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PRECISION AGRICULTURE: PARAMETER-BASED OPTIMIZING SPRAYING DRONE FOR OKRA FARMING

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ABSTRACT

Agriculture is the backbone of India's economy, employing over 54.6% of the workforce and contributing 17.76% to the GDP. However, India's agricultural mechanization rate remains low at 40-45%. Drones, especially for pesticide spraying, offer an innovative solution to the challenges of traditional methods, including inefficiency, environmental harm and health risks. This study focuses on optimizing drone spraying for okra crops to improve efficiency and reduce the drawbacks of manual pesticide application. Laboratory and field tests were conducted to assess the performance of a drone sprayer, examining factors like droplet density, Volume Median Diameter (VMD), Number Median Diameter (NMD) and spray drift at different heights and speeds. Results showed that droplet density decreased with higher spray heights and forward speeds. The best performance was at 2 meters height and 3 m/s speed, achieving 39.30 droplets/cm^2, compared to just 9.52 droplets/cm^2 with a battery-operated knapsack sprayer. The drone sprayer also provided more uniform droplet sizes, ensuring better coverage than the knapsack sprayer. The drone sprayer's field capacity was 2.8 ha/h, much higher than the knapsack sprayer's 0.085 ha/h and it used significantly less water (48.34 l/ha), saving 350 liters per hectare. Although, spray drift was higher at greater heights, the drone sprayer was more cost-effective, with an operational cost of ` 292 per hectare, compared to ` 790 per hectare for the knapsack sprayer. The study concludes that a spraying height of 2 meters and a speed of 3 m/s are optimal for drone-based pesticide application on okra crops, offering greater efficiency, cost savings, and safety.

Key words : Agricultural drone sprayer, Droplet density, Droplet size, Number Median Diameter (NMD), Precision agriculture, Spray coverage, Volume Median Diameter (VMD).

Introduction

Agriculture is the backbone of India's economy, employing more than 54.6% of the country's labor force and contributing around 17.76% to its GDP. Currently, the agricultural sector is growing at a compound annual growth rate (CAGR) of 3.4% (Bharad, 2024). In the 2023-24 period, India set a new record in food grain production, reaching 332.298 million tonnes (MT), which is an increase of 2.611 MT from the 329.687 MT produced in 2022-23 (Anonymous, 2023).

India is largely dependent on agriculture, but it lags behind in adopting modern technologies (Bharad and Khanpara, 2024). India's agricultural mechanization rate stands at around 40-45%, which is significantly lower compared to nations like the USA (95%), Brazil (75%), and China (57%). Mechanization can lead to considerable benefits, such as saving 15-20% on seeds, 15-25% on fertilizers, 5-20% on cropping intensity, 20-30% on time, 20-30% on labor and 10-15% on total farm productivity, thereby boosting efficiency and cutting input costs (Tiwari *et al.*, 2019). With India's population projected to grow from 1.34 billion to 1.51 billion by 2030, and further to 1.66 billion by 2050, the countries predominantly comprised of small-scale farmers must confront these pressing issues head-on (Bharad *et al.*, 2024).

Okra (*Abelmoschus esculentus*) is a widely cultivated crop known for its nutritional and economic importance, particularly in tropical and subtropical regions.

Effective pest and disease control is crucial for maintaining high yields in okra farming. Traditional methods of pesticide application, such as manual spraying, are often inefficient, labor-intensive and lead to non-uniform distribution of chemicals, resulting in environmental pollution and crop damage (Jensen *et al.*, 2019). The advent of precision agriculture, coupled with advancements in unmanned aerial vehicle (UAV) technology, offers an innovative solution to these challenges (Xiongkui *et al.*, 2017).

Spraying drones or UAVs have gained significant attention in modern agriculture due to their ability to provide uniform coverage, reduce chemical wastage, and minimize human exposure to harmful chemicals (Huang *et al.*, 2019). In okra farming, where the crop height and canopy structure present unique challenges for pesticide application, optimizing drone parameters such as flight speed, altitude, nozzle type, and spray volume can significantly enhance application efficiency (Yang *et al.*, 2020). These parameters influence droplet size, spray uniformity and penetration, all of which directly affect pest control efficacy and crop health.

