EFFECT OF NOZZLE ANGLE OF PLANT PROTECTION UNMANNED AERIAL VEHICLE ON DROPLET DEPOSITION DISTRIBUTION
/
植保无人机喷头角度对雾滴沉积分布的影响

Zhihao BIAN [1,3)], Yubin LAN *[1,2,3)], Meng WANG [1,3)], Changfeng SHAN [1,3)], Haozheng GU [1,3)], Jingang HAN [1,3)]
[1)] School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo / China;
[2)] College of Electronic Engineering, College of Artificial Intelligence, South China Agricultural University, Guangzhou / China;
[3)] National Key Laboratory of Green Pesticide, Guangzhou / China;
Tel: 8615689316561; E-mail: ylan@sdut.edu.cn
DOI: https://doi.org/10.35633/inmateh-72-20

***Keywords:** UAV, flat-fan nozzle, spraying deposition test, droplet distribution*

ABSTRACT
During the field application of pesticides by plant protection UAV, due to the interference of meteorological factors or operating parameters, the deposition effect of droplets is poor. In order to explore the impact of the nozzle angle of plant protection UAV on droplet deposition distribution, this article is based on field experiments and collects data on different flight speeds (1, 3, 5 m/s) and nozzle angles (±60°, ±45°, ±30°, 0°), and performs variance analysis and regression analysis on the test results. The results showed that adjusting the nozzle angle had a significant effect on the amount of droplet deposition and deposition uniformity. Compared with 0°, the nozzle angle of -30° increased the amount of deposition by 76.94% and 61.04% at flight speeds of 1.2 m/s and 3 m/s, respectively. The flight speed had a significant effect on the amount of droplet deposition, and the increase in flight speed decreased the amount of droplet deposition by 55.97%-77.06% and had no significant effect on the uniformity of droplet deposition. This study provides a reference for improving the droplet deposition effect of plant protection UAV field pesticide application operations.

摘要
植保无人机在田间施药过程中，由于气象因素或作业参数的干扰，导致雾滴的沉积效果较差。为了探究植保无人机的喷头角度对雾滴沉积分布的影响，本文基于田间试验，采集不同飞行速度(1、3、5m/s)与喷头角度(±60°、±45°、±30°、0°)下的雾滴沉积分布情况，并对试验结果进行方差分析和回归分析。结果表明，调节喷头角度对雾滴沉积量与沉积均匀性影响显著。与0°相比，喷头角度-30°在飞行速度1.2m/s与3m/s下的沉积量分别增加了 76.94%与 61.04%。飞行速度对雾滴沉积量影响显著，飞行速度增加雾滴沉积量降低了 55.97%-77.06%，并且对雾滴沉积均匀性影响不显著。该研究对提高植保无人机田间施药作业的雾滴沉积效果提供参考。

INTRODUCTION
In recent years, the rapid development of plant protection UAV aerial pesticide application operations has received widespread attention *(Wang et al., 2023)*. As a new method of plant protection operations, plant protection UAV pesticide application has the advantages of high operating efficiency, low operating costs, and small geographical restrictions *(Wang et al., 2020)*. However, due to interference from environmental factors or operating parameters during actual field spraying operations, the droplet deposition distribution is affected, reducing the spray quality and the control effect of pests and diseases *(Sun et al., 2021).*

The factors that affect the droplet deposition distribution of plant protection UAVs mainly include droplet size, drone operating parameters (flight height, flight speed), spraying amount, and rotor downwash wind field (*Xiao et al., 2019*). Relevant studies have shown that the smaller the droplet size, the greater the amount of liquid deposited per unit area, and the better the distribution uniformity and droplet penetration (*Li et al., 2018a*). During the field spraying operation of plant protection UAVs, the flight operation parameters will have a significant impact on the deposition amount of the chemical solution.

---

[1] *Zhihao BIAN, MS candidate, Student;* *[2] *Yubin LAN, PhD, Professor;* [3] *Meng WANG, MS candidate, Student;*
[4] *Changfeng SHAN, PhD candidate, Student;* [5] *Haozheng Gu, MS candidate, Student;* [6] *Jingang HAN, MS candidate, Student;*

The appropriate flight height and flight speed are reduced, and the droplet deposition amount increases (*Chen et al., 2016; Wang et al., 2017*). Different spraying amounts have significant effects on the deposition and efficacy of the liquid. Appropriately increasing the amount of spraying will increase the amount of deposition, but excessive amounts will lead to an increase in the residual amount of the liquid (*Xin et al., 2018*). The rotor movement of plant protection UAV will produce a downwash wind field, which will enhance the amount and penetration of droplet deposition, and the distribution and strength of the wind field will affect the droplet deposition distribution characteristics (*Chen et al., 2017*). During the actual field application process, the downwash wind field of the plant protection UAV will produce canopy vortices on the crops, and the canopy vortices will promote the deposition and distribution of droplets *(Li et al., 2018b*). The nozzle type and structure can also affect the distribution of droplet deposition. The hydrodynamic ultrasonic atomizing nozzle has a great advantage in generating small droplet sizes and performs well in deposition effect (*Song et al., 2023*). Increasing the conical airflow field on the outside of the nozzle can accelerate the initial speed of droplet movement and improve the effect of droplet deposition (*Liu et al., 2023*). In addition to the above factors, adding adjuvant to agricultural spray on the deposited spray quality is also significant (*Milanowski et al., 2023*).

