these test fields all were sprayed with the volume of 15 L·hm^{-2}.

3.3 Characteristics of droplet deposition in different parts of cotton plants

The number of droplets deposited at different layers of the cotton plant and the upper and backside of the leaf is shown in Figure 6, where a, b, and c are the treatments during the day, d, e, and f are the treatments at night.

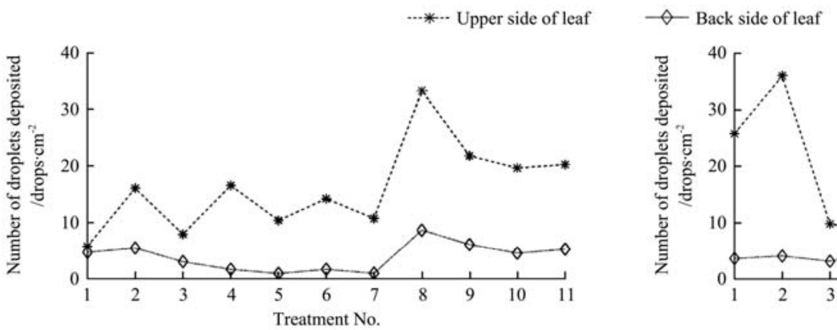


a. Night application

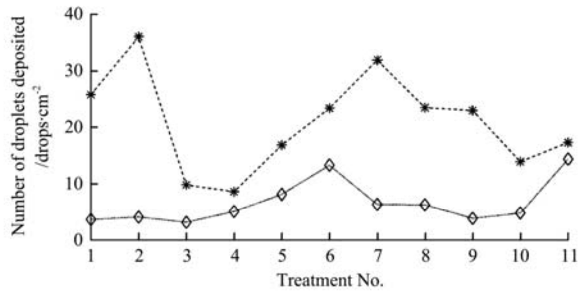


b. Day application

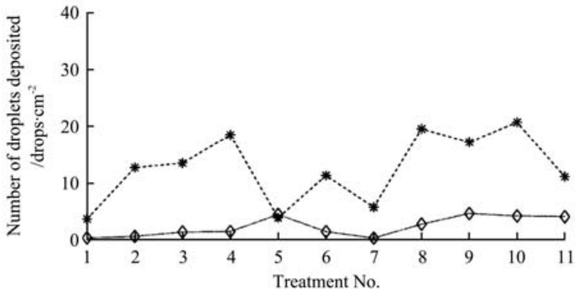
Figure 5 Effect of different operating parameters on number of droplets deposited



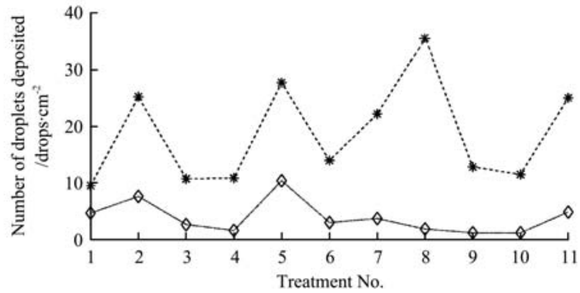
a. Droplet number in plant upper layer



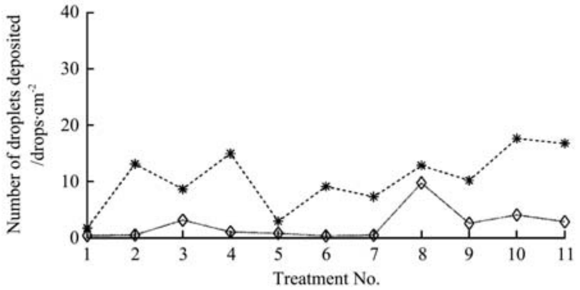
b. Droplet number in plant upper layer



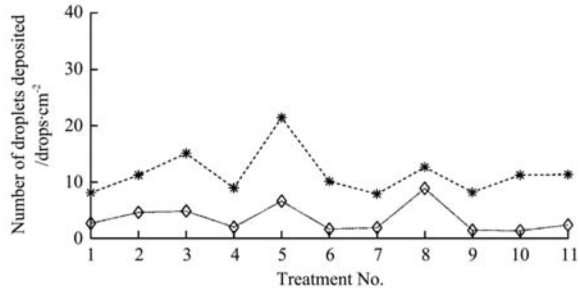
c. Droplet number in plant middle layer



d. Droplet number in plant middle layer



e. Droplet number in pant lower layer



f. Droplet number in plant layer

Figure 6 Comparison of the number of droplets deposited on the upper and backside of leaf at each sampling layer of cotton plants (a, b, and c are the results of daytime applications, and d, e, f are the results of nighttime applications)

The number of droplets deposited on each sampling layer can be obtained by summing the number of droplets on the upper and backside of the leaf. The average number of droplets deposited on the upper, middle, and lower layer of cotton plants for the nighttime application were 21.63, 18.73, and 12.09 drops/cm^2, and the proportion of the number of the droplets on each layer to the total number of droplets in the vertical direction of the plant were 41.24%, 35.71%, and 23.05%. For the daytime application, the average number values of droplets on each layer were 15.91, 12.55, and 8.46 drops/cm^2, and the proportion of droplets in each layer were 43.09%, 33.99%, and 22.91% respectively. In the vertical direction of the cotton plant, the droplet number decreased from top to bottom. The droplets deposited at different heights of the plant for nighttime application were more than those by the daytime application. There are more droplets deposited on the middle and lower layer of the plant when spray at night, indicating that the penetration of droplets at night is better than that in the day.

