Journal of Experimental Agriculture International

Volume 47, Issue 1, Page 105-120, 2025; Article no.JEAI.122393
ISSN: 2457-0591
(Past name: American Journal of Experimental Agriculture, Past ISSN: 2231-0606)

Optimization of Operational Parameters for Agricultural Drone Spraying in Maize Crops

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/jeai/2025/v47i13208

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/122393

Original Research Article

Received: 13/08/2024
Accepted: 15/10/2024
Published: 11/01/2025

ABSTRACT

This research on an agricultural drone sprayer for maize crops aimed to standardize various operational parameters—such as spraying height, discharge rate, and drone forward speed—based on metrics like effective swath width, droplet density, Volume Median Diameter (VMD), Number Median Diameter (NMD), Homogeneity Factor (HF), spray volume consumed, effective field capacity, field efficiency, and spray deposition at two crop stages (stage 1: 60 DAS and stage 2: 70 DAS). Field experiments indicated that droplet density decreased as spraying height, discharge rate, and forward speed increased. The maximum droplet densities were 12.39, 12.91, and 12.80 droplets/cm² at a spraying height of 2 m, a discharge rate of 100%, and a forward speed of 3 m/s, respectively, for crop stage 1. Average VMD and NMD ranged from 234 µm to 263 µm and 139 µm to 148 µm, respectively, across different parameter levels. An HF close to one was achieved, with values of 1.71, 1.59, and 1.70 at a spraying height of 2.5 m, a discharge rate of 80%, and a forward speed of 5 m/s, respectively, for both stages.

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Cite as: *Dhakad, Shubham, R. C. Shalunkhe, Kripanarayan Shukla, Neeraj Seth, K. L. Dabhi, and Duda B. Balas. 2025. "Optimization of Operational Parameters for Agricultural Drone Spraying in Maize Crops". Journal of Experimental Agriculture International 47 (1):105-20. https://doi.org/10.9734/jeai/2025/v47i13208.*

Spray volume consumption per hectare decreased with increasing spraying height, decreasing discharge rate, and increasing forward speed. The maximum effective field capacity (EFC) was found as 2.84 ha/h with 80% field efficiency (FE) at a spraying height of 3 m, and 3.02 ha/h with a 73.08% FE for crop stage 1 and 2. Based on the study, the optimal operational parameters were standardized as a spraying height of 2.5 m, a discharge rate of 80%, and a forward speed of 5 m/s.The drone sprayer significantly reduced time, covering one hectare in only 0.32 hours compared to 11.62 hours with a battery-operated manual knapsack sprayer. This research provides valuable insights for optimizing agricultural drone spraying parameters, potentially improving the efficiency of drone sprayers in crop protection practices.

Keywords: Agricultural drone sprayer; spraying; droplet analysis; maize; VMD NMD and HF.

1. INTRODUCTION

Maize is a key crop in India, with the country ranking 4th in area and 7th in production globally. In Gujarat, Dahod and Panchmahal districts are significant producers. Despite high potential yields, maize is vulnerable to pests, causing substantial crop losses (Dhaliwal et al., 2015). Spraying pesticides is vital but challenging with hand-operated sprayers leading to inefficiency and environmental pollution. Recent advancements include engine-operated and battery-powered sprayers, providing more uniform application and mobility.

Drones are emerging as transformative tools in agriculture, aiding in surveying, crop scouting, spraying, and more. They offer precision, efficiency, and reduced labor dependence, but challenges like high initial costs and standardization issues remain. Drones can optimize pesticide application, especially in difficult terrains, though careful calibration is needed to minimize drift and environmental impact.

Huang et al. (2009) developed a UAV-integrated spray system with a maximum payload of 22.7 kg, utilizing a PWM pump speed controller and GPS for precision spraying. This system showed promise for precision agriculture and low-volume spraying. Huang et al. (2013) designed a UAV for site-specific crop management, with field tests showing effective ULV spraying with a 30-meter swath width. The study highlighted the potential for integrating remote sensing with UAV spraying. Xinyu et al. (2014) evaluated UAV-based ULV spraying in paddy fields, finding improved deposition and penetration compared to traditional methods. Drift data showed minimal off-target impact. Huang et al. (2015) developed a low-volume sprayer integrated with unmanned helicopters, showing potential for higher target rates and larger droplet sizes in crop production. Qin et al. (2016) studied UAV spraying in rice fields, finding that increased height and velocity improved droplet coverage at the bottom of plants. UAV spraying showed superior control efficiency over traditional methods. Xue et al. (2016) developed an UAV-based spraying system with precise route planning. Tests indicated superior spray uniformity under varying wind conditions. Yallappa et al. (2017) developed a hexacopter drone sprayer, achieving effective field capacity and uniform spray distribution in groundnut and paddy crops. Balaji et al. (2018) created a hexacopter UAV with sensors for crop monitoring, highlighting significant water, chemical, and labor savings. Kurkute et al. (2018) developed a cost-effective hexacopter UAV with a universal sprayer system for both liquid and solid materials. Mat et al. (2018) compared drone and knapsack spraying in rice fields, finding similar uniformity and drift effects for both methods. Tang et al. (2018) investigated UAV spraying in citrus plants, emphasizing uniform droplet distribution and the influence of flight path deviations. Shaw and Vimalkumar (2020) developed an octocopter drone for spraying and monitoring, achieving effective thrust and spray uniformity. Ahmad et al. (2020) studied UAV operational parameters, recommending optimal forward speed and height for effective spray deposition. Dua (2021) tested nozzles to reduce drift in UAV spraying, identifying optimal pressure and height settings for different crops. Parmar et al. (2021) developed a UAV spraying system, finding optimal deposition at specific orifice sizes, pressures, and heights. Dhakad et al. (2023) developed a patternater of size 4 x 2 m to determine the effective swath width for an agricultural drone sprayer, analyzing uniformity and off-target losses. They found that effective swath width was influenced by spraying height but not discharge rate. The effective swath widths were reported as 2.1 m, 2.3 m, and 2.5 m for spray heights of 2.0 m, 2.5 m, and 3.0 m, respectively.

Manual spraying methods are labor-intensive and hazardous to the operator whereas tractor-mounted spraying methods are required more volume of spray liquid pollute soil and water. Drones offer a safer, more efficient alternative for pesticide application. However, issues such as cost and operational standardization need addressing. Therefore, the research was conducted with objectives:

1. To standardize operational parameters of drone spraying for maize crop.
2. To evaluate the techno-economic feasibility of drone sprayers.