This research focuses on a parameter-based approach to optimize spraying drones in okra farming. By analyzing key operational factors such as drone speed and spray volume this study aims to determine the optimal settings for effective pesticide application in okra fields. Such optimization can lead to reduced pesticide usage, lower operational costs, and improved crop yield, while mitigating environmental impacts (Jensen *et al.*, 2019; Yang *et al.*, 2020).

Materials and Methods

Selection of Agricultural Drone Sprayer

There are various types of drones available in the market for agricultural spraying *i.e.*, fixed wing aircraft, single rotor helicopter and multicopter UAV. Multicopter are generally easier to maintain as compared to fixed wing aircraft and helicopter due to their complex structure and more components. The hexacopter type agriculture drone sprayer was selected for the study. It consists of a chemical tank, motor, pump, discharge controller valve, pipe, nozzle holder and nozzles. The tank had a capacity of approximately 10 liters and a brushless diaphragm pump type motor was used to transfer the chemical from the tank to the nozzles through pipes (Fig. 1).

Laboratory study of Agricultural Drone Sprayer

The laboratory study was conducted at Department of Farm Machinery and Power Engineering, College of Agricultural Engineering and Technology, Junagadh Agricultural University, Junagadh.

Fig. 1 : View of selected agricultural drone sprayer for study.

Fig. 2 : View of spraying of water by drone on the patternator.

For conducting each of above trial the following steps were conducted.

- The sprayer tank was filled with known quantity of water.
- The parameters of the drone flying were set according to the treatment combinations.
- The drone was flown directly over the patternator and kept it steady over the center position of the patternator (as shown in Fig. 2).
- Once the drone was stabilized at the targeted height, the spraying process began over the patternator.
- The spray discharge from each channel of patternator was collected in the separate plastic container.
- After completion of drone's spraying over the patternator, the water collected in each plastic container was measured using a measuring cylinder, and the readings were recorded for each of 70 containers.

Investigated variable in laboratory study

The parameters like coefficient of variation (CV), uniformity coefficient (UC) and off-target losses were calculated in laboratory study using following standard formulas.

Coefficient of variation : The spray distribution was determined in terms of coefficient of variance (CV) by using the standard equation given below (Gomaa *et al.*, 2017).

$$\text{Coefficient of variation CV}(\%) = \frac{\text{SD}}{\bar{x}} \quad (1)$$

Where, SD is the standard deviation and $\bar{x}$ is the mean of data.

Uniformity coefficient : The uniformity of spray distribution was determined by Christiansen's uniformity coefficient (UC) method of calculating the uniformity of the spraying systems (Gomaa *et al.*, 2017).

$$\text{Uniformity coefficient (UC)}\% = 100 \times \left(1 - \frac{\Sigma|x - \bar{x}|}{n \times \bar{x}}\right) \quad (2)$$

Where,

n = number of data, $\bar{x}$ = mean of data, x = individual data

Off target losses : Off-target losses refer to the spray liquid that is deposited outside the patternator. At the time of laboratory experiment, the liquid spread over patternator was collected in a plastic container. The volume of collected liquid was measured using a measuring cylinder. To calculate the off-target losses, the total volume of liquid collected in the containers is subtracted from the volume of liquid initially filled into the sprayer tank. The off-target losses were determined using the following formula (Dhakad *et al.*, 2023).

Off target losses %

$$= \frac{\text{Total volume of liquid filled in spray tank (ml)} - \text{Total volume of liquid collected in cyliner (ml)}}{\text{Total volume of liquid filled in spray tank (ml)}} \quad (3)$$

Determination of effective Swath width : For each combination of different spray height, a specific spray pattern was generated and overall swath width was determined in between two outermost edges of the spray pattern. The coefficient of variation CV, uniformity coefficient UC and off target losses were calculated for each combination based on the observed overall swath width.

