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Evaluation of spray penetration on different planes in pesticide applications using an agricultural Unmanned Aerial Vehicle (UAV) sprayer*

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Abstract

This study aimed to evaluate the spray performance of an agricultural unmanned aerial vehicle (UAV) equipped with four fan-type hydraulic nozzles (LU 120-01; IDK 100-01; AD 90-01-C; and ST 01-110) on target horizontal and vertical planes. Analysis of variance (ANOVA) revealed statistically significant differences ($p < 0.05$) among nozzle types and sampling heights in terms of droplet coverage and distribution uniformity. The LU 120-01 nozzle achieved the highest mean horizontal surface coverage (6.40%), while the IDK 100-01 nozzle produced the highest vertical coverage (1.89%) and exhibited more uniform droplet distribution. LU nozzles generally performed better at lower heights, whereas ST 01-110 nozzles achieved superior coverage at higher altitudes. Overall, the results highlight the necessity of evaluating horizontal and vertical deposition patterns in UAV-based pesticide applications to ensure uniform and effective chemical delivery across crop canopies.

Keywords

Droplet distribution uniformity, Pesticide application, Spray coverage, UAV spraying efficiency, Vertical deposition

Introduction

With the world's increasing population, the demand for food is also increasing. In 2050, in order to meet the nutritional needs of the world's population, agricultural production should be increased by approximately 40% (Van Dijk et al. 2021). In recent years, agricultural areas worldwide, including Turkey, have reached their limits (Fukase and Martin 2020). The agricultural area in Turkey decreased from approximately 42 million hectares in 1990 to 38 million hectares in 2023. In addition, the active population working in agriculture is gradually decreasing. The current agricultural production's insufficiency to meet the food demands of the increasing population, the necessity to ensure agricultural sustainability, the shortage of the labor force, increasing labor costs, and food safety have made new approaches mandatory in agricultural production (Morinoudi et al. 2024).

With technological advancements, the integration of technology into agriculture has gained momentum in the last decade. One of the most important examples of this integration is the unmanned aerial vehicle (UAV). UAVs are being used in agricultural production for tasks such as remote sensing, plant health monitoring, identification of weeds, spraying, fertilization, planting, and herd control (Aydoğan and Topakçı 2022). With acknowledgement of

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their potential benefits, UAVs produced for agricultural purposes have become an important technology in agriculture. Agricultural UAVs, as they are known in the literature, are becoming increasingly widespread in Turkish agriculture. UAVs are notable for their low energy requirements when spraying hilly and sloping lands, prevention of soil compaction, reduction in field traffic, elimination of operator contact with the pesticide, and their ability to save water (Alkan and Ertuğrul 2022). Despite the increasing interest in UAVs in agricultural areas worldwide, their adoption in Turkey is still in its infancy. Therefore, a limited number of studies have evaluated the performance and impacts of UAVs.

Some studies showed no difference in yield between UAV applications and conventional spraying. However, the same application can be carried out with UAVs using 30% less pesticide and water mixtures. It was emphasized that UAVs can be an effective method of spraying (Ferguson et al. 2016). Similar effects were found in studies conducted with field sprayers and UAVs on red spider mite (Tetranychus urticae) pest in cotton (Caputti et al. 2025). Although the effects on pests are similar for UAVs and conventional spraying, a study on wheat plants revealed that UAVs were 20 times more efficient than a back sprayer and 1.7 times more efficient than a field sprayer in terms of operational efficiency (Wang et al. 2020).

Determining the optimal application parameters in agricultural pest control with UAVs is important for spraying efficiency. The most preferred application parameters in agricultural control using UAVs were achieved with flat fan nozzles that spray at low volumes (Chen et al. 2020; Sayıncı et al. 2020; Biglia et al. 2022; Özyurt and Çelen 2022; Anken et al. 2024). Another important factor is the spray height. In studies conducted with spray heights, 150 cm and 200 cm were determined as the ideal spray heights for paddy plants, while the ideal results were obtained at a height of 110 cm for cotton, respectively, (Mat et al. 2018; Chen et al. 2021). Studies on pineapple determined that the best spraying height was 250 cm, while the ideal height for corn was 200 cm (Hu et al. 2022; Vera et al. 2023).