2. MATERIALS AND METHODS

2.1 Study Area

The calibration of selected drone was done at Department of Farm Machinery and Power Engineering, College of Agricultural Engineering and Technology, Anand Agricultural University, Godhra, Gujarat, India and the field study was conducted at Instructional Farm of the college in April, 2023.

2.2 Selection of Agricultural Drone Sprayer

A hexacopter agricultural drone sprayer with a 12-liter tank capacity and 15-minute endurance limit was chosen (Fig. 1). The drone had boasted features such as carbon fiber construction, 6 rotors, 180KV motors, and a 18000mAh battery, among others. The spraying system included components like a chemical tank, motor, pump, nozzles, and nozzle holders, ensuring stable and efficient spraying. The site specifics calibration was done for operation of the drone's navigation system, involving steps like connecting batteries, establishing connections, and rotating the drone for calibration.

2.3 Laboratory Study of Drone Sprayer

Laboratory experiments were conducted to determine the effective swath width on the basis of spray uniformity and spray pattern achieved by the drone sprayer.

- **Development of Patternater -** A 4-meter-long patternater was developed using MS angle and GI sheet. It features 40 V-channels connected to plastic bottles for collecting sprayed liquid.
- **Laboratory Experiment Details -** Experiments were conducted with different combinations of spray height and discharge rate, measuring parameters like coefficient of variation (CV), uniformity coefficient (UC), and off-target losses.
- **Determination of Dependent Parameters -** Parameters like CV, UC, and off-target losses were calculated using standard formulas, ensuring accurate assessment of spraying efficiency.
- **Determination of Effective Swath Width -** Effective swath width was determined, influenced by spraying height but not discharge rate, was 2.1 m, 2.3 m, and 2.5 m for heights of 2.0 m, 2.5 m, and 3.0 m, respectively by overlapping spray patterns and identifying the point of maximum UC and minimum CV (Dhakad et al. 2023).

Fig. 1. Selected agricultural drone sprayer for study

2.4 Field Study of Drone Sprayer

The field studies were conducted to assess the performance of the drone sprayer in real agricultural conditions, focusing on factors like spraying height, discharge rate, and forward speed. It was conducted on maize crop of variety GAYMH-3, sown at spacing of 20 × 60 cm.

The independent parameters, namely the height of spraying (H) (2.0, 2.5, and 3.0 meters); the discharge/flow rate (D) (100%, 80%, and 60%); and the forward speed (S) (3, 4, and 5 m/s) were selected. The evaluation of drone performance involved analyzing droplet size and field evaluation parameters. The details of the selected parameters are as follows:

2.4.1 Droplet size analysis

Droplet size analysis included finding of droplet density, number median diameter (NMD), volume median diameter (VMD), homogeneity factor, and various droplet diameters. For which (strips of known spread factor 1.16) glossy paper strip was put on upper and lower side of the leaf at top and middle of the plant and one strip was put on ground in between rows. The open-source image -j software was used for further analysis of the strip.

1. **Droplet Density:** Number of droplets deposited per cm².

$$Droplet\ density(droplets/cm^2) = \frac{Total\ number\ of\ droplets\ in\ selected\ image\ area}{Selected\ Image\ area}$$

2. **Number Median Diameter (NMD):** Diameter dividing droplets into two equal parts by number.

3. **Volume Median Diameter (VMD):** Mid-way droplet size when accumulated volume of smaller droplets accounts for 50% of sprayed liquid.

4. **Homogeneity Factor (HF):** Ratio of VMD to NMD, indicating droplet formation homogeneity.

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

5. **Minimum, Maximum, and Average Droplet Diameters:** Evaluated to understand droplet size distribution.

$$Average\ droplet\ diameter\ (\mu m) = \frac{Sum\ of\ the\ whole\ droplet\ diameter}{Total\ number\ of\ droplets}$$

6. **Droplet Deposition:** Volume deposited per cm².

$$Deposition\ (\mu l/cm^2) = \frac{Total\ volume\ of\ all\ droplets\ on\ the\ selected\ area\ of\ strip}{selected\ area\ of\ strip}$$

2.4.2 Field evaluation parameters

Field evaluation parameters comprised theoretical field capacity (TFC), effective field capacity (EFC), field efficiency (FE) and spray volume consumed and found by using standard formulas. The drift was measured as proportion of output deflected out of target area by wind and was calculated by using following formula

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

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

2.4.3 Other parameters

The crop parameters like crop height, number of leaves per plant and the number of plants per meter length were measured to provide comprehensive data on crop parameters. The Weather Parameters like dry bulb temperature, wind speed and wind direction were measured to know the weather condition at the time of experiment as drone spraying was done only at standard weather condition.

2.4.4 Experimental procedures

The drone specific calibration followed the same procedures as the laboratory experiment. the accurate measurement and mapping of plot boundaries were performed for experimental plot marking, with reference points established and a flight plan created, taking obstacles and wind direction into account. A methylene blue dye solution (20 gm/L) was prepared and filled into the drone sprayer tank. Glossy paper strips were then installed at various positions on the plants to capture spray data. The experimental procedure involved flying the drone over the marked plot according to the designated treatment combinations. The time taken to cover the length and area was recorded, and the volume of liquid sprayed/consumed was measured. The strips were removed for analysis after each pass and placed new for subsequent trials. Each treatment was replicated twice within a single day to ensure data reliability.

2.5 Techno-economical Evaluation

The parameters like operational Cost (fixed and variable costs), payback period and B:C ratio was calculated by using standard method and following formulas.

$$Breakeven\ point\ h/year = \frac{Annual fixed cost (Rs./h)}{Custom\ hiring\ charges\ (Rs./h)\ - Total\ cost\ of\ operation\ (Rs./h)}$$

$$Pay\ back\ period(Year) = \frac{Initial\ investment}{Net\ benifits}$$

Where,

Average net benefit (Rs./h) = (Custom rate, Rs./h -Total operating cost, Rs./h)

Custom rate, Rs./h = (cost of operation per hour + 25% over head charge) + 25% profit

$$B{:}\ C\ ratio = \frac{Total\ benefit}{Total\ cost\ of\ investment}$$

Where,

Total benefit = Average annual net benefit (Rs.) × Life of machine (L) in years

Total cost of investment = Initial cost of machine (Rs.).

3. RESULTS AND DISCUSSION

3.1 Field Evaluation

The average crop height was found as 130.25 cm and 140.5 cm, the average number of leaves per plant was found as 12 to 14 at crop stage 1 and 2 respectively. The plant-to-plant, row-to-row spacing and number of plants per square meter remained same as 20.2 cm, 60.1 cm and 10 at both crop stages respectively.