Field study of Agricultural Drone sprayer and Battery-Operated Knapsack Sprayer

Treatment combination details : The experiment of drone spraying was conducted according to the Table 1 treatment combinations.

Table 1 : Details of various treatment combinations.

S. no.	Treatments	Combinations	Operational height (m)	Operational speed (m/s)
1.	T_1	H_1S_1	2.0	3.0
2.	T_2	H_1S_2	2.0	5.0
3.	T_3	H_2S_1	3.0	3.0
4.	T_4	H_2S_2	3.0	5.0

One of the most critical aspects in any sprayer's effectiveness is the size of the droplets and how they are distributed on the plant. In addition to this, there are other important field parameters to consider when assessing the sprayer's performance. These parameters can be grouped into two main categories:

1. Droplet analysis 2. Parameters for field assessment

The analysis of droplet size focused on several parameters, including droplet density, Volume Median Diameter (VMD), Number Median Diameter (NMD), homogeneity factor, and droplet deposition. The drone was evaluated for operational speed, operational height, spray uniformity, drift, field efficiency as performance parameters.

Investigated variable in field study

From the collected data, the parameters like droplet density, Volume Median Diameter (VMD), Number Median Diameter (NMD), homogeneity factor, droplet deposition, theoretical field capacity, effective field capacity, field efficiency and drift were calculated using following standard formulas.

Droplet density : The droplet density is the number of droplets deposited per cm^2 area. It was calculated by the equation given below (Dhakad, 2023)

Droplet density (droplet/cm^2)

$$= \frac{\text{Total number of droplet in selected image area}}{\text{Selected Image area}} \quad (4)$$

Number Median Diameter (NMD) : It is the number median diameter NMD, which is the value that divides the spray into two equal parts by number of droplets, so that half the droplets are smaller and half larger (Bari *et al.*, 2019).

Volume Median Diameter (VMD) : It is the number that divides the spray into two equal parts by volume, one half (50%) containing droplets smaller than this diameter and the other half (50%) containing droplets larger than this diameter which is expressed in micrometer (µm) (Bari *et al.*, 2019).

Fig. 3 : Experimental plot marking in okra crop.

Fig. 4 : Installation of WSP strip.

Homogeneity factor (HF) : The homogeneity factor of spray droplets was measured with the help of the given equation (Dhakad, 2023),

$$HF = \frac{VMD\ (\mu m)}{NMD\ (\mu m)} \tag{5}$$

A HF value close to 1 indicates more homogeneous droplet diameters, while values further from 1 suggest larger droplets. For effective spraying, HF should be near 1.

Droplet deposition : The UAV spraying experiment aimed to study droplet deposition on plants. Water-sensitive paper was placed on randomly selected plants and collected after the spray dried. The strips were cropped to remove the background, converted to 8-bit format, and threshold adjusted to include only spray droplets. Droplets were then analyzed using DepositScan software. The droplet deposition is the volume deposited per cm^2 area. It was calculated by following equation (Dhakad, 2023).

Deposition (µl/cm^2)

$$= \frac{\text{Total volume of all droplets on the selected area of strip}}{\text{Selected area of strip}} \tag{6}$$

Drift : Pesticide application using spray equipment often results in only a fraction of the liquid reaching its target, with some lost to runoff or scattered in the air. Spray drift, as defined by ISO:22866 (ISO, 2005) refers to the portion of spray carried away by wind during application. It was measured using WSP strips placed outside the target area.

$$\text{Drift}\ (\%) = \frac{\text{Average deposition on strip outside field}\ (\mu l/cm^2)}{\text{Total deposition}\ (\mu l/cm^2)} \tag{7}$$

Where,

Total deposition = Deposition on strip inside the field + Average deposition on strip outside the field.