In terms of the proportion of the droplet number deposited on the backside of the leaf to the total number of droplets on the leaf, it was 21.92% on average for the nighttime and 20.23% for the daytime. The number of droplets deposited on the backside of the leaf at each sampling layer was upper layer> lower layer> middle layer. The downwash of UAV caused the upper leaves of the cotton canopy to turn over, which improved the droplet deposition effect on the backside of leaves at the upper layer. However, the number of droplets deposited on the backside of leaves at lower layer is more than that at the middle layer. After comparing the droplet size at each sampling height, it was found that the average droplet size was upper layer > middle layer > lower layer (Table 2). The most of smaller droplets are deposited at the bottom of the plant. Because downwash becomes turbulent due to the obstructive effect of plant leaves and stems, it took droplets to move within the plants in different directions, in the process of travelling the larger droplets deposited on the plants at the turn due to the larger centrifugal force, while the smaller droplets can continue to spread with the airflow. In all the treatments for the day and night, the proportion of the droplet deposited on the backside of the leaf did not exceed 25%. The cotton aphids are mainly parasitic on the back of cotton leaves. The more droplets deposited on the backside of leaves, the bigger chance that the cotton aphids will be exposed to pesticides[21,22].

Table 2 Proportion of droplet number on backside of leaf and average droplet size for different sampling layer

Application time	Sampling layer	Proportion of droplet number/%	Average droplet size/μm
Day	Upper	20.29	178.12
	Middle	17.38	152.44
	Lower	23.02	139.54
Night	Upper	24.32	187.38
	Middle	18.10	158.71
	Lower	23.34	144.32

As shown in Figure 6, there are more droplets deposited at the middle and lower layers of the cotton plant and the backside of leaves for the treatments of 2, 5, and 8. These treatments were all applied with lower operating speed and height with larger spray volumes, which indicates that the UAV downwash would help to promote the penetration of droplets only when (i) the downwash is not weakened, and (ii) the droplets do not lose a lot.

4 Discussion

In this paper, spray experiments for the daytime and nighttime of UAV was carried out in the cotton bud stage. The results showed that the droplet deposition effect of nighttime application was better than that in the daytime, whether it is the number of droplets deposited at different layers of the cotton plant or on the backside of the leaves. Because there were a stable atmosphere environment and slower wind speed at the night, which was helpful to mitigate the droplets drift. On the other hand, the average air temperature at night was 5.9°C lower than that in the day while the relative humidity was 13.1% higher, this situation was not easy to cause much droplets evaporation. Under the same meteorological conditions, small droplets are easier to evaporate. Due to the low air temperature and high relative humidity at night, the small droplets are protected from evaporation, they can shuttle inside the cotton plant and finally reach the middle and lower layers of the plant and the backside of the leaves, and therefore the deposition effect on the backside of leaves at night was better. On the contrary, due to the large centrifugal force, the large droplets are more likely deposited on the plant when turning, it was difficult for them to travel to the lower layer of the plant and the backside of the leaves.

According to the occurrence period of cotton aphids, it can be divided into seedling stage aphid and summer day aphid[23]. In different occurrence stages, the physical characteristics of the cotton plant such as height, canopy size, and leaf density are different, these factors will affect microclimates such as air temperature, leaf temperature and relative humidity in cotton field[24], so maybe there have a different droplet deposition results. On the other hand, cotton plants in the bud stage are high and the leaves are dense and interlaced, it is necessary to reduce the flight height and speed of UAV to obtain strong downwash to improve the penetration of the droplets. In the seedling stage, cotton plants are short and leaves are sparse, there is a large area of exposed soil in the cotton field, to avoid damaging the plants caused by the strong downwash and raising the dust (the droplets will be adsorbed by dust), maybe the higher flight height is required. So the future works should focus on the other growth stages of cotton.

Theoretically, the downwash generated by UAV rotors is beneficial for droplets depositing on the backside of leaf[25]. But in this paper, the test results showed that only less than 25% of droplets deposited on the backside of leaves within all treatments, which contradicted the fact that the cotton aphids are mainly parasitized on the back of the leaf. Observations revealed that there was a canopy vortex below the UAV body when it hovering, the plants in the vortex swung seriously and much of the cotton leaves turned over. At the same time, the droplets stream flushed in the vortex. When UAV moved forward fast, the vortex area and deposition area of droplets stream both lagged, they were behind of UAV but not overlap, this is the main reason why downwash had a little contribution on improving droplets number on the backside of leaves. Because different particles have different traveling speeds in the air, at the same time droplets and airflow have a different traveling distance, so they were not in the same place when reached cotton canopy. Therefore, bridging the gap between the droplet deposition area and the plant vortex area is a potential point in future research.

5 Conclusions

In this paper, the droplet deposition characteristics for P20 UAV spraying under day and night meteorological conditions were compared, the effects of different application time and operating parameters on the droplet deposition were explored, and specifically, the droplet number on different parts of cotton plant was evaluated. The results showed that under the same operating parameters the different application times had a significant effect on the number of deposited droplets and coverage rate. The average deposited droplets number and coverage rate for the nighttime application was 43.47% and 37.21% higher than that for the daytime. For the nighttime application, the proportion of the droplet deposited on the upper, middle, and lower layer to the total droplets in the vertical direction of the plant were 41.24%, 35.71%, and 23.05%, respectively the daytime application were 43.09%, 33.99%, and 22.91%, and there were more droplets deposited on the plant middle and lower layer when spraying at night. Additionally, the proportion of droplets deposited on the backside of the leaf to the total droplets on leaf was 21.92% on average for the nighttime and 20.23% for the daytime, this proportion did not exceed 25% within all treatments. In the daytime when the UAV sprayed with the flight speed of 3.0~3.5 m/s and height of 1.5~2.0 m the droplet deposition was better, but for the nighttime application, the best parameters were the speed of 3.0~4.5 m/s and flight height of 2.0 m.

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