When the literature is examined, there are no studies on the spray penetration to the trunk, branches, and similar vertical parts of plants when using agricultural UAVs for spraying. For this reason, in this study, spraying was carried out with different fan beam nozzles at constant speed, height, and application volume on water-sensitive papers placed horizontally and vertically on platforms. In this way, this study aimed to reveal the performance of fan beam nozzles, which are preferred in UAVs, in horizontal and vertical planes. In addition, the spray penetration of these nozzles on sampling surfaces was also analyzed at different heights.

Materials and methods

Climate conditions

The average air temperature was 15 °C, the average wind speed was 4.9 km^{-1}, and the average relative humidity was 75%.

Hydraulic nozzle types and application parameters

Four different hydraulic nozzle types were used in the study. Specifications of the nozzles are given in Table 1. The trials were conducted at 40 L ha^{-1} application volume and 2.4 bar constant pressure. The application volume was calculated using Eq. 1.

$$V = \frac{1}{3.6} \times \frac{600Q}{BN} \quad \text{[Eq. 1]}$$

V: Forward speed, ms^{-1}
Q: Nozzle discharge, l min^{-1}
B: Nozzle spacing, m
N: Application volume, l ha^{-1}

Agricultural UAV sprayer

A UAV with four rotors was used in the experiments. The image of the UAV is shown in Fig. 1. Hydraulic nozzles were placed on the boom arms under the UAV. There were two nozzles at 100 cm intervals. The specifications of the UAV used in the trials are shown in Table 2.

Table 1. Hydraulic nozzle types and operational parameters.

Nozzle types	Nozzle images	Nozzle material	Pressure (bar)	Discharge (l min^{-1})	Application volume (l ha^{-1})	Forward speed (km h^{-1})
IDK 120-01		POM	2.4	0.706	40	10
LU 120-01		Stainless steel	2.4	0.700	40	10
TCSI 110-01		POM	2.4	0.696	40	10
AD 90-01-C		Ceramic	2.4	0.660	40	10

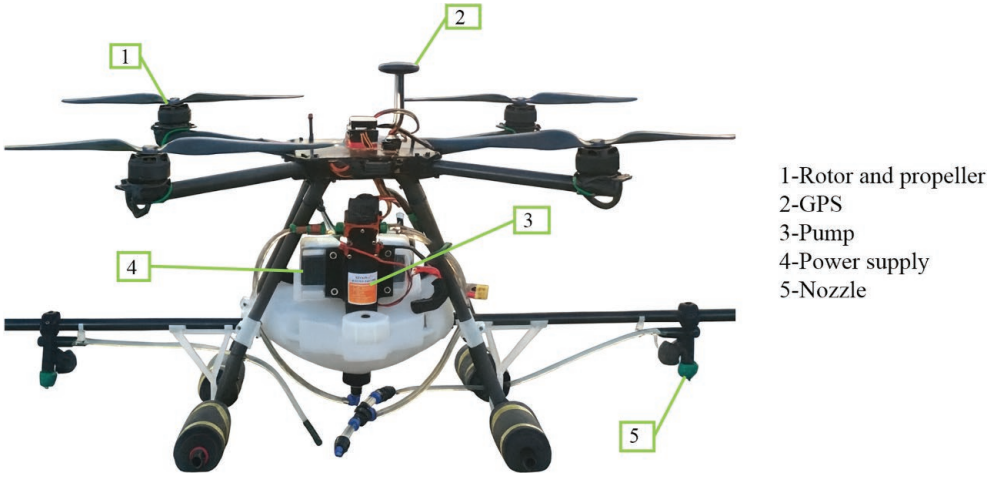

Figure 1. Agricultural UAV and the spraying system.