The average dry bulb temperature was 30.2°C and 32.4°C, the wind speed at the time of spraying was 2.54 km/h and 2.48 km/h, the average relative humidity was 54.4% and 52.2% recorded at crop stage 1 and 2 respectively. The wind direction was recorded as South-west (225°) for both stages.

3.1.1 Effect of independent variables on droplet density and spray volume consumed

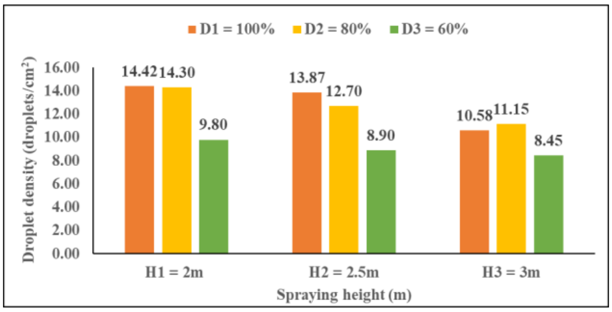
The experiment aimed to investigate the influence of spraying height, discharge rate, and drone forward speed on droplet density at two crop stages (60 DAS and 70 DAS). The results indicated that the effect of spraying height, discharge rate, and drone forward speed, along with their interactions, on droplet density and spray volume consumed was significant at a 5% level of significance (statical analysis Appendix Table 7 and 8), for both crop stages. The average droplet density and spray volume consumed for different levels of independent variables at each crop stage is summarized in Table 1 which showed that the droplet density and spray volume consumption decreased with increasing spraying height, forward speed and decreasing discharge rate. This trend was consistent across both crop stages and aligned with previous research findings (Zang et al., 2021).

The maximum droplet density was observed at H1 spraying height (12.39 and 12.24 droplets/cm^2), at D1 discharge rate (12.91 and 12.78 droplets/cm^2), and at S1 drone forward speed (12.80 and 12.68 droplets/cm^2) for crop stages 1 and 2 respectively. Conversely, the minimum droplet density was recorded at H3 spraying height (10.50 and 10.45 droplets/cm^2), at D3 discharge rate (9.05 and 8.97 droplets/cm^2), and at S3 drone forward speed (10.87 and 10.73 droplets/cm^2) for crop stages 1 and 2 respectively. Further analysis revealed that droplet density decreased with increasing spraying height and forward speed, and decreasing discharge rate, for all levels of the variables studied. The effect of distend parameters on droplet density is shown through graphical representation in Fig. 2.

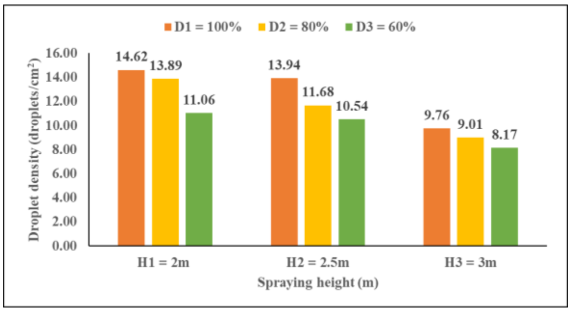
When examining the effect of the combination of spraying height and discharge rate on spray volume consumed, the maximum spray volume (41.27 l/ha) occurred at a spraying height of 2 m (H1) and 100% discharge rate (D1) for crop stage 1. For crop stage 2, the maximum spray volume (40.54 l/ha) was at the same spraying height and discharge rate. Conversely, the minimum volumes were observed at higher spraying heights and lower discharge rates. Similarly, the combination of spraying height and forward speed showed that the maximum spray volume consumed (40.67 l/ha for crop stage 1 and 40.41 l/ha for crop stage 2) was at a spraying height of 2 m (H1) and a forward speed of 3 m/s (S1).

Table 1. Average droplet density and volume consumed for individual variables

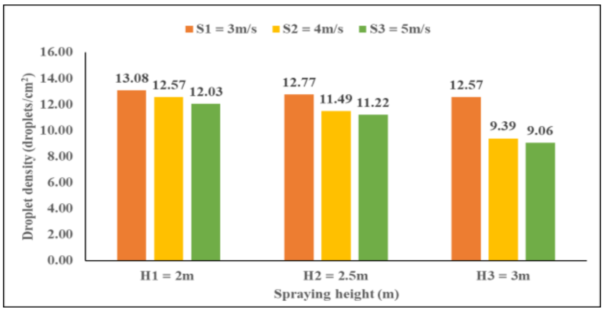
Variables	Droplet density (droplets/cm^2)		Volume consumed (l/ha)	
	Crop stage 1	Crop stage 1	Crop stage 1	Crop stage 2
H1	12.39	12.24	38.73	38.23
H2	11.82	11.52	35.33	34.80
H3	10.50	10.45	32.22	32.19
D1	12.91	12.78	38.13	37.42
D2	12.75	12.45	35.08	35.82
D3	9.05	8.97	29.07	28.98
S1	12.80	12.68	36.64	36.33
S2	11.03	10.80	35.95	35.76
S3	10.87	10.73	33.70	33.13



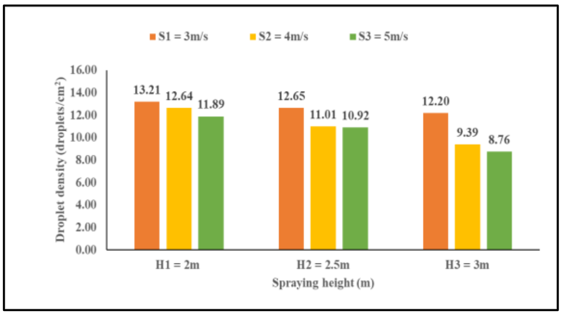
(a) Effect of spraying height on droplet density for different levels of discharge rate for crop stage 1 (60 DAS)



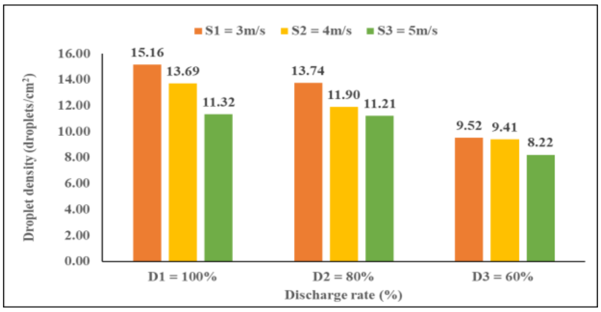
(b) Effect of spraying height on droplet density for different levels of discharge rate for crop stage 2 (70 DAS)



