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# Combined Performance Evaluation of Multiple Types of UAV Sprayers in Controlling Agricultural Pests

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## ABSTRACT

The capabilities of UAV sprayers have led to the growing adoption of this technology by farmers. This study aimed to evaluate the combined performance of several common UAV sprayer types in the country and to provide a scientific method for selecting the most suitable sprayer for different crops and pests. Three UAV sprayer types were evaluated in three different regions and prioritized based on parameters affecting spraying quality. These UAV sprayers were used to control canola aphid, Tuta pest of tomato, and spider mite of beans. The technical parameters for each UAV sprayer were measured. The UAV sprayer was then ranked, and after normalizing the data, they were prioritized using a combined performance index (CPI). Based on the results, the mean flow rate was 2.1 L/min, the mean flight speed was 18.5 km/h, and the mean effective field capacity was 5.2 ha/h. The lowest spray volume applied (8.4 L/ha), the highest field efficiency (68.3%), and the lowest spray drift (9.9%) belonged to UAV sprayer 2; the highest spraying efficacy (92.1%) belonged to UAV sprayer 1; and the highest effective field capacity (7.3 ha/h), the best uniformity coefficient (0.89), and the lowest energy consumption (0.59 kWh/ha) belonged to UAV sprayer 3. In terms of the combined performance index, UAV sprayer 1 exhibited superior performance under the evaluated crop–pest and environmental conditions, followed by UAV sprayer 2 and UAV sprayer 3, respectively.

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## INTRODUCTION

Plant pests and diseases are among the main factors reducing the yield of agricultural crops. Chemical control of pests and diseases is the conventional method for controlling them. According to the Food and Agriculture Organization of the United Nations (F.A.O), global pesticide consumption in 2020 was approximately 2.7 million tons (Mai et al., 2025). Excess chemical pesticides contaminate water and soil, leading to unhealthy crops and environmental pollution. Therefore, the use of precision sprayers is essential to improve crop and environmental health as well as the safety of users and consumers. Hence, in recent years, the use of unmanned aerial vehicles for spraying has increased.

Based on the results of previous studies, spraying with UAV srayers has increased spraying precision and efficiency while reducing labour costs and pesticide consumption (Coombes et al., 2022; Zhan et al., 2022). Furthermore, operators are not harmed due to their distance from chemical pesticides (Häfner et al., 2021; Mogili & Deepak, 2018; Myers et al., 2016). UAV sprayers equipped with advanced control systems have greater stability, field efficiency, and spraying precision compared to other sprayers (Okuda et al., 2023; Qu et al., 2022). Additionally, UAV sprayers can spray muddy and wet fields, and tall crops, a capability that other sprayers lack. Furthermore, using UAV sprayers reduces water consumption and pesticide losses (Giles & Billing, 2015), and the spraying cost for small fields is also lower (Yuru et al., 2023).