Regarding the study of how changing the nozzle angle affects the droplet deposition distribution, some scholars conducted spray experiments on the amount of liquid deposited at different nozzle angles of a boom sprayer. The results found that the horizontal direction will increase when the nozzle angle is consistent with the forward direction of the spray boom. When the spraying amount increases, the deposition amount and penetration of the liquid in the vertical direction are enhanced, and the optimal nozzle angle is 30° (*Song et al., 2006*). An experiment on the influence of nozzle angle on droplet drift was carried out under wind tunnel conditions. It was found that when the wind speed increased from 0m/s to 5.92m/s, the nozzle angle in the windward direction increased, the amount of deposition increased, and the droplet drift distance decreased by 33.7% (*Chen et al., 2019*). Taking the downwind direction as the positive direction of the nozzle angle and the nozzle angle 0° as a comparison reference, when the wind speed is 3m/s, the nozzle angles of 15° and -15° can reduce drift, the drift distance is reduced, and -15° has a better deposition effect (*Ding et al., 2019*). Through the study of the downwash wind field of plant protection UAVs, it was found that the canopy vortex and droplet deposition generated during pesticide application at different flight speeds are shifted in position. The canopy vortex area is shifted backward. Adjusting the angle of the centrifugal nozzle can increase the amount of droplet. Regarding droplet deposition amount and penetration, the number of droplets deposited on the leaves increased by 21.58%, and the number of droplets deposited on the back of the leaves increased by 66.05% (*Tian et al., 2022*). At present, there are few studies on the influence of adjusting the angle of the nozzle on the droplet deposition and distribution characteristics, and the relevant research is not comprehensive enough. This paper takes the commonly used fan-shaped nozzles of plant protection UAVs as the research object to explore the droplet deposition distribution characteristics under the influence of different flight speeds and nozzle angles and obtains the regression equation of nozzle angle, flight speed, and droplet deposition. It provides a theoretical reference for increasing spray droplet deposition in field pesticide application operations.

MATERIALS AND METHODS

Equipment

This experiment uses a self-designed X4 four-rotor plant protection UAV. Solidworks is used for 3D structural design. The entire body is made of carbon fiber material. The actual object of the drone are shown in Figure 1. The plant protection UAV flight control system uses the DJI A3 series, including the main control module, power module, LED module, GPS module, and wires. The control system adopts the DJI Lightbridge series, including an image transmission module and remote control. The rotor and motor adopt the DJI E5000 series, with a single-axis pulling force of 7kg, a maximum continuous current of 80A, and a 12S power supply. The weight of the whole machine is 8.5kg, the wheelbase is 1431mm, the arms can be folded laterally, and the drug loading capacity is 10L.

The spray system consists of a spray solution tank, a brushless water pump, a nozzle angle adjustment structure, pipelines, a nozzle body, a nozzle head, etc. The nozzle is a fan-shaped nozzle with 4 nozzles, a nozzle spacing of 1m, the nozzle number is SX110015VS, the spray pressure is 0.3MPa, and the working flow rate is 2.44L/min.

Fig. 1 - Plant protection UAV actual object

The structure and angle adjustment diagram of the nozzle angle control unit is shown in figure 2. The structural parts of the control unit are obtained by 3D printing. Two servos are assembled on the structural parts and control the moment of inertia in two directions. The structural unit is fixed directly below the motor. In this test, the nozzle angle adjustment is consistent with the direction of the flight path. The forward direction of the aircraft body is the negative direction of the angle, and the nozzle angles of the four control units are consistent.

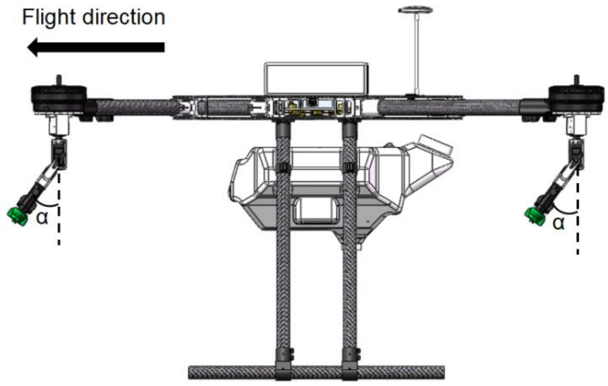

Fig. 2 - Nozzle angle adjustment structural unit and assembly

Figure 3 shows the nozzle angle adjustment controlling system. The controller adopted the STM32F103C8T6 microcontroller. The IO port was programmed to output PWM signals. The PWM signals with different duty cycles controlled the rotation of the servo to control the nozzle angle. In this test, the nozzle angles choosed ±60°, ±45°, ±30°, and 0°. And 0° was used as the reference control group for analysis and comparison. The nozzle angle adjusted by the controlling system is measured by the deLi DL294001 angle measuring instrument, and the program was modified to reduce the angle error.