Results and Discussion

Laboratory Evaluation of Drone Sprayer

The "Agribot" agricultural drone sprayer was evaluated in the laboratory using a patternator to determine its effective swath width. This evaluation was based on the coefficient of variation (CV), uniformity coefficient (UC), and off-target losses. Laboratory experiments were conducted at two different spray heights: 2 m and 3 m. The effects of these two heights on CV (%), UC (%), and off-target losses (%) were analyzed. Table 2 presents the CV (%), UC (%) and off-target losses (%) of overall swath width for various spraying height.

The spray pattern at various height of drone sprayer was illustrated in Figs. 5 and 6.

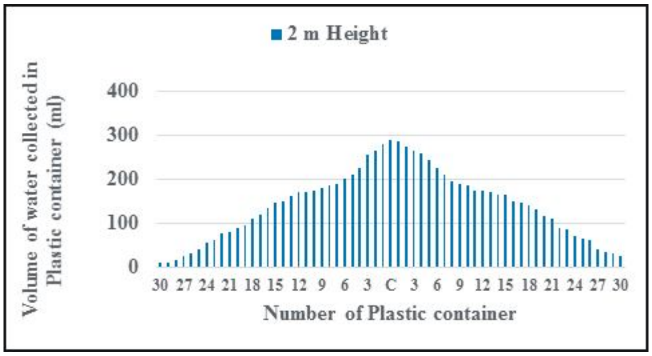

Fig. 5 : Spray pattern observed at a spraying height of 2 m.

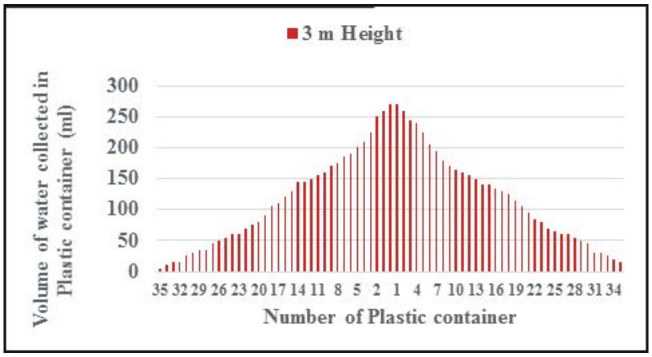

Fig. 6 : Spray pattern observed at a spraying height of 3 m.

Table 2 : CV, UC and off target losses for different height in laboratory evaluation.

Height	Water filled in Chemical Tank of Drone (ml)	Total water collected in container (ml)	Average (ml)	SD (Mean)	CV (%)	UC (%)	Off target losses (%)
2 m	10000	8675	142.21	79.26	55.73	53.04	13.25
3 m	10000	8405	118.38	52.94	63.30	45.59	15.95

Table 3 : ANOVA for droplet density at okra crop.

SV	d.f.	S S	MS	Fcal	TEST	Ftab 5%	Ftab 1%	S.Em. ±	C.D. at 5%
H	1.00	105.61	105.61	163.74	*	5.32	11.26	0.33	1.07
S	1.00	108.00	108.00	167.44	*	5.32	11.26	0.33	1.07
H × S	1.00	9.01	9.01	13.97	*	5.32	11.26	0.46	1.51
Error	8.00	5.16	0.64						
Total	11.00	227.79				C.V.% =	2.47		

Table 4 : ANOVA for VMD at okra crop.

SV	d.f.	S S	MS	Fcal	TEST	Ftab 5%	Ftab 1%	S.Em. ±	C.D. at 5%
H	1.00	3960.33	3960.33	52.00	*	5.32	11.26	3.56	11.62
S	1.00	68403.00	68403.00	898.07	*	5.32	11.26	3.56	11.62
H × S	1.00	507.00	507.00	6.66	*	5.32	11.26	5.04	16.43
Error	8.00	609.33	76.17						
Total	11.00	73479.67				C.V.% =	1.09		

Table 5 : ANOVA for NMD at okra crop.