Table 2. Agricultural UAV specifications.

Parameter	Description
Dimension	1150×150×450 mm
Configuration	X-Quad
Propeller	1861
Method of operation	Remote Control
Spraying system	Hydraulic orifice nozzle
Number of nozzles	2
Positioning mode	GPS or Manual
Hovering time	10–15 min.

Sampling method

For spraying at constant height, 200-cm-long square wooden poles were used to evaluate the distribution of droplets in the vertical and horizontal planes. In each application, the UAV was positioned 100 cm above the top of the pole (approximately 300 cm above the ground) (Fig. 2). Trials were conducted in three replicates.

Water sensitive papers (WSP; Syngenta Crop Protection) measuring 2.6×7.6 cm were placed on poles in both horizontal and vertical planes (Fig. 3). The sampling method was applied as follows:

Horizontal plane sampling: WSP cards were placed parallel to the ground at 50 cm intervals from the top of the pole downwards, and were used to measure the surface contact efficiency of free-falling droplets in the vertical direction.

Vertical plane sampling: At the same intervals, WSP cards were placed vertically on the square profile of the pole on three different surfaces (front, rear, side) according to the flight direction of the UAV. On these surfaces, both the orientation of the droplets and their performance in reaching the vertical surfaces were analyzed. For each sampling height, the averages were calculated for the cards on the front, back, and side surfaces. In this way, the average spray penetration performance in the vertical plane was statistically evaluated.

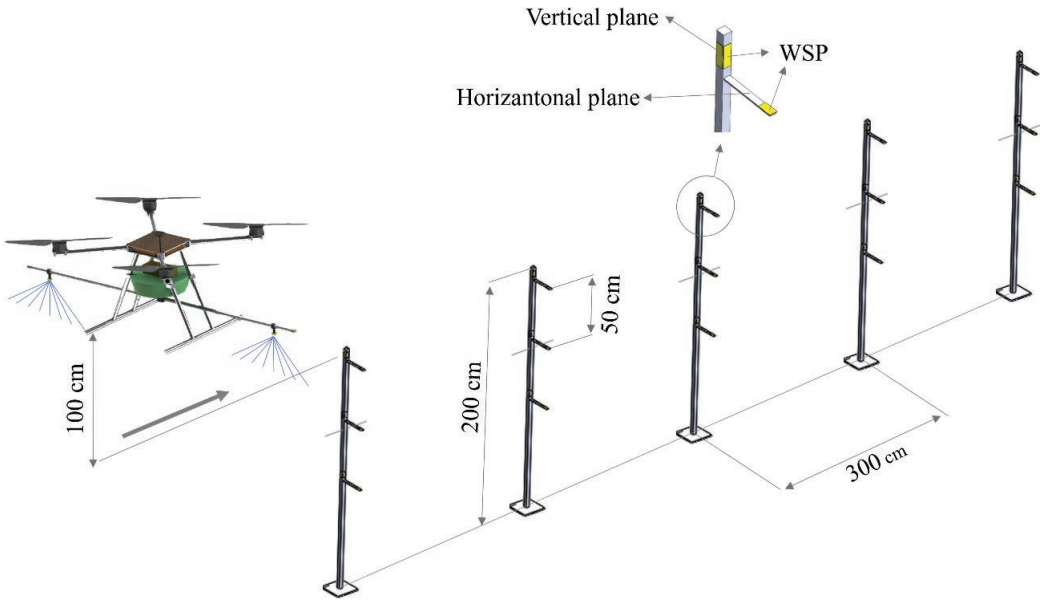

Figure 2. Trial plan.

Figure 3. Sampling poles and the WSP fixing positions.