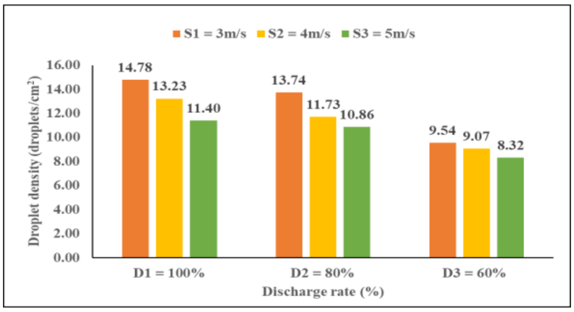
(c) Effect of spraying height on droplet density for different levels of forward speed for crop stage 1 (60 DAS)



(d) Effect of spraying height on droplet density for different levels of forward speed for crop stage 2 (70 DAS)

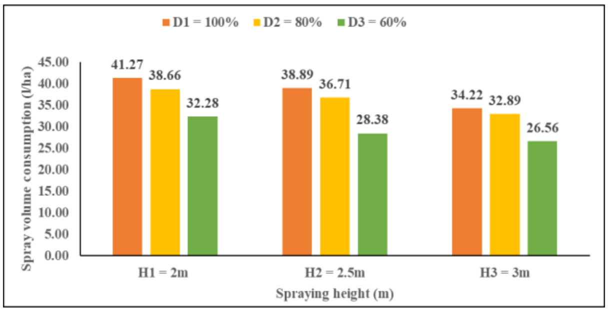


(e) Effect of discharge rate on droplet density for different levels of forward speed for crop stage 1 (60 DAS)

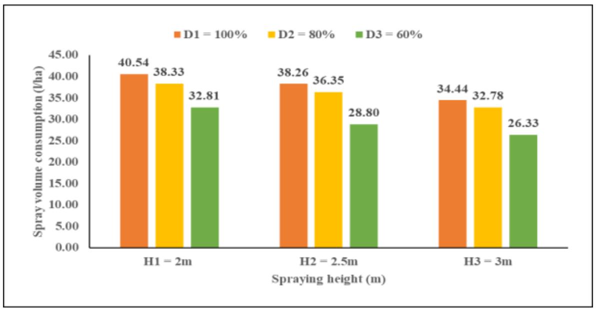


(f) Effect of discharge rate on droplet density for different levels of forward speed for crop stage 2 (70 DAS)

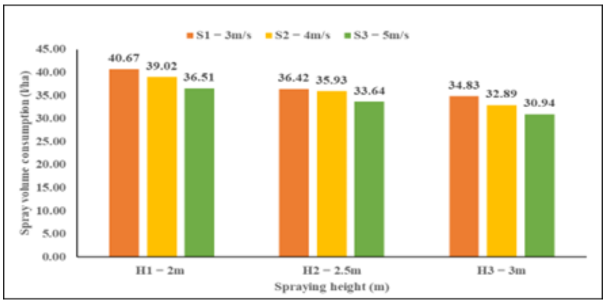
Fig. 2. Effect of independent variables on droplet density



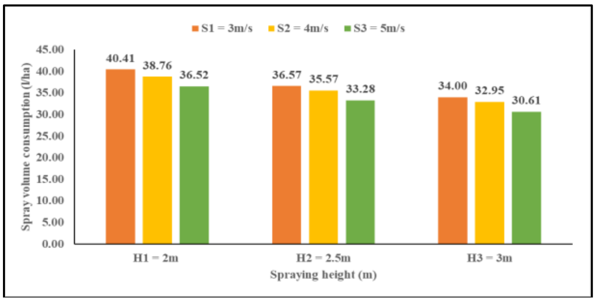
(a) Effect of spraying height on spray volume consumed for different levels of discharge rate for crop stage 1 (60 DAS)



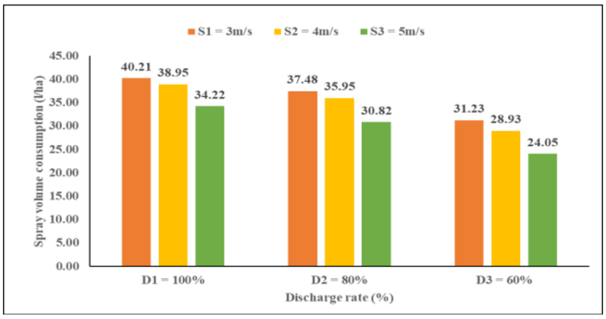
(b) Effect of spraying height on spray volume consumed for different levels of discharge rate for crop stage 2 (70 DAS)



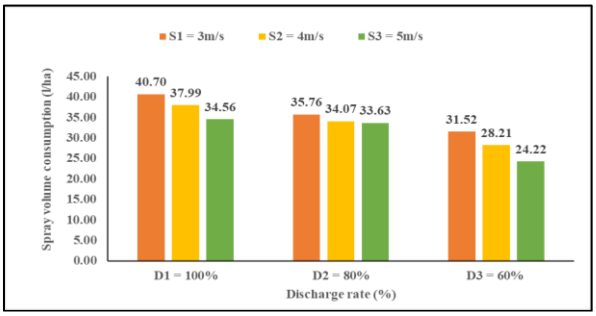
(c) Effect of spraying height on spray volume consumed for different levels of forward speed for crop stage 1 (60 DAS)



(d) Effect of spraying height on spray volume consumed for different levels of forward speed for crop stage 2 (70 DAS)



(e) Effect of discharge rate on spray volume consumed for different levels of forward speed for crop stage 1 (60 DAS)



(f) Effect of discharge rate on spray volume consumed for different levels of forward speed for crop stage 2 (70 DAS)

Fig. 3. Effect of independent variables on spray volume consumed

Similarly considering the combination of discharge rate and forward speed, the maximum spray volume consumed (40.21 l/ha for crop stage 1 and 40.70 l/ha for crop stage 2) occurred at 100% discharge rate (D1) and a forward speed of 3 m/s (S1). Conversely, the minimum volumes were observed at lower discharge rates and faster forward speeds. These findings suggest that spraying height, discharge rate, and forward speed can significantly influence spray volume consumption, which is crucial for efficient pesticide application in precision agriculture.

3.1.2 Effect of independent variables on VMD, NMD and HF

The statical analysis (Appendix Table 9, 10 and 11) revealed significant effects of spraying height and discharge rate on VMD at a 5% significance level, while forward speed's effect was non-significant. However, combinations of spraying height and discharge rate, and all three independent variables together showed significance on VMD. For NMD, all three variables and their interactions significantly affected droplet size. Regarding HF, discharge rate and forward speed significantly influenced it, while spraying height alone did not, though its interaction with other factors was significant. The average values of VMD, NMD, and HF for individual variables at both crop stages are tabulated in Table 2. While no distinct pattern was observed for VMD and NMD across individual parameters, HF varied significantly. Notably, higher HF values indicate less uniform droplet size distribution.