SV	d.f.	S S	MS	Fcal	TEST	Ftab 5%	Ftab 1%	S.Em. ±	C.D. at 5%
H	1.00	10502.08	10502.08	150.21	*	5.32	11.26	3.41	11.13
S	1.00	23852.08	23852.08	341.15	*	5.32	11.26	3.41	11.13
H × S	1.00	126.75	126.75	1.81	NS	5.32	11.26	4.83	NS
Error	8.00	559.33	69.92						
Total	11.00	35040.25				C.V.% =	2.06		

From Table 2 value of SD found that at 2 m height effective swath width was obtained 1.9 m and at 3 m height effective swath width was obtained 2.3 m.

Field Evaluation of Drone Sprayer

Effect of independent variable on droplet density

Droplet density was determined by putting water sensitive paper strips at different places on plant. The data obtained during the experiment was analyzed statistically and ANOVA table is given in Table 3 for droplet density at okra crop.

From ANOVA table, it was found that the spraying height had significant effect on droplet density. It meant that droplet density was changed according to the change in operating speed and operating height. Droplet density at different treatment combination of height and speed were obtained as shown in Fig. 7.

Effect of independent variable on VMD, NMD and HF

VMD, NMD and HF was determined by putting water sensitive paper strips at different places on plant. The data obtained during the experiment was analyzed statistically and ANOVA table are given in Tables 4 to 6 for VMD, NMD and HF at okra crop.

The VMD and NMD was no specific pattern on the individual parameters, but the HF is defined as the effect of VMD and NMD on the spraying. A lower HF value indicates a more uniform droplet size distribution, meaning that the droplets' sizes are more consistent. A higher HF value suggests a less uniform distribution, indicating an uneven distribution of droplet sizes.

From ANOVA table, it was found that the spraying height had significant effect on HF. It meant that at 2 m

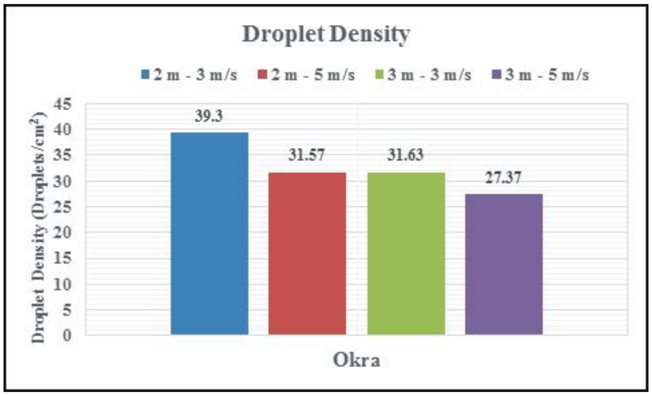

Fig. 7 : Effect of spraying height and forward speed on droplet density for okra crops.

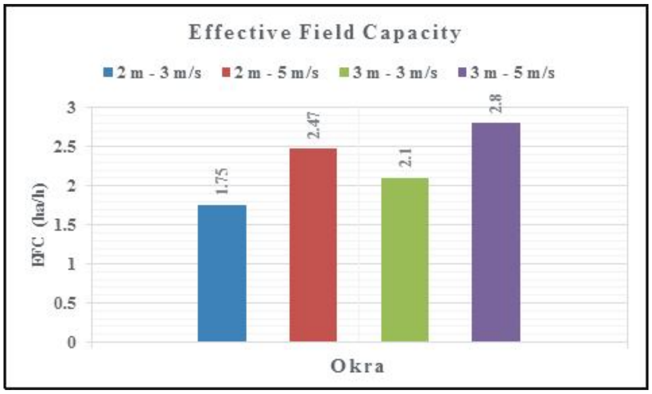

Fig. 8 : Effect of spraying height and forward speed on effective field capacity for okra crops.

height and 3 m/s operating speed found more uniform droplet distribution. The maximum HF was obtained at H_2S_2 (2m – 3 m/s) *i.e.*, 2.08 in okra crop and minimum HF was obtained at H_1S_1 (2m – 3 m/s) 1.83 okra crop according to this value the more homogenous droplets were obtained at H_1S_1 (2m – 3 m/s) combination.