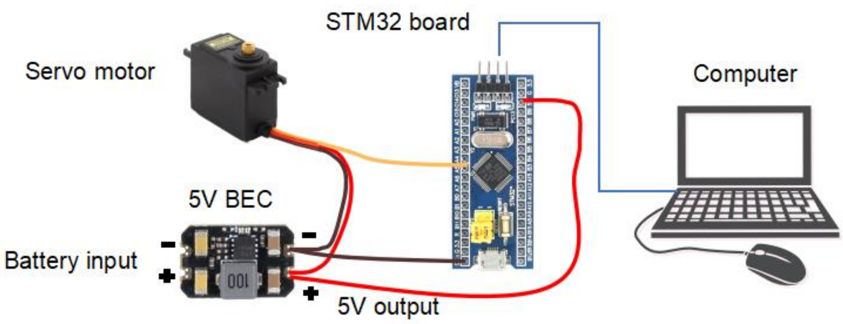

Fig. 3 - Nozzle angle adjustment control system

Meteorological parameter monitoring uses the American Kestrella 5500 wind speed meteorological instrument, which can measure five meteorological parameters: wind speed, wind direction, temperature, humidity, and atmospheric pressure.

Method

The experiments were carried out at the Shandong University of Technology in Zibo City, Shandong Province and between 10:00-16:00. The environmental temperature was about 10°C and the environmental humidity was about 30%. The wind speed was within 2 m/s. The liquid volume of each test used Allura Red solution with a ratio of 5g/L, and a white paper card was used as a droplet collection card. The card size is 60mm × 30mm, and the card sampling height is 0.3m. The card is fixed horizontally to the plastic water pipe with a clip.

In this test, the effective spraying swath adopts the 50% effective deposition determination method. According to ASAE standard S341.3, the sampling point positions on both sides of the aircraft route that can reach 50% of the maximum deposition amount of the droplet collection zone are regarded as the effective spraying swath area. The distance between the starting and ending points is regarded as the effective spraying swath at this working height. According to the test, it could be seen that the effective spraying swath under the flight height of 4m was 2-3m.

Figure 4 shows the layout of the test site. The plant protection UAV route was located on the center line of the test site. The test was arranged with three droplet collection belts (the distance between collection belt A and sampling belt B was 5m, and the distance between collection belt B and collection belt C was 15m). There were 16 sampling points arranged in each collection belt, and the sampling points were numbered X-1~X-16 from left to right (X represented the labels of the three collection belts: A, B, and C).

The droplet sampling zone was divided into a deposition area and two drift areas. The width of the deposition area was set to 5m. The width of the drift area was also set to 5m. The intervals between each sampling point were 1m.

This test aims to explore the droplet deposition distribution rules of plant protection UAV's nozzle angles at different flight speeds. The nozzle angles were ±60°, ±45°, ±30°, and 0°. Under the flight speed of 1 m/s, the droplets would be too large to use. After the test, the flight speeds were 1.2, and 3 m/s, the flight height was 4m as the operating height. After each group of tests was completed, waited until the droplets on the collection card were completely dry, collected them according to the serial numbers and put them into corresponding sealed bags respectively.