Therefore, in recent years, numerous studies have been conducted on the evaluation of UAV sprayers for spraying various agricultural crops. Qin *et al*. showed that flight height and speed affect droplet penetration and spray uniformity on rice crops (Qin et al., 2016). They obtained the maximum spray volume in the lower layers of the rice canopy at a flight speed of 5 m/s and a flight height of 1.5 m. Yallappa et al. used a UAV sprayer to control ground nut and rice pests (Yallappa et al., 2017). The effective field capacity at a height of 1 m above the crop canopy and a forward speed of 3.6 km/h was 1.15 and 1.08 ha/h, respectively. Spray uniformity increased with increasing spray pressure. The mean volume median diameter and mean number median diameter of droplets under laboratory conditions were 345 μm and 270 μm, respectively. Yanliang *et al*. evaluated a UAV sprayer at four flight heights (1.5, 2, 2.5, and 3 m) and different wind speeds (1, 1.8, 2.6, 3.8, 4.6, and 5.8 m/s) with different spray volumes (25%, 50%, 75%, and 100%) (Yallappa et al., 2017). Spraying heights of 1.5 m and 2 m with 50% spray volume were recommended for uniform spraying. At a flight height of 2.5 m and spray volumes of 50%, 75%, and 100% under wind speeds below 2 m/s, spray uniformity was good. Spraying at wind speeds between 2 and 3 m/s was uniform only with spray volumes of 75% and 100%. At wind speeds of 3.8 (up to 4.5) m/s, only 100% spray volume yielded good results. Spraying at heights of 3 m or more was not suitable. Furthermore, the researchers emphasized reducing the spraying height to less than 2 m when wind speeds exceed 5 m/s. Wang *et al*. compared four common UAV sprayer models in China in terms of spray coverage, penetrability, droplet density, and field efficiency. Under identical flight conditions and with the same applied spray volume, the volume median diameter had a negative correlation with droplet density (Wang et al., 2017). Operational downtime of the UAV sprayer typically occurred due to clogging of nozzles, pumps, and delivery lines, amounting to 3.7% to 4.4% of the total operational time. Liao *et al*. compared three UAV sprayers (quadcopter, hexacopter, and octocopter) in a cotton field (Liao et al., 2019). Applied spray volume, flight height and speed, spray coverage, spray uniformity, leaf drop and boll opening rate, field efficiency, and costs were measured and evaluated. The results indicated that the optimal applied spray volume was 48 L/ha in flight height of 1.5 m, and flight speeds of 3.1, 2.5, and 3.8 m/s, for the quadcopter, hexacopter, and octocopter, respectively. Wang *et al*. compared droplet deposition, spraying efficacy, and field efficiency of a hexacopter sprayer with a boom and two conventional knapsack sprayers for spraying wheat crops (Wang et al., 2019). Their results showed that the effective field capacity of the UAV sprayer was 4.1 ha/h, which was 1.7 to 20 times (1.7, 2.6, and 20 times) higher than that of the boom sprayer and the two knapsack sprayers. The results indicated that the efficacy of the UAV sprayer against wheat aphids was comparable to that of other spraying equipment, while its field efficiency was significantly higher. Droplet deposition with the UAV sprayer was not significantly different from the other three sprayers, but ground losses were the lowest. Spraying efficacy of the UAV sprayer against wheat aphids seven days after spraying was 70.9%, which was comparable to the other sprayers. Kharim *et al*. evaluated the effect of flight speed and nozzle flow rate of a UAV sprayer on droplet deposition (Kharim et al., 2019). Field experiments were conducted at flight speeds of 2, 4, and 6 m/s, flow rates of 0.75, 1.5, 2.25, and 3.0 L/min, and at a constant height of 2 m above the rice canopy. The results showed that droplet uniformity and deposition were highest at flight speeds below 2 m/s and a flow rate of 3 L/min compared to other treatments. This method was recommended for rice spraying. Zhou *et al*. evaluated spraying efficiency of a UAV sprayer in rice fields under different crop growth stages (Zhou et al., 2020). They assessed a UAV sprayer at flight speeds of 3, 4, and 5 m/s with two types of nozzles. The UAV sprayer performed best at a flight height of 2 m, spraying swath width of 4 m, and flight speed of 4 m/s. Also, the spraying efficiency of the UAV sprayer was higher than that of conventional sprayers at all growth stages. Norouzieh *et al*. compared the spray quality of a UAV sprayer with two conventional sprayers (a boom sprayer and a tractor-mounted lance sprayer) for cotton spraying (Nowrouzieh et al., 2022). The results showed that the UAV sprayer had the lowest surface coverage percentage at the top, middle, and bottom of the plant. The best spray quality belonged to the boom sprayer, followed by the UAV sprayer. In terms of water savings, the UAV sprayer was the best option. Sheikhigarjan *et al*. compared the technical and economic aspects of using a UAV sprayer with a lance sprayer for controlling wheat pests (Sheikhigarjan et al., 2024). The results showed no significant difference in spraying efficacy between the two methods. However, the UAV sprayer had higher field efficiency, lower spray volume consumption and droplet drift. Pranaswi *et al*. (2024) compared a UAV sprayer with a knapsack sprayer for controlling weeds in wheat. Under low wind conditions and flight heights up to 3 m, drift was negligible. Based on the results, crop yield increased with UAV spraying. Eskandari Nasab and Maghsoudi evaluated several UAV sprayer models in Kerman province and prioritized them using the Analytic Hierarchy Process (AHP) (Nasab & Maghsoudi, 2024). Spray coverage, spray quality coefficient, consumed value, spray uniformity, price, and droplet diameter were evaluated. The highest weight was assigned to coverage percentage (0.34) and the lowest to spray uniformity (0.10). The T16 UAV achieved the highest rank among the tested UAV sprayers.

In most of the studies reviewed above, UAV sprayers were employed for the control of a specific pest in a single crop. In addition, UAV sprayers were generally compared with other types of spraying equipment, whereas direct comparisons of the technical performance and spraying efficiency among different UAV sprayer models have rarely been reported. However, considering the significant influence of UAV type, rotor number and power, nozzle type and configuration, flight height, and flight speed on spraying performance, it is essential to evaluate and compare multiple UAV platforms under diverse cropping systems and environmental conditions.

Furthermore, the selection of the most appropriate UAV sprayer should be based on a comprehensive assessment of all relevant technical parameters and their combined performance, rather than on a limited number of individual criteria. Therefore, the objective of this study is to evaluate the integrated performance of several UAV sprayer types and to develop a scientific framework for selecting the most suitable UAV sprayer according to crop characteristics and pest management requirements. Unlike previous studies that primarily focused on evaluating individual UAV sprayers or comparing UAVs with conventional spraying systems, this study provides a comprehensive multi-criteria assessment of different UAV sprayer types by integrating key technical and operational parameters into a unified evaluation framework. This approach offers a more robust basis for UAV selection under varying crop and pest management conditions.

## MATERIALS AND METHODS

In this study, three types of UAV sprayers were evaluated and their results were compared with each other. The UAV sprayers were prioritized based on the parameters influencing spraying quality. Prior to spraying, the output flow rate of UAV sprayers was calibrated (Safari et al., 2025; Sheikhigarjan et al., 2024). During the tests, air temperature, relative humidity, and wind speed were measured using a digital device. The specifications of the UAV sprayers are presented in Table 1.

**Table 1.** Specifications of the evaluated UAV sprayers for pest control

| **Row** | **Name** | **Sprayer type** | **Manufacturer/Model** | **Tank volume** (L) | **Nozzle type** | **Number of nozzles** | **Theoretical field capacity** (ha h$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 1 | UAV 1 | Quadcopter | TopXGun | 10 | Flat Fan (Teejet01) | 4 | 9.7 |
| 2 | UAV 2 | Hexacopter | J80 | 6 | Centrifugal | 2 | 4.9 |
| 3 | UAV 3 | Quadcopter | MG-1P | 10 | Flat Fan (XR11001VS) | 4 | 6.7 |

For each crop–pest system, the experiment was conducted using three independent and spatially separated plots as replicates. All treatments were applied separately in each plot, and measurements were collected independently from each replicate. Details of the tests are as follows:

- **UAV 1:** Field tests were conducted using a quadcopter to control canola aphid (*Brevicoryne brassicae*) when at least 20% of the plants were infested, in Mohammad Shahr, Alborz Province. The length and width of the experimental plots were 100 m and 10 m, respectively. The pesticide imidacloprid was applied at a rate of 1 L/ha and mixed with water at a ratio of 1:10. During spraying, the average air temperature was 21°C, relative humidity was 10%, and wind speed was 3 m/s.
- **UAV 2:** Field tests were conducted using a hexacopter to control the tomato Tuta pest when at least 20% of the plants were infested, in the Safadasht of Alborz Province. The length and width of the experimental plots were 40 m and 10 m, respectively. The pesticide used was indoxacarb, which was applied at a rate of 250 mL/ha according to the manufacturer's recommendation and mixed with an appropriate ratio of water. During spraying, the average air temperature was 29°C, relative humidity was 55%, and wind speed was 0.3 m/s.
- **UAV 3:** Field tests were conducted using a quadcopter to control the spider mite (*Tetranychus urticae complex*) on bean in Shazand, Markazi Province. The length and width of the experimental plots were 34 m and 5 m, respectively. The miticide hexythiazox (Nissorun) was applied at a dose of 0.5 per

thousand. The average air temperature was 28.3°C, relative humidity was 24%, and wind speed was 1.8 m/s. An image of the sprayer drones is shown in Figure 1.


**Figure 1 .** Evaluated UAV sprayers (a: UAV 1, b: UAV 2, c: UAV 3).

The measured parameters for each sprayer drone are as follows:

**Effective swath width**

Effective swath width is the maximum working width within which the spray distribution falls within an acceptable uniform range. To measure the effective swath width, water-sensitive papers (WSPs) were placed at intervals of 1 m perpendicular to the UAV's direction of travel. The number of papers was twice the nominal swath width. The flight height and speed for each sprayer were set according to Table 2. The centre-to-centre distance between two papers on which the number of droplets was at least half the maximum number of droplets on the wettest WSP was considered the effective swath width (Bonds et al., 2023).

**Applied spray volume**

The spray volume applied per hectare was calculated using Equation (1) (Chen et al., 2020):

$$Q = \frac{600q}{V.W} \tag{1}$$

where:

V: Forward speed (km/h)

q: Flow rate of all nozzles (L/min)

Q: Applied spray volume (L/ha)

W: Effective swath width (m)

**Field efficiency**

Field efficiency is obtained from the ratio of effective field capacity to theoretical field capacity according to Equation (2). Effective field capacity was determined by measuring the time required to spray one hectare of land. Theoretical field capacity was calculated using Equation (3) (Safari et al., 2025):

$$E = \frac{C_0}{C_t} \tag{2}$$

where:

E: field efficiency (%), and Co: effective field capacity (ha $h^{-1}$).

$$C_t = \frac{W \times S}{10} \tag{3}$$

where:

W: working width (m), S: forward speed (km $h^{-1}$), and Ct: theoretical field capacity (ha $h^{-1}$).

**Energy Consumption**

The energy of the UAV sprayer is supplied by batteries. To determine energy consumption, the total power consumption of the batteries—including the UAV batteries and the remote control (radio control) batteries—was obtained. This value was then multiplied by the effective field capacity of the UAV sprayer to obtain the electrical energy consumption in kWh/ha (Safari et al., 2025).

**Spray Droplet Drift**

To measure drift, water-sensitive papers (WSPs) were placed outside the effective spraying swath in the field and on top of the plants at intervals of 1 m. After spraying, they were collected and the wetted WSPs were counted. The drift percentage was obtained by dividing the number of wetted papers by the total number of WSPs (Kharim et al., 2019).

**Spray Uniformity**

The spray quality coefficient is a measure of spray uniformity, obtained by dividing the volume median diameter (VMD) by the number median diameter (NMD) (Zhu et al., 2011). To measure this parameter, WSPs were placed perpendicular to the UAV's direction of travel at 1 m intervals (twice the nominal swath width in number) along the spray path. After spraying, the papers were collected and scanned. The papers were processed using Image J software as follows: the digital images of the WSPs were first binarized and scaled. Then, by setting an appropriate threshold for each image, droplets were separated from the background image, counted, and their diameters were measured. The number median diameter and volume median diameter were obtained using Equation (4) (Sheikhigarjan et al., 2024):

$$D_{pq}^{p-q} = \left(\sum_{i=1}^{n} NiD_i^p \,\Big|\, \sum_{i=1}^{n} Ni\, D_i^q\right)^{\frac{1}{(p-q)}} \tag{4}$$

where:

p and q: integers, p > q. (For number median diameter: p = 1, q = 0; for volume median diameter: p = 3, q = 0)

Di: droplet diameter for size group i (µm)

Ni: number of droplets in size group i

i: number of group size

n: number of size groups

The closer the spray quality coefficient is to the number of one, the higher the spraying quality (Safari et al., 2025).