Scanning of samples

After spraying, the WSPs were left for 15–20 minutes to dry. The dried samples were placed in envelopes and labelled. The stains on the surface of the WSPs were scanned (HP Officejet Pro X476dw MFP) to be analyzed by an image processing method. The scans with 600 dpi resolution and 8-bit greyscale depth (2^8 = 256) (0–255 range), were saved to the computer as image files (*.tif) (Shan et al. 2021).

Image processing

Before spot analysis, the average greyness level (g) of the computer-scanned WSPs was determined using a module in the image processing software. Then, the threshold (t) value to be applied in the range of 0–255 to card images was calculated with Eq. 2. After applying the threshold, secondary images were obtained according to the calculated value. Using the secondary images, the software ImageJ (Wayne Rasband, National Institutes of Health, USA, Java 1.6.0_02) calculated the surface coverage rate (%) (Martinez et al. 2020; Sayıncı 2020).

$$t = 0.38g + 78.75 \qquad \text{[Eq. 2]}$$

t: threshold level
g: greyness level

Statistical analysis

SPSS (version 20) was used to compare the variables. The data obtained were compared by analysis of variance (ANOVA). Differences between the means of the factors, found to be significant, were analyzed using multiple comparison tests (Duncan, Tukey, or Tamhane's T2) at a 95% confidence level (Çelik and Bayhan 2020).

Results and discussion

The average surface coverage rates across the vertical plane were much lower than those across the horizontal plane. This is an indication that spray penetration to the vertical plane is physically more difficult and limited (Sayıncı et al. 2019; Çömlek 2024), (Fig. 4).

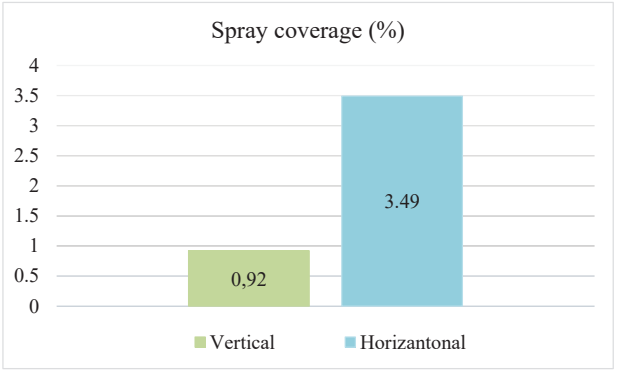

Figure 4. Average spray coverage ratios at horizontal and vertical planes.

Spray penetration on the horizontal plane

The spray penetration efficiency of the hydraulic nozzles on the horizontal plane was evaluated in terms of surface coverage ratio (%) at different sampling heights (100, 150, and 200 cm) on the sampling poles. The nozzles had significantly ($p < 0.05$) different spray penetration efficiencies at different spray positions (Table 3).

The highest surface coverage rate was obtained with the LU nozzle at a height of 100 cm. However, this effect decreased significantly at 150 and 200 cm. This indicates that the LU nozzle provides effective horizontal penetration at low sampling heights, but as the sampling heights increase, it has an unstable distribution profile (Chen et al. 2020). In contrast, the ST nozzle had the highest surface

coverage rate of 4.57% at 200 cm height. This shows that ST type nozzles provide more effective spray penetration than other nozzles, when the sampling heights increase. However, it has been noted that the spray penetration of the ST nozzle may vary with different types of UAVs or propeller speeds (Chang et al. 2023).

The highest value was obtained at 150 cm with the AD nozzle, but this value remained around 3% at 100 and 200 cm. This indicates that AD type nozzles provide the most effective penetration at medium heights, but show instability at low and high sampling heights. The IDK nozzle provided a lower but more homogeneous surface coverage than the other nozzles at all heights. This result shows that IDK nozzles provide even penetration when the sampling height is changed (Changling et al. 2021).

Table 3. Spray penetration on the horizontal plane.