Effect of independent variable on effective field capacity

Effective Field Capacity (EFC) was represented the amount of land area covered by the drone in each time period. The data obtained during the experiment was analyzed statistically and ANOVA table is given in Table 7 for effective field capacity at okra crop.

From Table 7, it is clear that EFC was increased with increase in the spray height. The reason behind this is that as spray height increases which increases the area covered by the drone in a single pass and it is also seen that EFC was increased with increase in the forward speed.

EFC 1.75 ha/h were obtained at the spraying height of 2 m (H_1) and at 3 m/s forward speed (S_1) in okra crop and highest EFC 2.80 was obtained at spraying height of 3m (H_2) and at 5 m/s forward speed (S_2) in okra crop. Effective Field Capacity at different treatment combination of height and speed were obtained as shown in Fig. 8.

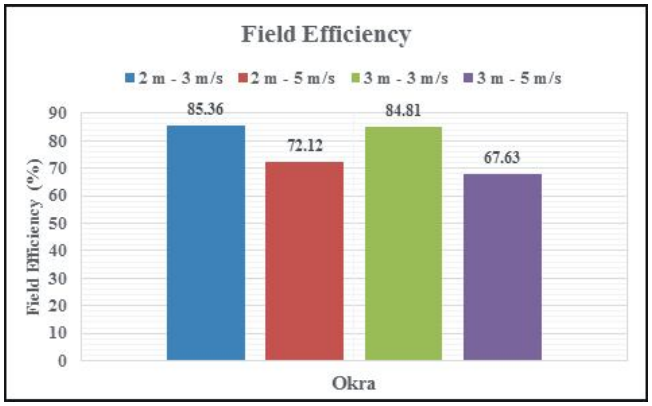

Fig. 9 : Effect of spraying height and forward speed on field efficiency for okra crops.

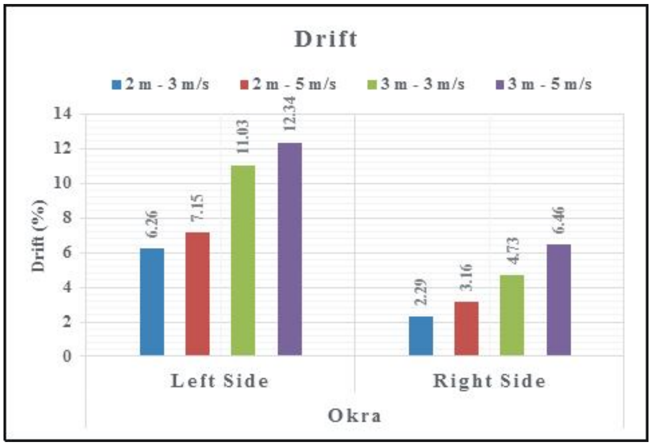

Fig. 10 : Effect of spraying height and forward speed on drift for okra crops.

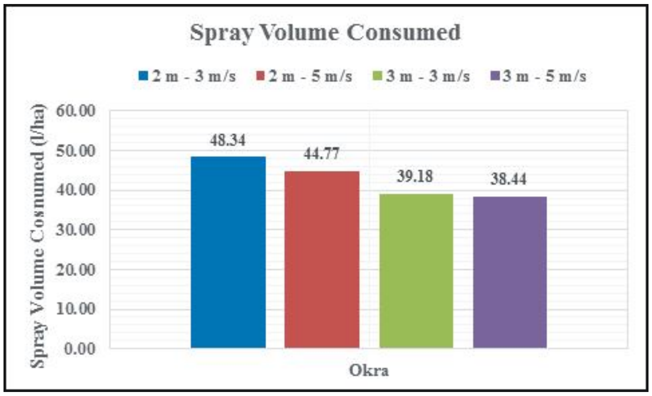

Fig. 11 : Effect of spraying height and forward speed on spray volume consumed for okra crops.

Effect of independent variable on field efficiency

The field efficiency is defined as the ratio of effective field capacity to theoretical field capacity. The data obtained during the experiment was analyzed statistically and ANOVA table is given in Table 8 for field efficiency at okra crop.