Among spraying heights, H2 yielded the lowest HF, for discharge rate, D2 resulted in the lowest HF and forward speed, S3 led to the lowest HF indicating greater droplet size uniformity at this level of independent variables.

3.1.3 Effect of independent variables on EFC and FE

The statistical analysis (Appendix Table 12 and 13) showed significant effects of spraying height and drone forward speed, along with their interaction, on EFC at a 5% significance level. However, the effect of discharge rate and its interaction with spraying height were deemed non-significant.

Overall, the EFC tended to increase with higher spraying heights and faster forward speeds, while discharge rate showed no significant effect. The field efficiency tends to increase with higher spraying height, attributed to a wider effective swath width. Conversely, increasing forward speed decreases field efficiency. It was happened because EFC was not increased with the same rate of TFC with increase in the forward speed as the time loss in turning remained same in all levels of forward speed. The discharge rate showed no significant effect on field efficiency, as the drone maintained a consistent speed and swath width across different discharge levels. Fig. 4 and Fig. 5 shows the effect of independent variables on EFC and FE respectively.

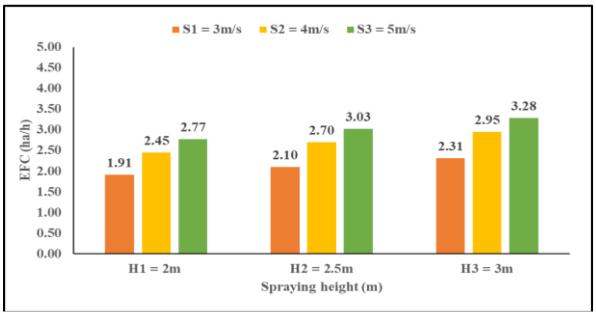
Fig. 3 (a) and (b) demonstrated that EFC peaked at a spraying height of 3 m and a forward speed of 5 m/s while the lowest EFC occurred at a spraying height of 2 m and a forward speed of 3 m/s. Fig. 3 (c) and (d) indicated that the maximum EFC was consistently achieved at a forward speed of 5 m/s, regardless of the discharge rate, while the minimum EFC varied slightly across different combinations of forward speed and discharge rate.

Table 2. Average of VMD, NMD and HF for individual variables

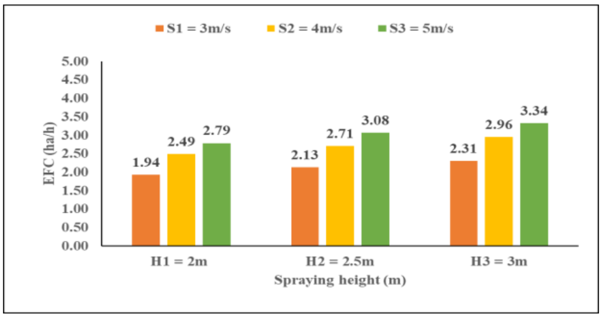
Variables	VMD (μm)		NMD (μm)		HF	
	Crop stage 1	Crop stage 2	Crop stage 1	Crop stage 2	Crop stage 1	Crop stage 2
H1	245.76	244.82	143.03	143.03	1.736	1.732
H2	252.47	254.88	147.97	147.99	1.708	1.712
H3	238.72	237.58	136.14	138.39	1.753	1.757
D1	259.01	263.72	139.40	140.70	1.865	1.882
D2	238.20	241.58	139.04	142.32	1.595	1.592
D3	239.75	231.98	148.70	146.38	1.617	1.697
S1	247.72	249.28	141.87	143.62	1.749	1.735
S2	247.60	251.19	146.21	145.15	1.742	1.730
S3	241.64	236.82	139.06	140.64	1.706	1.699

Table 3. Average EFC and FE for individual variables

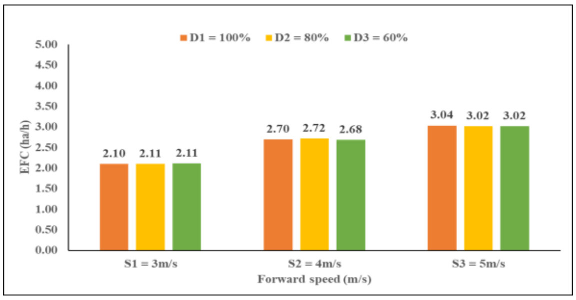
Variables	EFC (ha/h)		Field efficiency (%)	
	Crop stage 1	Crop stage 1	Crop stage 1	Crop stage 2
H1	2.37	2.40	79.52	80.52
H2	2.60	2.63	79.70	80.60
H3	2.84	2.86	80.00	80.63
D1	2.61	2.63	79.75	80.45
D2	2.61	2.63	79.93	80.58
D3	2.60	2.63	79.62	80.71
S1	2.10	2.12	84.72	85.52
S2	2.70	2.72	81.49	82.15
S3	3.02	3.06	73.08	74.08



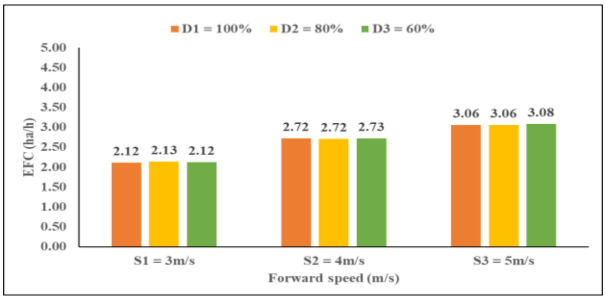
(a) Effect of spraying height on EFC for different levels of forward speed for crop stage 1 (60 DAS)



(b) Effect of spraying height on EFC for different levels of forward speed for crop stage 2 (70 DAS)

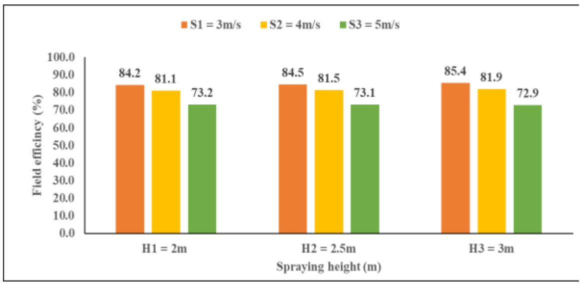


(c) Effect of forward speed on EFC for different levels of discharge rate for crop stage 1 (60 DAS)