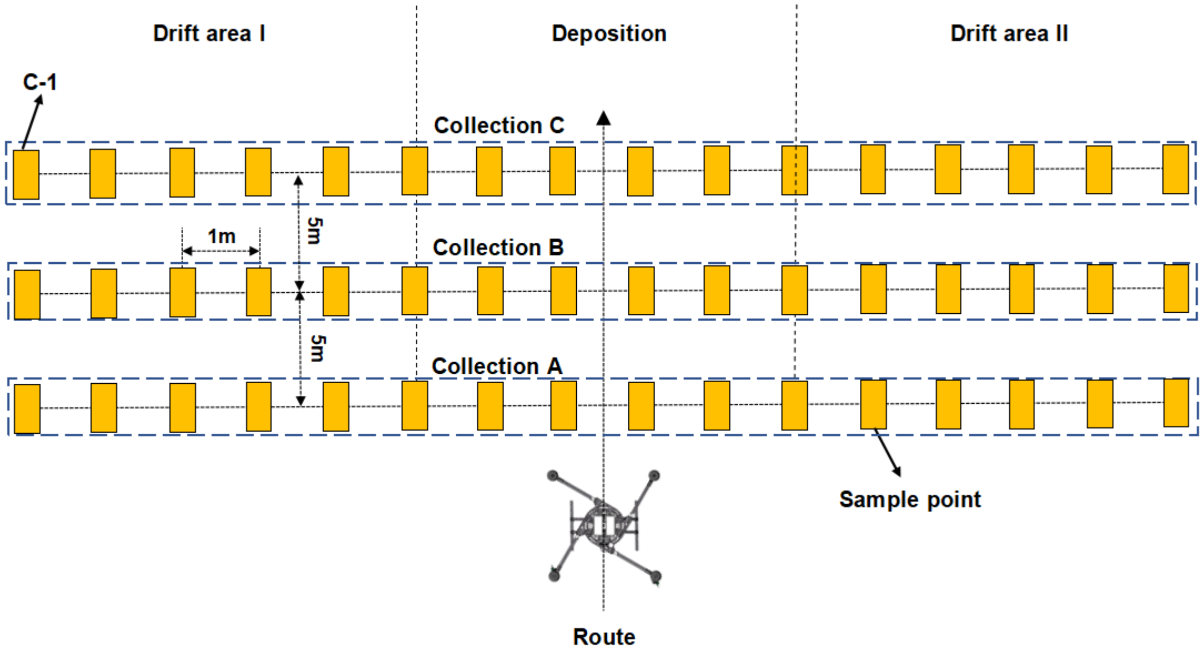

Fig. 4 - Deposition test

Data processing and analysis

Figure 5 shows the results of scanning paper cards and droplet deposition analysis. The paper card was scanned with a scanner. The scanned image was used through the image analysing software DepositScan to obtain parameters such as droplet size, deposition amount, deposition density, and coverage rate of each paper card, and then the data is analyzed.

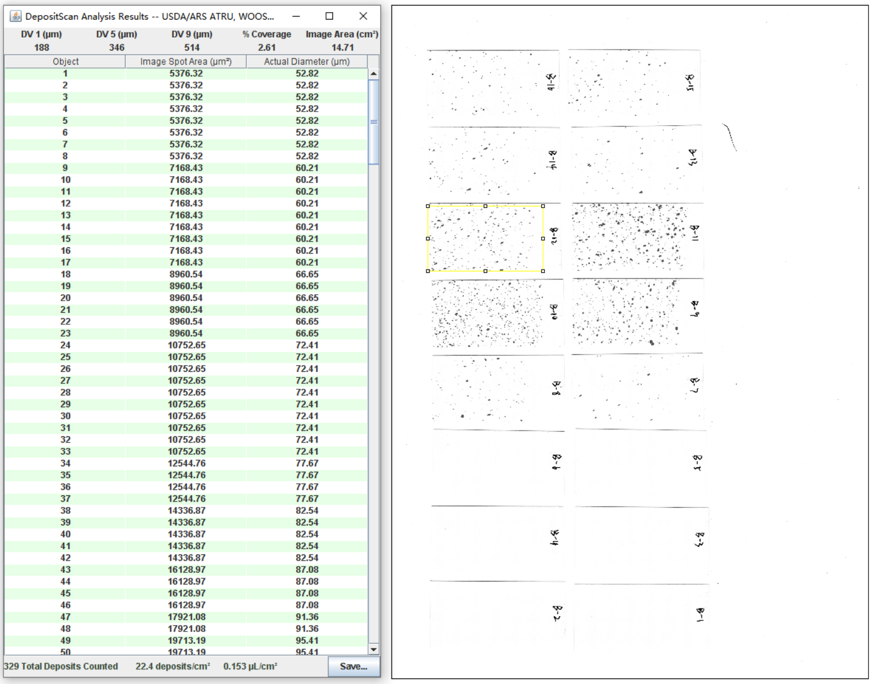

Fig. 5 - Paper card scanning and data analysis

In order to measure the uniformity of droplet deposition distribution between each collection point, this article uses the coefficient of variation (CV) for calculation and analysis. The calculation method of the coefficient of variation (CV) is as follows:

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

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

Where, S is the standard deviation of the samples collected in the same test group; X_i is the deposition rate of each collection point, μL/cm²; $\bar{X}$ is the mean value of deposition rate in each test group, μL/cm²; n is the number of collection points in each test group.

To analyze the droplet deposition distribution of plant protection UAV's nozzle angles at different flight speeds, the experimental data were analyzed using multiple linear stepwise regression methods using SPSS V25.0 software for variance analysis and regression analysis to establish the relationship between droplet deposition distribution and different nozzle angles. The regression model with flight speed was used to test the fitting degree of the regression model and the sample data. The test results were charted using OriginPro 2021 software.

RESULTS

Droplet deposition distribution

Figures 6 and 7 show the distribution of droplet deposition at flight speeds of 1.2 m/s and 3 m/s by adjusting the nozzle angles for the spraying test respectively.