Furthermore, the droplet size distribution range (S) was obtained from Equation (5):

$$S = \frac{VMD - NMD}{NMD} \tag{5}$$

**Spraying Efficacy**

Spraying efficacy indicates how successful the spraying has been in controlling pests. To measure spraying efficacy for each of the three spraying methods, a control treatment was considered. The efficacy measurement for each pest is described below:

**Spraying efficacy for controlling canola aphids**

To determine spraying efficacy using the UAV sprayer, sampling of the aphid's population was conducted at 7 and 14 days after spraying. To count the aphids on each marked plant, 30 stems were selected from each plot, and the live aphids on the terminal 10 cm of each stem were counted. For aphid counting, a scale from zero to four was used as follows: 0: no infestation, 1: 1–5 aphids, 2: 6–20 aphids, 3: 21–100 aphids, and 4: more than 100 aphids. The efficacy of the treatments was calculated using the Henderson–Tilton formula based on the number of live aphids according to Equation (6) (Henderson & TILTON, 1955):

$$E = \left(1 - \frac{(T_a * C_b)}{(T_b * C_a)}\right) * 100 \tag{6}$$

where:

$T_a$: number of live aphids in the treatment plot after spraying

$T_b$: number of live aphids in the treatment plot before spraying

$C_a$: number of live aphids in the control plot after spraying

$C_b$: number of live aphids in the control plot before spraying

**Spraying efficacy for controlling tomato pest**

To measure spraying efficacy using the UAVs for controlling tomato pests, the number of live larvae was counted at 7 and 14 days after spraying. For sampling, the number of live larvae and the tunnels created on the leaves were counted. Subsequently, spraying efficacy was determined using Equation (7) (Chen et al., 2020):

$$R(\%) = \left(\frac{PT0 - PT1}{PT0}\right) \times 100 \quad (7)$$

where:

R: the number of killed pests (%)

PT0: number of live pests before spraying

PT1: number of live pests after spraying

**Spraying efficacy for controlling bean pest**

To measure spraying efficacy for controlling the bean pest, sampling was conducted at 7 and 14 days after spraying. For sampling, 10 plants were randomly selected from each treatment, and from each plant, two leaves from the lower and upper parts (totally 20) were selected and scored. Since pest feeding causes necrotic spots on leaves, the criterion for visible damage was based on a 1–6 scale: 1 – no damage, 2 – damage less than 5%, 3 – damage between 5% and 25%, 4 – damage between 25% and 45%, 5 – damage between 45% and 65%, and 6 – damage more than 65% (Ashtari et al., 2025). Then, the spraying efficacy was obtained based on equation (7).

**Prioritization of UAV Sprayers Based On the Combined Performance Index (CPI)**

The combined performance index (CPI) was used to priorities the UAV sprayers. This index weights the key parameters influencing the UAV sprayer performance, compares them with each other, and identifies the most suitable one in terms of overall performance. The parameters considered included spraying efficacy, field efficiency, spray uniformity coefficient, droplet drift, effective field capacity, and energy consumption. Based on expert opinions, given the importance of spraying efficacy, spray uniformity and droplet drift, the weights of these parameters were assigned higher values. This approach is consistent with expert-based weighting methods commonly used in multi-criteria decision analysis. The weights were as follows: spraying efficacy = 0.4, spray uniformity coefficient = 0.15, spray drift = 0.15, field efficiency = 0.1, effective field capacity = 0.1, and energy consumption = 0.1. The sum of the weights must equal one. The direction of optimality (positive or negative) was also determined for each parameter: all parameters except spray drift, energy consumption, and droplet size distribution range had a positive direction, meaning that higher values indicate better performance. Subsequently, the data were normalized to values between 0 and 1. Normalization for parameters for which higher values are better was performed using Equation (8) (Belton & Stewart, 2012):

$$\text{Normalized Value} = \frac{\text{Actual Value} - \mathit{Minimum\ Value}}{\text{Maximum Value} - \text{Minimum Value}} \quad (8)$$

For parameters for which lower values are better, Equation (9) was used:

$$\text{Normalized Value} = \frac{\text{Maximum Value} - \mathit{Actual\ Value}}{\text{Maximum Value} - \text{Minimum Value}} \quad (9)$$

The combined performance index (CPI) was then obtained using Equation (10):

$$\text{CPI}_i = \sum_{j=1}^{n} (\text{Normalized Value}_{ij} \times \text{Weight}_j) \quad (10)$$

where i represents the UAV sprayer, j represents the parameter, and n is the number of key parameters. The UAV sprayer that achieved the highest CPI score was selected as the best option.

The performance data used in this study were obtained from experiments conducted with appropriate treatments and replications. Statistical analyses of the original experimental data were performed and reported in the respective studies. However, the objective of the present research was to integrate multiple performance indicators and rank UAV sprayers using a Combined Performance Index (CPI). Therefore, mean values of the evaluated parameters were used for data normalization and

CPI calculation, and no additional inferential statistical analyses were performed.

## RESULTS AND DISCUSSION

### 3.1 Results of technical parameter measurements

The results of the technical parameter measurements for the UAV sprayer are presented in Table 2. Furthermore, for better and faster comparison of the sprayer sprayers, the results are shown as a bar chart in Figure 2. Based on the table, the spraying height range of the UAV sprayer was 1.5–1.8 m, the effective swath width ranged from 4 to 5 m, the spray volume applied ranged from 8 to 13 L/ha, the energy consumption ranged from 0.6 to 0.9 kWh/ha, and the field efficiency ranged from 51% to 68%. Furthermore, the mean flow rate was 2.1 L/min, the mean flight speed was 18.5 km/h, and the mean effective field capacity was 5.2 ha/h.

The performance indicators obtained in the present study were generally consistent with, and in some cases superior to, those reported in previous studies. The average effective field capacity of the evaluated UAV sprayers was 5.2 ha h−1, which is close to the 5.5 ha h−1 reported by Safari et al. and falls within the range of 3.75–5.5 ha h−1 reported by Sheikhigarjan et al. (Safari et al., 2025; Sheikhigarjan et al., 2024). Moreover, UAV sprayer 3 achieved an effective field capacity of 7.3 ha h−1, exceeding the values reported by Wang et al. (4.1 ha h−1) (Wang et al., 2019).