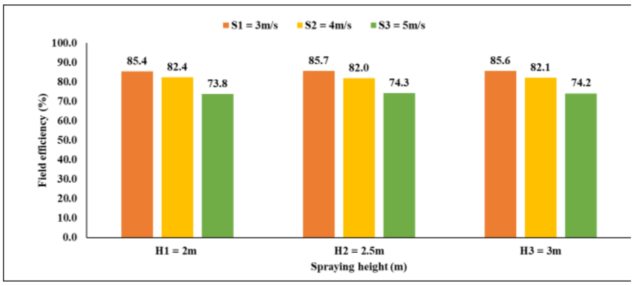


(d) Effect of forward speed on EFC for different levels of discharge rate for crop stage 2 (70 DAS)

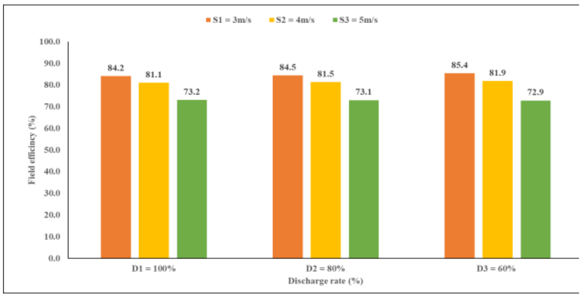
Fig. 4. Effect of independent variables on EFC



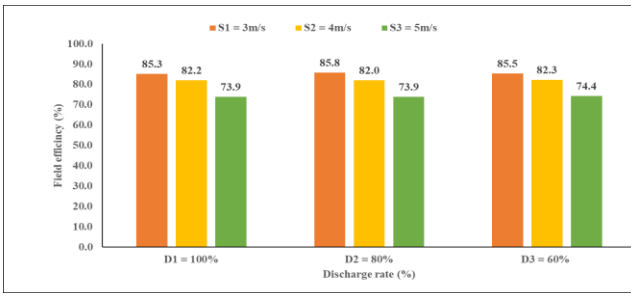
(a) Effect of spraying height on field efficiency for different levels of forward speed for crop stage 1 (60 DAS)



(b) Effect of spraying height on field efficiency for different levels of forward speed for crop stage 2 (70 DAS)



(c) Effect of discharge rate on field efficiency for different levels of forward speed for crop stage 1 (60 DAS)



(d) Effect of discharge rate on field efficiency for different levels of forward speed for crop stage 2 (70 DAS)

Fig. 5. Effect of independent variables on FE

The maximum field efficiency occurs at specific combinations of spraying height and forward speed or discharge rate and forward speed. The above figure showed that field efficiency was decreased as forward speed increased. These findings align with previous research, as noted by Zang et al. (2021), highlighting the importance of optimizing spraying height, forward speed, and discharge rate to enhance field efficiency in drone-based agricultural operations.

3.1.4 Minimum, maximum and average diameter of droplets

At crop stage 1, the average droplet diameter ranges from 148.34 µm to 160.00 µm, minimum droplet diameter ranges from 48.46 µm to 51.53 µm and maximum droplet diameter ranges from 315.27 µm to 349.31 µm. whereas at crop stage 2, average droplet diameter ranges from 131.17 µm to 145.18 µm, minimum droplet diameter ranges from 47.47 µm to 49.49 µm and maximum droplet diameter ranges from 324.65 µm to 384.13 µm. These droplet sizes found during the study are within the range reported in the previous studies.

3.1.5 Deposition of spray volume throughout the plant height

The spray volume deposition throughout the plant was measured at four different places on the plant i.e. on upper and lower side of the top leaves, upper and lower side of middle leaves. The off-target deposition of spray volume was measured as the part of it reached at ground. The graphical presentation of this percentage distribution are given in Fig. 6 (a), (b) and (c).

The experiment investigated the impact of spraying height, discharge rate, and forward speed on spray volume deposition throughout the plant canopy at two crop stages. Across both stages, spraying at H1 generally resulted in the highest deposition percentages, while H3 tended to yield the lowest. For instance, at stage 1, TU saw 54.13% deposition at H1, compared to 49.14% at H3. Similarly, at stage 2, TU had 56.47% at H1 versus 49.68% at H3. Discharge rate D3 consistently led to higher deposition percentages compared to D1. For instance, at stage 1, TU had 61.07% deposition at D3, while only 53.57% at D1. Similarly, at stage 2, TU had 60.15% at D3 compared to 54.78% at D1. Regarding forward speed, S1 resulted in the highest deposition percentages. For example, at stage 1, TU had 56.14% deposition at S1, whereas only 51.71% at S3. Similarly, at stage 2, TU recorded 53.11% at S1 compared to 49.49% at S3. Overall, these findings suggest that adjusting spraying height, discharge rate and forward speed can significantly influence spray volume deposition throughout the plant.

3.1.6 Standardization of different independent variables for maize crop

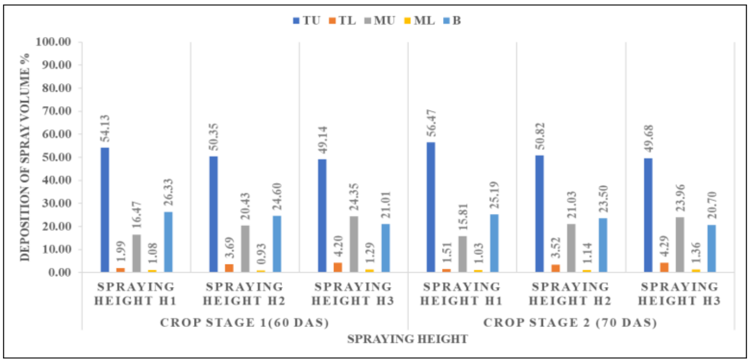
The standardization of independent variables under study with drone sprayer for maize crop was done by dependent parameters as listed in Tables 4, 5 and 6.