From the distribution of droplet deposition in Figure 6, it can be seen that the trend of droplet deposition under each nozzle angles were basically the same, and the droplet deposition first increased and then decreased. With the increase of the nozzle angle, the droplet deposition increased, then decreased, and then increased. Among them, the amount of droplet deposition at -30° and 60° was larger than that at 0°, and the amount of deposition at -30° was the largest. The droplets were mainly deposited in sampling points from 6# to 10#, but -60°, -45°, and 0° were slightly shifted to the left area, which might be due to the lateral wind that caused the droplets to be shifted to the left area during spraying by the plant protection UAV.

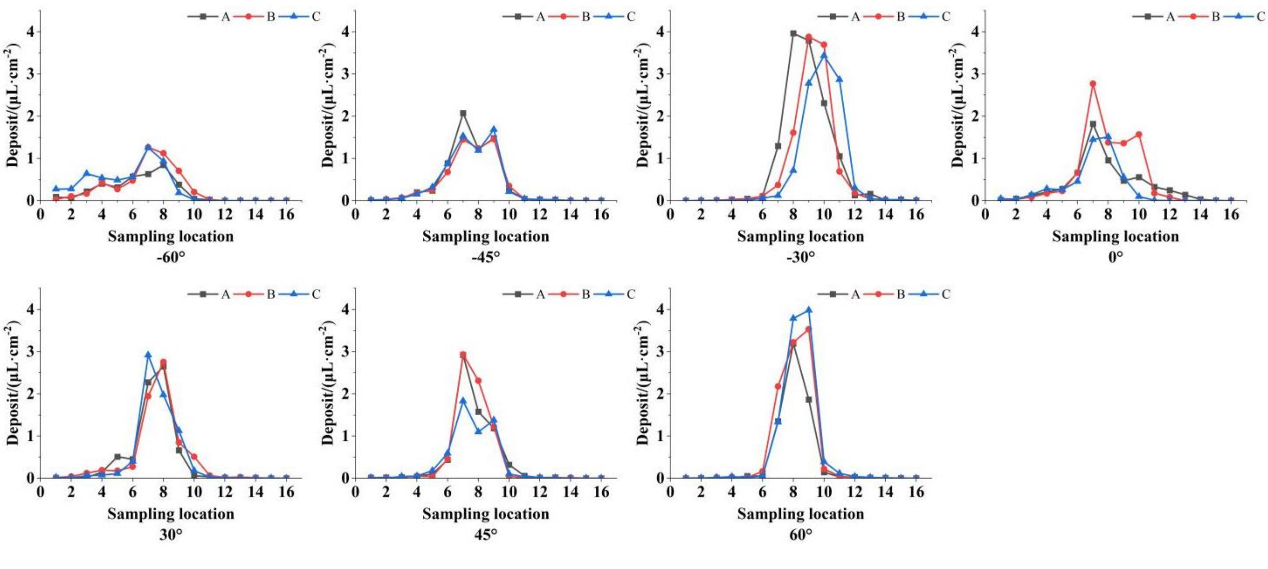

Fig. 6 - Droplet deposition at flight speed of 1.2 m/s

From the distribution of droplet deposition in Figure 7, it can be seen that the trend of droplet deposition under each nozzle angles at a flight speed of 3 m/s were basically the same as that at 1.2 m/s, and the amount of droplet deposition increased first and then decreased. With the increase of the nozzle angle, the amount of droplet deposition first increased and then decreased before increasing. Among them, the amount of droplet deposition at -30°, 45°, and 60° was slightly larger than that at 0°, and the difference was small. The droplets were mainly deposited in sampling points from 6# to 10#, but the deposition at -45° was slightly shifted to the side area, which might be caused by the course shifting to the right area during the application of the plant protection drone.