The average field efficiency in the present study was 62.3%, while UAV sprayers 2 and 3 achieved field efficiencies of 68.3% and 67.3%, respectively. These values are substantially higher than the 52% reported by Zhou et al. although slightly lower than the 72.75% reported by Safari et al. (Safari et al., 2025; Zhou et al., 2020). In terms of spray volume application, the evaluated UAV sprayers applied between 8.4 and 13.2 L ha−1, with an average of 10.9 L ha−1, which is approximately 40% lower than the 18.2 L ha−1 reported by Safari et al. (Safari et al., 2025). This reduction in spray volume, while maintaining acceptable pest control performance, demonstrates the potential of the evaluated UAV sprayers to improve spraying efficiency and reduce liquid consumption.

Overall, the quantitative agreement between the present results and previously published studies confirms the reliability of the measured performance indicators and highlights the operational advantages of certain UAV sprayer configurations under the evaluated crop–pest conditions. Based on Figure 2, the highest flow rate, the highest effective swath width, the highest spray volume, and the highest energy consumption belong to UAV 3.

**Table 2.** Technical parameters of the evaluated UAV sprayers

| Row | Sprayer type | Spraying height (m) | Nozzle flow rate (L $min^{-1}$) | Total flow rate (L $min^{-1}$) | Effective swath width (m) | Mean travel speed (km $h^{-1}$) | Spray volume (L $ha^{-1}$) | Energy consumption (kWh) | Effective field capacity (ha $h^{-1}$) | Energy consumption per unit area | Field efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | UAV 1 | 1.8 | 0.45 | 1.8 | 4.5 | 21.6 | 11.1 | 3.4 | 5.0 | 0.68 | 51.4 |
| 2 | UAV 2 | 1.5 | 1.01 | 2.02 | 4.0 | 12.2 | 8.4 | 3.1 | 3.3 | 0.93 | 68.3 |
| 3 | UAV 3 | 1.5 | 0.6 | 2.4 | 5.0 | 21.6 | 13.2 | 4.3 | 7.3 | 0.59 | 67.3 |
| 4 | Ranges | 1.5-1.8 | 0.45-1.01 | 1.8-2.4 | 4-5 | 12.2-21.6 | 8.4-13.2 | 3.1-4.3 | 3.3-7.3 | 0.59-0.93 | 51.4-68.3 |
| 5 | Average | 1.6 | 0.69 | 2.1 | 4.5 | 18.5 | 10.9 | 3.6 | 5.2 | 0.73 | 62.3 |

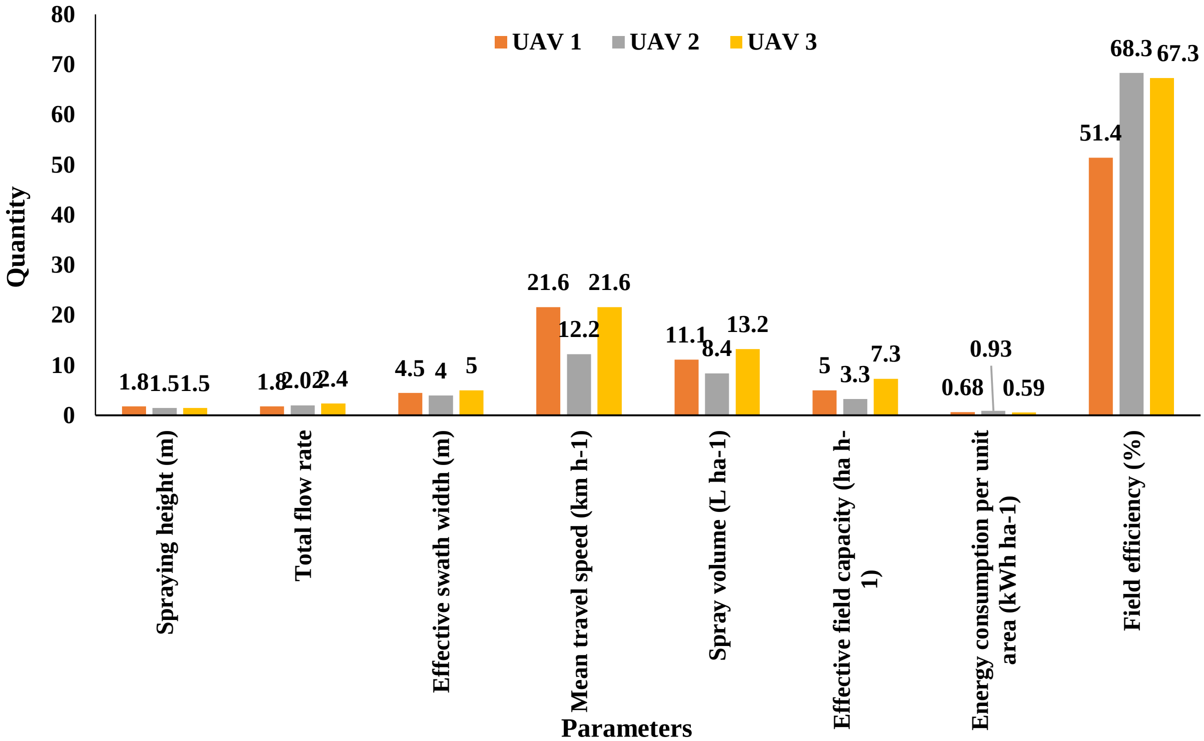


**Figure 2.** Comparison of technical parameters of the UAV sprayers

### Spray Uniformity

The parameters related to spray uniformity are presented in Table 3. The UAV 3 had the highest volume median diameter (932.1 µm) compared to the other two UAVs. A larger VMD means coarser droplets, which reduces the drift but at the same time results in poorer coverage. However, the results show that the drift of the UAV 3 was higher than that of the UAV 2 and UAV 3, which may be due to its high spray velocity. On the other hand, the UAV 2 had the smallest VMD, which means better coverage but an increased risk of drift, especially under high wind conditions, and increased evaporation, particularly in hot weather. However, the results indicate that the UAV 2 had less drift than the other two UAVs. The reason for this is its lower spray velocity and appropriate spraying height, which allowed sufficient time for droplets to settle. In general, droplet deposition is influenced by flow rate, droplet size, wind speed and direction, etc. (Hołownicki et al., 2017).