Table 4. Values of dependent variables for different levels of spraying height (H)

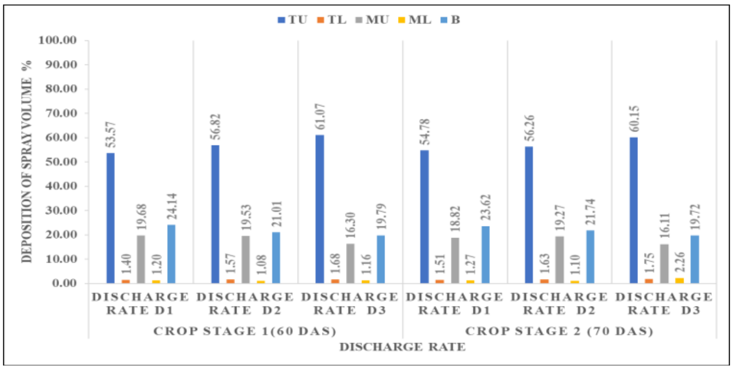
Parameters	Crop stage 1 (60 DAS)			Crop stage 2 (70 DAS)		
	H1	H2	H3	H1	H2	H3
Droplet density(droplets/cm^2)	12.39	11.82	10.50	12.24	11.52	10.45
HF	1.736	1.708	1.753	1.732	1.712	1.757
Volume consumption (l/ha)	38.73	35.33	32.22	38.23	34.80	32.19
EFC (ha/h)	2.377	2.608	2.846	2.406	2.639	2.868
FE (%)	79.52	79.70	80.09	80.52	80.60	80.63
Percentage of Off target deposition	26.33	24.60	21.01	25.19	23.50	20.70
Drift %	6.95	10.08	11.49	6.70	10.62	13.62

Table 5. Values of dependent variables for different levels of discharge rate (D)

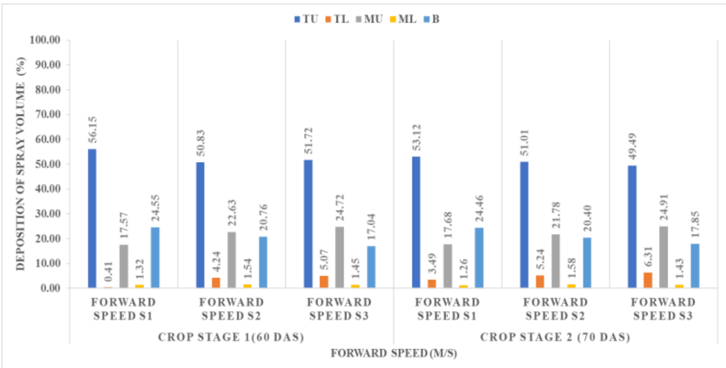
Parameters	Crop stage 1 (60 DAS)			Crop stage 2 (70 DAS)		
	D1	D2	D3	D1	D2	D3
Droplet density(droplets/cm^2)	12.91	12.75	9.05	12.78	12.45	8.97
HF	1.865	1.595	1.617	1.885	1.592	1.697
Volume consumption (l/ha)	38.13	35.08	29.07	37.42	35.82	29.98
EFC (ha/h)	2.61	2.61	2.61	2.63	2.63	2.63
FE (%)	79.75	79.93	79.08	80.52	80.60	80.63
Percentage of Off target deposition	24.14	21.01	19.79	23.62	21.74	19.72
Drift %	8.10	10.74	12.28	7.30	10.30	13.07



a. Percentage deposition of spray volume throughout the plant at different level of spraying height for crop stage 1 & 2



b. Percentage deposition throughout the plant at different level discharge rate for crop stage 1 & 2



c. Percentage deposition throughout the plant at different level forward speed for crop stage 1 & 2

Fig. 6. Percentage deposition of spray volume throughout the plant height

Table 6. Values of dependent variables for different levels of forward speed (S)

Parameters	Crop stage 1 (60 DAS)			Crop stage 2 (70 DAS)		
	S1	S2	S3	S1	S2	S3
Droplet density(droplets/cm^2)	12.80	11.03	10.87	12.68	11.52	10.45
HF	1.749	1.742	1.706	1.735	1.730	1.699
Volume consumption (l/ha)	36.64	35.95	33.70	36.33	35.76	33.13
EFC (ha/h)	2.10	2.7	3.02	2.12	2.72	3.06
FE (%)	84.72	81.49	73.08	85.52	82.15	74.08
Percentage of Off target deposition	24.55	20.76	17.04	24.45	20.39	17.84
Drift %	5.77	9.05	11.28	5.74	10.21	11.15

The spraying height H2, i.e. 2.5m, was selected as the optimized parameter as H.F. was find close to 1, percentage of off target deposition was found more at H1 but drift was less where as in case of H3 percentage of off target deposition was less but drift increased but at H2 both are in between H1 and H3. The level of discharge rate selected as D2 (80%), as at this level as the HF value was found more closer to 1, indicating uniform droplet size formation, and percentage of off target deposition and drift were found in between to D1 and D3. Regarding drone forward speed optimization, out off three levels (S1, S2, S3), S3 (5 m/s) selected as the optimized parameter. This decision was influenced by its close HF value to 1, indicating uniform droplet size formation, and percentage of off target deposition and drift were found in between to S1 and S3.

3.2 Techno Economical Evaluation

The comparison between the Agricultural Drone Sprayer and the Battery-Operated Knapsack Sprayer reveals significant advantages of the drone sprayer. Through the initial investment for the drone sprayer was higher, the drone sprayer proves to be more cost-effective and time-efficient in the long run. The drone sprayer operating cost was found as Rs.186 per hectare, while the knapsack sprayer costs was found as Rs.1223 per hectare. Additionally, the drone sprayer covers one hectare in just 0.32 hours, while the knapsack sprayer requires 11.62 hours. The drone sprayer saves Rs.1037 per hectare. It was approximately 35 times faster than the knapsack sprayer for covering the same area. The payback period of the drone sprayer was estimated as 3.70 years. Furthermore, the B:C ratio for the drone sprayer was derived as 2.15, indicating a significant return on investment over its operational life. Overall, the agricultural drone sprayer stands out as a cost-effective and time-saving solution, particularly for larger agricultural areas.

4. CONCLUSIONS

From the study, following conclusions were drawn. During drone spraying,

1. Droplet density decreased with increase in spray height, decrease in discharge rate, and increase in forward speed.
2. Maximum droplet density was found at 2m height, 100% discharge, and 3m/s forward speed for both crop stages.
3. Average VMD and NMD ranged from 234 to 263µm and 136 to 148µm respectively for different combinations of spraying height, discharge rate, and forward speed.
4. Most uniform droplet size was found at 2.5m height, 80% discharge, and 5m/s forward speed as HF was closer to one.
5. Maximum spray volume consumed was found at 2m height, 100% discharge, and 3m/s forward speed, while minimum was found at 3m height, 60% discharge, and 5m/s forward speed for both stages.
6. EFC increased from 2.38 to 2.85 ha/h with increase in spray height and from 2.10 to 3.03 ha/h with increase in forward speed.
7. The drone sprayer could be operated 2.5 m spray height, 80% discharge, and 5 m/s forward speed while spraying in the maize crop.
8. The drone sprayer proves to be more time-efficient as it coved a hectare field in 0.32 hours while manual knapsack sprayer needed 11.62 hours.
9. The drone sprayer proves to be more cost-effective as the operational cost of drone sprayer was derived as Rs. 565/h with saving of 5.57 times cost over manual knapsack sprayer.