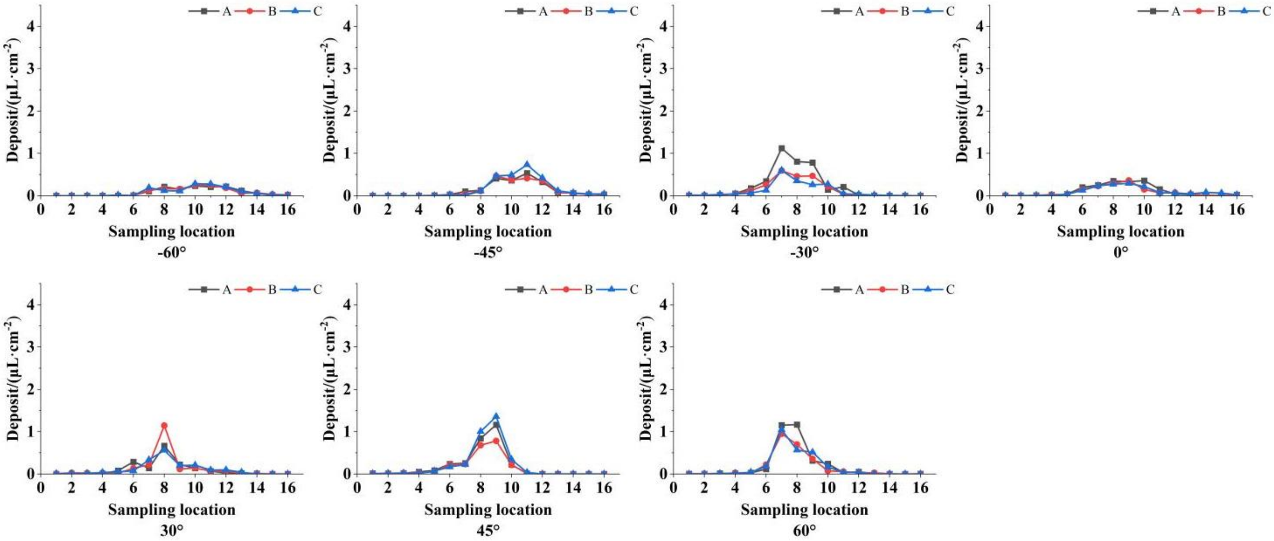

Fig. 7 - Droplet deposition at flight speed of 3 m/s

Figure 8 compares the total droplet deposition amount for each nozzle angle at different flight speeds. The total amount of droplet deposition is obtained by averaging the total deposition for each row of collection belts A, B and C. It can be seen from the results that at a flight speed of 1.2 m/s, there is a large difference in the total amount of droplet deposition for each nozzle angle. Taking the nozzle angle of 0° as a comparison, the total amount of droplet deposition for -30° and 60° increased by 76.94% and 35.28%, respectively. At a flight speed of 3 m/s, the difference in the total amount of droplet deposition for each nozzle angle is smaller, and the total droplet deposition decreases. Taking the nozzle angle 0° as a comparison, the total amount of droplet deposition increased by 61.04%, 74.4%, and 70.32% for -30°, 45° and 60°, respectively.

From the analysis of the results of the distribution of droplet deposition, it can be seen that the speed of flight is increased and the droplet deposition is reduced by about 55.97%-77.06%. Changing the nozzle angle changes the initial position of droplet deposition. When the nozzle angle is -45° and -60°, we found that the droplets had a “rolling-up effect” during flight, causing in some of the droplets being deposited on the fuselage surface. When the plant protection UAV flied forward, there was an attitude angle between the drone and the horizontal plane, and the droplets would produce backward inertia under the influence of the flight speed, and the nozzle angle of 0° tilted backward would lead to droplet drift. The nozzle angle of -30° would offset part of the force, so the amount of droplet deposition increased. The forward flight of the airframe would also cause the downwash wind field to be shifted backward, and when the nozzle angle was 45° or 60°, the droplets were accelerated to be deposited under the coercion of the downwash wind field after being sprayed, thus increasing the amount of droplet deposition.

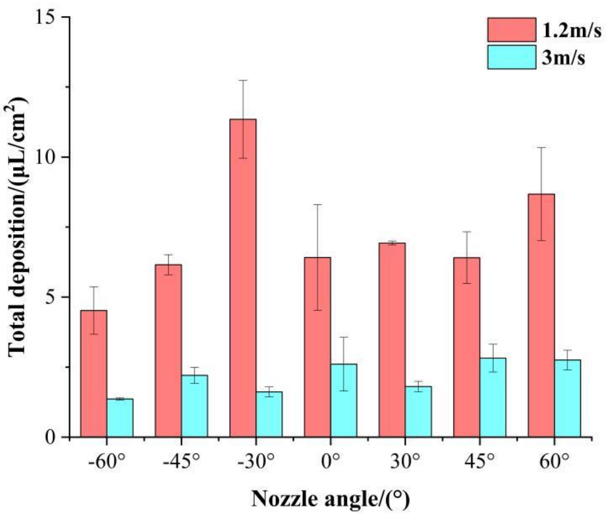

Fig. 8 - Comparison of total deposition at different flight speeds

Droplet deposition uniformity

Tables 1 and 2 show the uniformity of droplet deposition distribution at different flight speeds. It can be seen from the tables, the uniformity of droplet deposition on each collection point under different nozzle angles at the same flight speed is different.

When the flight speed was 1.2 m/s, the uniformity of droplet deposition on collection belt B was different from that on collection belts A and C, and the uniformity of droplet deposition on collection belts A and C was poor. Among them, the variance of droplet deposition reached 71.5% and 79.86% among the collection points on collection belt A at the nozzle angles of -30° and 60°, and the variance of droplet deposition reached 84.14% and 81.11% among the collection points on collection belt C at the nozzle angles of -30° and 0°. The reason for this phenomenon might be due to the uneven distribution of droplet deposition caused by the poor positioning accuracy of the plant protection UAV at the take-off and landing points. The droplet deposition uniformity was best on collection belt B, in which the droplet deposition uniformity was better than 0° at other nozzle angles compared to 0°. The experimental results showed that adjusting the nozzle angle improved the droplet deposition uniformity when the flight speed was low.