Nozzle type*	WSP sampling height (cm)		
	100	150	200
	Mean ± SS	Mean ± SS	Mean ± SS
AD 90-01 C	3.11Bb** ± 1.88	5.10Aa ± 3.13	3.65ABb ± 4.50
IDK 100-01	3.51Ba ± 2.58	3.06Ba ± 2.46	2.21Ba ± 1.09
LU 120-01 S	6.40Aa ± 2.88	3.00Bb ± 3.16	2.47Bb ± 1.55
ST 110-01	2.80Bb ± 2.56	2.79Bb ± 1.76	4.57Aa ± 2.03
Std. Error of Mean: 0.13755			

*AD: anti-drift flat spray nozzles; IDK: air injector flat spray nozzles; LU: multi-range flat spray nozzles; ST: standard flat spray nozzles;
**Means with different lowercase letters in the same row and means with different uppercase letters in the same column are different at $p < 0.05$ significance level.

Spray penetration on the vertical plane

The spray penetration performance of the same nozzle and height combinations in the vertical plane is given in Table 4. The highest surface coverage rate was obtained with the IDK nozzle at a height of 150 cm. The ST type nozzle had the highest surface coverage rate of 1.21% at 200 cm. This indicates that ST nozzles have better vertical spray penetration at 100 cm. The LU nozzle had the highest spray penetration at 100 cm. Spray penetration decreased significantly to 0.66% and 0.75% at 150 cm and 200 cm, respectively. This indicates that the spray penetration of the LU type nozzle in the vertical plane decreased as the height increased. The AD nozzle generally provided homogeneous spray penetration at all heights. It has been emphasized that it is important to adjust the application volume sufficiently so that more droplets can penetrate the plant canopy. (Changling et al. 2022).

Conclusion

The data obtained in the horizontal plane show that the droplets reaching the target are directly dependent on the nozzle type and sampling height. The fact that LU and ST type nozzles perform differently at low and high elevations shows that nozzles should be carefully considered according to the application scenario. LU type nozzles can be preferred at low heights (close to vegetation), while ST type nozzles provide an advantage at higher heights.

Table 4. Spray penetration on the vertical plane.

Nozzle type*	WSP sampling height (cm)		
	100	150	200
	Mean ± SS	Mean ± SS	Mean ± SS
AD 90-01 C	0.70Aa** ± 1.88	1.28Ab ± 3.13	0.93BCa ± 4.50
IDK 100-01	0.81Aa ± 2.58	1.89Bb ± 2.46	0.46Aa ± 1.09
LU 120-01 S	1.55Bb ± 2.88	0.66Cb ± 3.16	0.75ABb ± 1.55
ST 110-01	0.69Aa ± 2.56	0.49Ca ± 1.76	1.21Cb ± 2.03
Std. Error of Mean: 0.03537			

* AD: anti-drift flat spray nozzles; IDK: air injector flat spray nozzles; LU: multi-range flat spray nozzles; ST: standard fan beam spray nozzles;
** Means with different lowercase letters in the same row and means with different uppercase letters in the same column are different at ($p < 0.05$) significance level.

Spray penetration in the vertical plane is much more limited than in the horizontal plane. In the vertical plane, IDK type nozzles provided significant advantages. The decrease in drag due to the large droplet diameters in IDK type nozzles may contribute to this performance. In addition, the downward airflow produced by the UAV propeller may have disintegrated large droplets. This suggests that nozzles producing large droplets tend to increase the surface coverage rate because the droplets disintegrate under the influence of the air flow.

The findings indicate that under real field conditions, it is challenging for the spray to reach vertical areas such as the stem and root collar of the plant. When spraying with a UAV, the focus should be on the horizontal coverage rate and whether droplets reach different parts of the plant. Therefore, analyzing both planes is mandatory for holistic success in plant protection applications.

Author contributions

RÇ contributed to data collection and analysis; BS contributed to research design and model selection; TY contributed to writing and editing the article..

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Conflict of interest

The authors declare that they have no conflict of interest.

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