Furthermore, the presence of six rotors on the UAV 3 and the greater power of the downwash airflow generated by them increased the pressure on the droplets for faster settling, compensating for their small size and reducing drift. Chen *et al*. showed that the downwash airflow generated by the rotors of a UAV sprayer has a significant effect on pesticide penetrability (Chen ShengDe et al., 2017). In that research, low spraying height and speed were recommended to improve droplet penetrability. Wang *et al*. also reported that the downward air flow causes greater droplet penetration into the crop, especially in its lower parts (Wang et al., 2017). Gong *et al*. also attributed greater pesticide adhesion to the crop and better penetration into the plant canopy to the downwash airflow produced by the UAV sprayer's rotors (Gong et al., 2019).

The droplet size range for UAV 1, UAV 2, and UAV 3 was 0.12, 0.22, and 0.12, respectively, indicating that although the mean droplet size of UAV 2 is smaller, their size range is more dispersed, and UAV 1 and UAV 3 are more uniform in terms of droplet size. This result is due to the finer droplet diameter of UAV 2, which causes a more non-uniform distribution across the swath width. Research has shown that smaller droplets, despite providing greater coverage, have less uniform distribution across the swath width because they are more influenced by environmental conditions such as temperature and wind.

The uniformity coefficient for UAV 1, UAV 2, and UAV 3 was 1.15, 1.20, and 0.89, respectively. The closer this coefficient is to one, the more uniform the spray. Therefore, UAV 3, had a better spray uniformity.

In terms of droplet drift, UAV 1 and UAV 2 were approximately similar and had less drift than UAV 3, the reason for which was explained above. In the study by Wang *et al*. reduced flight height and low wind speed were identified as factors reducing droplet drift (Wang et al., 2017). Safari *et al*. reported a spray uniformity coefficient of 1.34 and a drift of 13% for a UAV sprayer (Safari et al., 2025). Yallapa *et al*. also reported a UAV sprayer uniformity coefficient of 1.3, which is consistent with the results of the present study (Yallappa et al., 2017).

**Table 3.** Spray uniformity and droplet drift

| Sprayer Type | VMD (μm) | Droplet Size Range | Uniformity Coefficient | Droplet Drift (%) |
|---|---|---|---|---|
| UAV 1 | 618.1 | 0.12 | 1.15 | 10.0 |
| UAV 2 | 335.0 | 0.22 | 1.20 | 9.9 |
| UAV 3 | 932.1 | 0.12 | 0.89 | 11.7 |

**Spraying Efficacy of UAV Sprayers**

The results of the spraying efficacy measurements for the tested UAV sprayers are presented in Table 4. At seven and fourteen days after spraying, the spraying efficacy of UAV 1 was 70.3% and 92.1%, UAV 2 was 46.3% and 58.8%, and UAV 3 was 27.1% and 34.6%, respectively. Therefore, when spraying with all three UAV types, spraying efficacy increased from one week to two weeks, indicating greater pesticide penetration over time and increased effectiveness. The UAV 1 had the best efficacy. Based on research findings, several parameters such as pesticide dose, nozzle type, working width, spraying height, and flight speed influence spraying efficacy (Hołownicki et al., 2017). The differences in spraying efficacy are related to the following parameters:

**- Droplet size:** Research has shown that for many insects (especially aphids and mites), droplets in the range of 300–600 µm provide the best balance between leaf surface coverage and penetration into the lower layers of the canopy. Droplets of this size are both heavy enough to deposit on leaves and small enough to adhere to them. However, fine droplets (UAV 2) evaporate too quickly or remain in the upper layer of the plant, while coarse droplets (UAV 3) bounce off the leaf and do not reach the pests below.

- Spray volume: The applied spray volume by UAV 1 was 11.1 L/ha, which is higher than that of UAV 2 (8.4 L/ha) and lower than that of UAV 3 (13.2 L/ha). Spray volume varied among the evaluated UAV sprayers, ranging from 8.4 to 13.2 L ha−1. UAV 1 applied an intermediate spray volume (11.1 L ha−1) and achieved the highest spraying efficacy and CPI ranking among the evaluated sprayers. This observation suggests that a moderate spray volume, combined with the operational characteristics of the UAV, may provide favorable spraying performance under the tested conditions. However, because multiple technical and operational factors differed among the UAV sprayers, the specific contribution of spray volume to pest control performance cannot be determined from the present study.

**- Droplet drift:** The lower the droplet drift, the greater the amount of spray solution that deposits on the plant and is absorbed, which improves spraying efficacy. Therefore, the higher drift of UAV 3 compared to the other two UAVs resulted in less pesticide reaching the plant and reduced spraying efficacy. The spraying efficacy of UAV 2, despite its smaller droplets, was improved due to lower drift; however, if its flow rate had been higher, the spraying efficacy could have been even greater.

In this study, spray drift was assessed using water-sensitive papers (WSPs) placed outside the effective spraying swath and on the upper canopy at 1 m intervals, following the methodology of Kharim et al. (Kharim et al., 2019). This approach has been widely adopted in field spray application research due to its operational simplicity, cost-effectiveness, and suitability for comparative evaluation of application technologies under real field conditions.