Table 1

Droplets deposition uniformity (CV %) at flight speed of 1.2 m/s

Collection belt	CV (%)						
	-60°	-45°	-30°	0°	30°	45°	60°
A	54.96	25.61	71.5	40.77	26.76	25.68	79.86
B	39.88	21.08	46.77	61.26	35.84	44.09	31.31
C	40.25	15.71	84.14	81.11	47.1	72.43	41.88

When the flight speed was 3m/s, the uniformity of droplet deposition on collection belt B and collection belts A and C was different, and the variance of droplet deposition of each collection point on collecting belt C reached 84.28% at the nozzle angle of -30°, and the variance of droplet deposition of each sampling point on collecting belt B reached 74.41% at the nozzle angle of 30°. The reason for this phenomenon might be due to the lateral wind during aerial application by the plant protection UAV, which caused the droplet drift and made the distribution of droplet deposition uneven. The best droplet deposition uniformity was found on collection belt B, where the difference in droplet deposition uniformity at other nozzle angles was smaller compared to nozzle angle 0°. The experimental results showed that when the flight speed increased, adjusting the nozzle angle had less effect on the droplet deposition uniformity.

Table 2

Droplets deposition uniformity (CV %) at flight speed of 3 m/s

Collection belt	CV (%)						
	-60°	-45°	-30°	0°	30°	45°	60°
A	23.91	19.41	61.74	33.66	52.92	12.2	51.3
B	15.42	31.65	38.76	30.63	74.41	65.6	30.92
C	25.32	33.84	84.28	24.26	65.97	40.28	43.4

Table 3 shows the results of variance analysis of the above experimental results. It indicates the effect of flight speed and nozzle angle on the uniformity of droplet deposition distribution at the collection point during the application operation. According to the analysis results, the influence of flight speed on the uniformity of droplet deposition was not significant, and the value of significance level was 0.24. The influence on the amount of droplet deposition was significant, and the value of significance level was less than 0.01. Adjusting the nozzle angle had a significant effect on the uniformity of droplet deposition distribution and deposition amount, and adjusting the nozzle angle had a large effect on the change of droplet deposition amount.

Table 3

Results of deposition rate variance analysis

Source difference	CV (%) Sig.-value	Total deposition (μL/cm²) Sig.-value
Flight speed (m/s)	0.237	0.000
Nozzle angle (°)	0.009	0.000

Note: This article took the significance level α=0.05

CONCLUSIONS

This paper explores the droplet deposition under different flight speeds and nozzle angles of plant protection UAVs through spray deposition test and obtains the distribution of droplet deposition amount and the uniformity of droplet deposition under different flight speeds and nozzle angles. According to the results of variance analysis, the following results can be obtained:

1) Flight speed has a significant effect on the amount of droplet deposition, but flight speed does not have a significant effect on the uniformity of droplet deposition. The increase in flight speed decreases the amount of droplet deposition and has less effect on the uniformity of droplet deposition.

2) The nozzle angle has a significant effect on the amount of droplet deposition and the uniformity of droplet deposition. When the flight speed was 1.2m/s, the deposition amount of nozzle angle -30° and 60° increased by 76.94% and 35.28% respectively with 0° as a comparison. When the flight speed was 3m/s, the deposition amount of nozzle angle -30°, 45°, and 60° increased by 61.04%, 74.4% and 70.32%, respectively, using 0° as a comparison. Adjusting the nozzle angle can improve the uniformity of droplet deposition, when the flight speed is low, adjusting the nozzle angle will improve the uniformity of droplet deposition, when the flight speed is increased, the uniformity of droplet deposition under each nozzle angle is not much different.

3) In the actual field spraying process, to increase the droplet deposition effect on the crop, you can adjust the nozzle angle or reduce the flight speed to increase the amount of deposition and improve the uniformity of droplet deposition. However, the lateral wind will affect the distribution of droplet deposition during the test, and droplet drift will affect the amount of deposition and the uniformity of droplet deposition on the target. Therefore, in the actual application process, it is necessary to consider the impact of wind speed and direction and other environmental parameters on the effect of droplet deposition to improve the effectiveness of the application operation.

ACKNOWLEDGEMENT

The authors thank the experts for editing our paper.This research was funded by the Ningxia Key Research and Development Plan Project (2023BCF01051); National Natural Science Foundation of China (32302410); Shandong Province Natural Science Foundation (ZR2021QC154). We also thank anonymous reviewers for their critical comments and suggestions to improve the manuscript.