Table 6 : ANOVA for HF at okra crop.

SV	d.f.	S S	MS	Fcal	TEST	Ftab 5%	Ftab 1%	S.Em. ±	C.D. at 5%
H	1.00	0.11	0.11	82.66	*	5.32	11.26	0.01	0.05
S	1.00	0.01	0.01	7.66	*	5.32	11.26	0.01	0.05
H × S	1.00	0.00	0.00	3.31	NS	5.32	11.26	0.02	NS
Error	8.00	0.01	0.00						
Total	11.00	0.14				C.V.% =	1.85		

Table 7 : ANOVA for Effective Field Capacity at okra crop.

SV	d.f.	S S	MS	Fcal	TEST	Ftab 5%	Ftab 1%	S.Em. ±	C.D. at 5%
H	1.00	0.35	0.35	331.53	*	5.32	11.26	0.01	0.04
S	1.00	1.50	1.50	1404.50	*	5.32	11.26	0.01	0.04
H × S	1.00	0.00	0.00	0.28	NS	5.32	11.26	0.02	NS
Error	8.00	0.01	0.00						
Total	11.00	1.86				C.V.% =	1.43		

Table 8 : ANOVA for Field Efficiency at okra crop.

SV	d.f.	S S	MS	Fcal	TEST	Ftab 5%	Ftab 1%	S.Em. ±	C.D. at 5%
H	1.00	19.10	19.10	12.25	*	5.32	11.26	0.51	1.66
S	1.00	694.03	694.03	444.97	*	5.32	11.26	0.51	1.66
H × S	1.00	11.64	11.64	7.46	*	5.32	11.26	0.72	2.35
Error	8.00	12.48	1.56						
Total	11.00	737.25				C.V.% =	1.61		

From Table 8, it was observed that FE decreased with increase in forward speed. As speed increased, the EFC was not increased in the same rate as drone take some time at the turning and could not turn with the same forward speed. Hence, it was decreased with increase in the speed.

It was observed from the Fig. 9, that the maximum field efficiency was found as 85.36% at spraying height of 2 m (H_1) and at forward speed of 3 m/s (S_1) whereas the minimum field efficiency 67.63% was obtained at the spraying height of 3 m (H_2) and at 5 m/s forward speed (S_2) in okra crop. Field Efficiency at different treatment combination of height and speed were obtained as shown in Fig. 9.

Effect of independent variable on drift

Spray drift is the proportion of the output from the drone sprayer that is deflected out of the target area by the action of wind. The data obtained during the experiment was analyzed statistically and ANOVA table is given in Table 9 for field efficiency at okra crop.

From Table 9, it was observed that drift was increased with increase in the height of spray. As height of spray increases the drift increases. It was also observed that drift decreased with decrease in forward speed. As speed increased drift was increased.

The maximum drift of spray was observed from the data, 12.34% in south side and 6.46% in north side at spraying height of 3 m (H_2) and at forward speed of 5 m/s (S_2) in okra crop and minimum drift of spray was found as 6.28% in south side and 2.29% in north side at spraying height of 2 m (H_1) and at forward speed of 2 m/s (S_1) in okra crop. Drift at different treatment combination of height and speed were obtained as shown in Fig. 10.

Effect of independent variable on spray volume consumed

The data obtained during the experiment was analyzed statistically and ANOVA table is given in Table 10 for spray volume consumed at okra crop.

From Table 10, it observed that the spray volume consumed was decreasing with increasing the spraying height and operational speed. The impact of spraying height and drone forward speed, as well as their combination, on the Spray Volume Consumed was founded significant okra crop.

Table 9 : ANOVA for Drift at okra crop.