Nevertheless, it is important to emphasize that WSP-based drift assessment provides a semi-quantitative and indirect estimation of spray drift, relying on the proportion of wetted collectors rather than direct measurement of airborne droplet mass or concentration. As a result, it does not fully capture key aspects of drift dynamics, such as droplet evaporation, transport under varying wind fields, and vertical dispersion processes. Consequently, the reported drift values should be interpreted as relative indicators of spray drift potential among the evaluated UAV sprayers rather than absolute or fully resolved physical measurements of drift behavior. Despite these limitations, the method remains robust and appropriate for comparative analysis under field-scale operational conditions, particularly when the objective is to evaluate relative differences among application systems rather than to model detailed atmospheric transport processes.

**- Spraying speed:** High spraying speed under conditions where droplet diameter is in the range of 300–600 µm creates controlled turbulence within the plant canopy, directing droplets better towards the plant. This phenomenon increases solution absorption and ultimately improves spraying efficacy, a condition that was achieved with UAV 1. For UAV 2, due to the small droplet size, a low spraying speed was chosen to allow sufficient time for droplets to impact and deposit. Hence, the spraying efficacy was acceptable. For UAV 3, both the spraying speed was high and the droplets were large, causing the droplets to not properly hit the target and to be deflected away from the plant, resulting in a significant reduction in spraying efficacy.

**Table 4.** Spraying efficacy of the UAV sprayers

| Treatment | Efficacy at days after spraying (%) | | Rank |
|---|---|---|---|
| | +7 | +14 | |
| UAV 1 | 70.3 | 92.1 | Excellent |
| UAV 2 | 46.3 | 58.8 | Moderate |
| UAV 3 | 27.1 | 34.6 | Poor |

**Ranking of UAV Sprayers**

The ranking results of the tested UAV sprayers are presented in Table 5. The lowest spray volume applied belonged to UAV 2 (8.4 L/ha), and the highest efficacy (92.1% at 14 days after spraying) belonged to UAV 1. The highest effective field capacity (7.3 ha/h), the best uniformity coefficient (0.89), and the lowest energy consumption (0.59 kWh/ha) belonged to UAV 3. The highest field efficiency (68.3%) and the lowest drift (9.9%) belonged to UAV 2. UAV 1 and UAV 3 had a smaller droplet size distribution range (0.12) compared to UAV 2 (0.22), meaning they had more uniform spray.

The higher effective field capacity of UAV 3 was due to its greater effective swath width (5 m) compared to the other two sprayers and its higher flight speed (21.6 km/h) compared to UAV 2. Furthermore, UAV 3, owing to its lower flight height (1.5 m) relative to UAV 1 and higher output flow rate (2.4 L/min) relative to the other two UAVs, had greater and better spray coverage; hence, its spray uniformity (0.89) was higher than that of the other two UAVs. UAV 1, despite a flight speed of 21.6 km/h, had lower field efficiency than the other two UAVs, which could be attributed to its smaller swath width compared to UAV 3, as well as its greater spraying height and lower output flow rate (1.8 L/min) compared to UAV 2 and UAV 3.

The higher energy consumption of UAV 2 compared to the other two UAVs was due to its six motors and the increased power required to start and operate them. Therefore, it can be said that quadcopter is more energy-efficient than hexacopters. The lower drift of UAV 2 (despite its smaller droplet size compared to the other two drones) was due to the greater number of motors and their increased power, which consequently increased the pressure exerted by the downwash airflow on the droplets, resulting in better deposition of the spray solution on the plant. The significantly reduced spraying efficacy of UAV 3 compared to the other two UAVs was explained earlier.

In general, it can be said that UAV 3, due to its higher spray volume, the highest effective field capacity, and the lowest energy consumption (economic efficiency in terms of energy use), can be introduced as a suitable UAV for spraying large fields. UAV 2, due to its lower spray volume (saving pesticide consumption) and higher energy consumption, is suitable for small fields. Furthermore, it is a good option for distributing sensitive or expensive chemicals. UAV 1 has moderate performance and is generally applicable in most fields.

**Table 5.** Ranking of UAV sprayers

| Sprayer Type | Spray volume applied (L $ha^{-1}$) | Effective field capacity (ha $h^{-1}$) | Field efficiency (%) | Energy consumption (kWh/ha) | Droplet size distribution range | Uniformity coefficient | Drift (%) | Spraying efficacy (%) |
|---|---|---|---|---|---|---|---|---|
| UAV 1 | 11.1 | 5.0 | 51.4 | 0.68 | 0.12 | 1.15 | 10.0 | 92.1 |
| UAV 2 | 8.4 | 3.3 | 68.3 | 0.93 | 0.22 | 1.20 | 9.9 | 58.8 |
| UAV 3 | 13.2 | 7.3 | 67.3 | 0.59 | 0.12 | 0.89 | 11.7 | 34.6 |
| Rank 1 | UAV 2 | UAV 3 | UAV 2 | UAV 3 | UAV 1, UAV 3 | UAV 3 | UAV 2 | UAV 1 |
| Rank 2 | UAV 1 | UAV 1 | UAV 3 | UAV 2 | UAV 2 | UAV 1 | UAV 1 | UAV 2 |
| Rank 3 | UAV 3 | UAV 2 | UAV 1 | UAV 1 | - | UAV 2 | UAV 3 | UAV 3 |

**Combined performance index**

The combined performance index (CPI) and the normalized scores for the key parameters influencing the performance of the UAV sprayers are presented in Table 6. Based on the evaluated performance indicators and the CPI, UAV sprayer 1 exhibited the highest overall performance under the crop–pest combinations and environmental conditions considered in this study. However, the relative ranking of UAV sprayers may vary under different crops, pest species, pesticide formulations, and operational conditions.