REFERENCES

[1] Chen, S., Lan, Y., Li, J., Zhou, Z., Jin, J., and Liu, A. (2016). Effect of spray parameters of small unmanned helicopter on distribution regularity of droplet deposition in hybrid rice canopy. *Transactions of the CSAE* 32, 40-46.

[2] Chen, Y.Y., Hou, C.J., Tang, Y., Zhuang, J.J., Lin, J.T., and Luo, S.M. (2019). An effective spray drift-reducing method for a plant-protection unmanned aerial vehicle. *Int. J. Agric. Biol. Eng*. 12, 14-20. doi:10.25165/j.ijabe.20191205.4289.

[3] Ding, S.M., Xue, X.Y., Qin, W.C., Gu, W., Cai, C., and Cui, L.F. (2019). Influencing factors research and performance experiment on droplets deposition at low wind speed. *Int. J. Precis. Agric. Aviat*. 2. doi:10.33440/j.ijpaa.20190201.0017.

[4] Li, J., Lan, Y., and Peng, J. (2018a). Effect of droplet size spraying by unmanned aerial vehicle on droplet deposition in rice canopy. *Journal of Hunan Agricultural University (Natural Sciences)* 44, 442-446.

[5] Li, J., Lan, Y., and Shi, Y. (2018b). Research progress on airflow characteristics and field pesticide application system of rotary-wing UAV. *Transactions of the CSAE* 34, 104-118.

[6] Liu C., Hu J., Li Y., Zhang W., Li Q. (2023). Experiment on spray flow field characteristics and deposition performance of conical wind field anti-drift spray. *INMATEH - Agricultural Engineering*, Vol.69(1), pp. 559–568.

[7] Milanowski, M.; Subr, A.; Combrzyński, M.; Różańska-Boczula, M.; Parafiniuk, S. (2022). Effect of Adjuvant, Concentration and Water Type on the Droplet Size Characteristics in Agricultural Nozzles. *Appl. Sci*. 12, 5821.

[8] Shengde, C., Yubin, L., Bradley, K., Jiyu, L., Aimin, L., and Yuedong, M. (2017). Effect of wind field below rotor on distribution of aerial spraying droplet deposition by using multi-rotor UAV. Nongye Jixie Xuebao / *Transactions of the Chinese Society of Agricultural Machinery* 48.

[9] Song, J., He, X., and Yang, X. (2006). Influence of nozzle orientation on spray deposits. *Transactions of the CSAE* 22, 96-99. doi:10.3321/j.issn:1002-6819.2006.06.019.

[10] Song, Z.Q., Gong, J.L., Zhang, Y.F. (2023). Deposition performance of hydrodynamic ultrasonic atomizing nozzles with different spray parameters. *INMATEH - Agricultural Engineering*, Vol.71(3), pp. 185–193.

[11] Sun, D.Z., Zhan, X.R., Liu, W.K., Xue, X.Y., Xie, J.X., Li, Z., Song, S., and Wang, W. (2021). Compensation of spray angle to droplet drift under crosswind. *Transactions of the CSAE* 37, 80-89. doi:10.11975/j.issn.1002-6819.2021.21.010.

[12] Tian, Z.W., Xue, X.Y., Duan, F.M., Yao, S., and Ma, W. (2022). Automatic system and method for improving aerial spray droplet penetration. *INMATEH-Agricultural Engineering*, Vol.68(3), pp.265–274.

[13] Wang, C., Song, J., He, X., Wang, Z., Wang, S., and Meng, Y. (2017). Effect of flight parameters on distribution characteristics of pesticide spraying droplets deposition of plant-protection unmanned aerial vehicle. *Transactions of the CSAE* 33, 109-116.

[14] Wang, G., Han, Y., Li, X., Andaloro, J., Chen, P., Hoffmann, W.C., Han, X., Chen, S., and Lan, Y. (2020). Field evaluation of spray drift and environmental impact using an agricultural unmanned aerial vehicle (UAV) sprayer. *Sci. Total Environ*. 737, 139793. doi:10.1016/j.scitotenv.2020.139793.

[15] Wang, J., Ma, C., Chen, P., Yao, W., Yan, Y., Zeng, T., Chen, S., and Lan, Y. (2023). Evaluation of aerial spraying application of multi-rotor unmanned aerial vehicle for Areca catechu protection. *Front. Plant Sci*. 14, 1093912.

[16] Xiao, Q., Xin, F., Lou, Z., Zhou, T., Wang, G., Han, X., Lan, Y., and Fu, W. (2019). Effect of aviation spray adjuvants on defoliant droplet deposition and cotton defoliation efficacy sprayed by unmanned aerial vehicles. *Agronomy* 9, 217.

[17] Xin, F., Zhao, J., Zhou, Y., Wang, G., Han, X., Fu, W., Deng, J., and Lan, Y. (2018). Effects of dosage and spraying volume on cotton defoliants efficacy: a case study based on application of unmanned aerial vehicles. *Agronomy* 8, 85.