SV	d.f.	S S	MS	Fcal	TEST	Ftab 5%	Ftab 1%	S.Em. ±	C.D. at 5%
H	1.00	74.20	74.20	533.70	*	5.32	11.26	0.15	0.50
S	1.00	3.54	3.54	25.48	*	5.32	11.26	0.15	0.50
H × S	1.00	0.15	0.15	1.08	NS	5.32	11.26	0.22	NS
Error	8.00	1.11	0.14						
Total	11.00	79.01				C.V.% =	4.05		

Table 10 : ANOVA for Spray Volume Consumed at okra crop.

SV	d.f.	S S	MS	Fcal	TEST	Ftab 5%	Ftab 1%	S.Em. ±	C.D. at 5%
H	1.00	179.72	179.72	7320.68	*	5.32	11.26	0.06	0.21
S	1.00	13.91	13.91	566.62	*	5.32	11.26	0.06	0.21
H × S	1.00	6.02	6.02	245.25	*	5.32	11.26	0.09	0.30
Error	8.00	0.20	0.02						
Total	11.00	199.85				C.V.% =	0.37		

The maximum spray volume consumed was found as 48.34 l/ha at spraying height 2 m (H_1) at forward speed of 3 m/s (S_1) whereas the minimum spray volume consumed *i.e.*, 38.44 l/ha was obtained at the spraying height 3 m (H_2) and at 5 m/s forward speed (S_2) in okra crop. From above result it conclude that spray volume consumed was decreasing with increasing the spraying height and operational speed. Spray volume consumed at different treatment combination of height and speed were obtained as shown in Fig. 11.

Economic evaluation of drone sprayer

A comparative analysis between the Agricultural Drone Sprayer and the Battery-Operated Knapsack Sprayer reveals significant differences in both cost and efficiency. The total operating cost per hectare for the drone sprayer is ` 292, whereas the knapsack sprayer incurs a much higher cost of ` 790. In terms of time, the drone sprayer covers one hectare in just 0.40 hours (approximately 24 minutes), while the knapsack sprayer takes 11.90 hours to cover the same area. These findings demonstrate that, although the Agricultural Drone Sprayer requires a higher initial investment, it is far more cost-effective and time-efficient, particularly for larger agricultural fields. This makes it a more suitable option for enhancing productivity in modern farming.

Conclusion

The performance evaluation of the agricultural drone sprayer in okra farming provided several valuable insights for its effective use. The effective swath width increased with higher spray heights, reaching 2.3 meters at a height of 3 meters. Droplet density, a key measure of spray effectiveness, decreased with increasing height and forward speed. The highest droplet density was achieved at a height of 2 meters and a forward speed of 3 m/s, recording 39.30 droplets/cm², which was significantly higher than the 9.52 droplets/cm² observed with the battery-operated knapsack sprayer. This highlights the superior coverage and uniformity of the drone sprayer.

Droplet characteristics such as Volume Median Diameter (VMD) and Number Median Diameter (NMD) showed that finer droplets were produced at lower heights and slower speeds, improving spray efficiency. The drone sprayer delivered significantly finer droplets than the knapsack sprayer, with VMD and NMD ranging between 1165 to 1332 µm and 559 to 811 µm, respectively. This was coupled with a higher droplet frequency, as indicated by the Homogeneity Factor (HF) of 1.83.

The drone's effective field capacity (EFC) was notably higher at 2.8 ha/h, compared to just 0.085 ha/h for the knapsack sprayer. The reduction in operational time was also significant, as the drone sprayer required just 0.41 hours per hectare compared to the knapsack sprayer's 10.63 hours. Additionally, the operational cost of the drone sprayer was calculated as ` 292 per hectare, significantly lower than the ` 790 per hectare for the knapsack sprayer, resulting in a 41.66% cost reduction.

However, spray drift increased with both spraying height and forward speed, with drift percentages reaching 12.34% and 6.46% in the south and north sides, respectively, at the highest height and speed combination. Based on these findings, the optimized parameters for drone spraying in okra farming are a spraying height of 2 meters and a forward speed of 3 m/s, providing the best balance between spray efficiency, bio-efficacy, and resource savings. This optimization not only enhances operational efficiency, but also offers a significant reduction in water and labor usage compared to traditional methods.

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