The reason for UAV 1 being superior was its higher spraying efficacy compared to the other two sprayers, as well as its low drift and low energy consumption. UAV 3 had the lowest index value due to its lower spraying efficacy and higher drift. UAV 2 also had weaknesses such as low spraying efficacy, high energy consumption, low effective field capacity, and a low uniformity coefficient, which reduced its index value.

A limitation of the present study is that the evaluated UAV sprayers were tested under different crop–pest systems and environmental conditions. Variations in crop canopy structure, pest species, pesticide formulations, and weather conditions may have influenced spray deposition and pest control efficacy. Therefore, the observed differences among UAV sprayers cannot be attributed solely to UAV characteristics and operational parameters. Although the study provides a practical comparison of UAV performance under real field conditions, future research should evaluate different UAV sprayers under standardized crop, pest, pesticide, and environmental conditions to isolate the effects of UAV design and operating parameters.

**Table 6.** Normalized scores and CPI values

| Sprayer Type | Effective field capacity | Field efficiency | Uniformity coefficient | Drift | Energy Consumption | Spraying efficacy | CPI |
|---|---|---|---|---|---|---|---|
| Weight | 0.1 | 0.1 | 0.15 | 0.15 | 0.1 | 0.4 | - |
| UAV 1 | 0.425 | 0.0 | 0.555 | 0.944 | 0.733 | 1.0 | 0.741 |
| UAV 2 | 0.0 | 1.0 | 0.0 | 1.0 | 0.0 | 0.420 | 0.444 |
| UAV 3 | 1.0 | 0.941 | 1.0 | 0.0 | 1.0 | 0.0 | 0.418 |

## CONCLUSIONS

This research was conducted with the aim of evaluating the combined performance of several common UAV sprayer types in the country and providing a scientific method for introducing the most suitable UAV sprayer for different pests of various agricultural crops. The overall results of this study are as follows:

- To achieve acceptable spraying efficacy and maximum work efficiency, the values of each parameter are recommended as follows: spraying height less than 2 m, effective swath width at least 4 m, minimum spray volume applied of 11 L/ha, minimum output flow rate of 2 L/min, and minimum effective field capacity of 5 ha/h. Furthermore, the spraying speed should be determined in accordance with other parameters and based on the VMD required to affect the target pest.
- UAV 3 had the highest VMD, while UAV 2 had the lowest VMD.
- The lowest and highest applied spray volume belonged to UAV 2 (8.4 L/ha) and UAV 3 (13.7 L/ha), respectively.
- The highest and lowest spraying efficacy belonged to UAV 1 (92.1%) and UAV 3 (34.6%), respectively.
- The highest and lowest effective field capacity belonged to UAV 3 (7.3 ha/h) and UAV 2 (3.3 ha/h), respectively.
- The best uniformity coefficient (0.89) and the lowest energy consumption (0.59 kWh/ha) belonged to UAV 3.
- The highest and lowest field efficiency belonged to UAV 2 and UAV 1, respectively.
- The lowest drift (9.9%) belonged to UAV 2; however, UAV 1 and UAV 3 had a smaller droplet size distribution range.
- Lower spraying speed and appropriate spraying height improved deposition and reduced drift, even under conditions of small VMD.
- The downwash airflow generated by the rotors improved droplet deposition.
- To increase effective field capacity, the effective swath width and flight speed should be increased up to optimal values. Furthermore, to increase the uniformity coefficient, a lower spraying height and a higher output flow rate were required.
- UAV 3, due to its higher spray volume, the highest effective field capacity, and the lowest energy consumption, can be considered a suitable sprayer for spraying large fields. UAV 2, due to its small tank volume and high energy consumption, is suitable for small fields or for distributing sensitive or expensive chemicals.
- In terms of overall performance based on the CPI, under the evaluated crop–pest and environmental conditions, UAV 1 was identified as the most suitable sprayer due to its superiority in spraying efficacy over the other two UAV sprayers, as well as its low drift and low energy consumption.
- The results show that to achieve the best performance of a UAV sprayer, it is necessary to adjust the parameters according to the conditions. In fact, a balance between parameter values must be achieved, considering the effect of increasing or decreasing each parameter on other parameters, as well as its effect on overall performance. Parameter settings should also be adjusted according to environmental conditions

and the purpose of spraying. Attention to the type of crop and pest, field conditions, and weather is very important.

- Since the most important goal of spraying is pest control, increasing field efficiency or reducing energy consumption without considering its effect on spraying efficacy does not achieve the desired objective. Therefore, it is recommended that all parameters be adjusted in such a way that the result is a maximization of spraying efficacy.

The nozzle type should be selected according to the expected droplet size, and the droplet size should be selected based on the characteristics of the pest and the type of pesticide.

- However, the findings of this study should be interpreted within the context of the evaluated crop–pest combinations, environmental conditions, pesticide formulations, field characteristics, and UAV operational settings. Because the UAV sprayers were evaluated under different experimental and operational conditions, the observed differences in performance indicators and CPI values cannot be attributed solely to UAV type. Therefore, the reported ranking reflects the combined effects of UAV characteristics and the specific conditions under which each sprayer was evaluated. Consequently, the relative ranking of UAV sprayers may differ under other conditions. Further studies conducted under standardized experimental conditions are recommended to validate the present findings and isolate the effect of UAV type on spraying performance. Furthermore, to further develop this study, it is suggested that spraying costs and the amount of solution penetration into the plant also be measured to make the CPI calculation more precise.

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