ACKNOWLEDGEMENT

Special Thanks to S. Agri udan Private limited. Ahmedabad For giving me The Agricultural Drone Sprayer and your support during my experiment.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX

Table 7. ANOVA table for droplet density at crop stage 1 (60 DAS) and crop stage 2 (70 DAS)

Source of variation	DF	F- Cri	crop stage 1 (60 DAS)					crop stage 2 (70 DAS)				
			SS	MS	F-Cal	S	C.D.	SS	MS	F-Cal	S	C.D.
Factor H	2	3.35	33.53	16.77	73.01	0.00*	0.33	29.22	14.61	79.51	0.00*	0.29
Factor D	2	3.35	172.31	86.15	375.16	0.00*	0.33	160.26	80.13	436.13	0.00*	0.29
Int H X D	4	2.73	53.91	13.48	58.68	0.00*	0.57	67.51	16.88	91.86	0.00*	0.51
Factor S	2	3.35	41.24	20.62	89.79	0.00*	0.33	44.13	22.07	120.10	0.00*	0.29
Int H X S	4	2.73	27.95	6.99	30.43	0.00*	0.57	38.42	9.61	52.28	0.00*	0.51
Int D X S	4	2.73	41.39	10.35	45.06	0.00*	0.57	29.35	7.34	39.93	0.00*	0.51
Int H X D X S	8	2.31	40.06	5.01	21.81	0.00*	0.98	43.82	5.48	29.81	0.00*	0.88
Error	27		6.20	0.23				4.96	0.18			
Total	53		416.59					417.67				

Table 8. ANOVA table for spray volume consumed at crop stage 1 (60 DAS) and crop stage 2 (70 DAS)

Source of Variation	DF	F- Cri	crop stage 1 (60 DAS)					crop stage 2 (70 DAS)				
			SS	MS	F-Cal	S	C.D.	SS	MS	F-Cal	S	C.D.
Factor H	2.0	3.4	382.0	191.0	400.5	0.00*	0.5	330.6	165.3	123.3	0.00*	0.8
Factor D	2.0	3.4	1099.3	549.7	1152.3	0.00*	0.5	1018.7	509.3	379.8	0.00*	0.8
Int H X D	4.0	2.7	13.4	3.4	7.0	0.00*	0.8	13.4	3.4	7.0	0.01*	0.8
Factor S	2.0	3.4	85.3	42.7	89.5	0.00*	0.5	85.3	42.7	89.5	0.00*	0.8
Int H X S	4.0	2.7	8.6	2.2	4.5	0.01*	0.8	8.6	2.2	4.5	0.01*	0.8
Int D X S	4.0	2.7	323.1	80.8	169.4	0.00*	0.8	323.1	80.8	169.4	0.00*	1.4
Int H X D X S	8.0	2.3	11.6	1.5	3.0	0.01*	1.4	11.6	1.5	3.0	0.00*	1.4
Error	27.0		12.9	0.5				36.2	1.3			
Total	53.0		1936.4					1827.6				

Table 9. ANOVA table for VMD at crop stage 1 (60 DAS) and crop stage 2 (70 DAS)

Source of Variation	DF	F- Cri	crop stage 1 (60 DAS)					crop stage 2 (70 DAS)				
			SS	MS	F-Cal	S	C.D.	SS	MS	F-Cal	S	C.D.
Factor H	2.0	3.4	1701.7	850.9	4.6	0.0189*	9.3	2718.0	1359.0	42.3	0*	3.9
Factor D	2.0	3.4	4837.7	2418.8	13.1	0.0001*	9.3	9542.3	4771.2	148.4	0*	3.9
Int H X D	4.0	2.7	4145.7	1036.4	5.6	0.0021*	16.1	9303.4	2325.9	72.3	0*	6.7
Factor S	2.0	3.4	435.3	217.6	1.2	0.3	N/A	190.2	45.1	1.1	0.4	N/A
Int H X S	4.0	2.7	1241.0	310.3	1.7	0.2	N/A	147.6	36.9	1.1	0.4	N/A
Int D X S	4.0	2.7	1128.9	282.2	1.5	0.2	N/A	204.6	51.1	1.6	0.2	N/A
Int H X D X S	8.0	2.3	4782.8	597.9	3.2	0.0102*	27.9	7078.5	884.8	27.5	0*	11.6
Error	27.0		4980.8	184.5				868.1	32.2			
Total	53		23254					417.67				

Table 10. ANOVA table for NMD at crop stage 1 (60 DAS) and crop stage 2 (70 DAS)

Source of Variation	DF	F- Cri	crop stage 1 (60 DAS)					crop stage 2 (70 DAS)				
			SS	MS	F-Cal	S	C.D.	SS	MS	F-Cal	S	C.D.
Factor H	2.0	3.4	1272.0	636.0	20.4	0.00*	3.8	828.6	414.3	113.1	0.00*	1.3
Factor D	2.0	3.4	1078.8	539.4	17.3	0.00*	3.8	307.8	153.9	42.0	0.00*	1.3
Int H X D	4.0	2.7	2483.5	620.9	19.9	0.00*	6.6	2771.0	692.8	189.1	0.00*	2.3
Factor S	2.0	3.4	467.3	233.7	7.5	0.00*	3.8	189.7	94.9	25.9	0.00*	1.3
Int H X S	4.0	2.7	560.7	140.2	4.5	0.01*	6.6	1229.6	307.4	83.9	0.00*	2.3
Int D X S	4.0	2.7	843.9	211.0	6.8	0.00*	6.6	433.3	108.3	29.6	0.00*	2.3
Int H X D X S	8.0	2.3	612.6	76.6	2.5	0.04*	11.5	1911.1	238.9	65.2	0.00*	3.9
Error	27.0		843.3	31.2				98.9	3.7			
Total	53.0		8162.2					7769.9				

Table 11. ANOVA table for HF at crop stage 1 (60 DAS) and crop stage 2 (70 DAS)

Source of Variation	DF	F- Cri	crop stage 1 (60 DAS)					crop stage 2 (70 DAS)				
			SS	MS	F-Cal	S	C.D.	SS	MS	F-Cal	S	C.D.
Factor H	2.00	3.40	0.02	0.01	1.62	0.22	N/A	0.00	0.00	1.24	0.30	N/A
Factor D	2.00	3.40	0.56	0.28	49.64	0*	0.05	0.78	0.39	252.12	0*	0.03
Int H X D	4.00	2.70	0.25	0.06	11.18	0.000*	0.09	0.37	0.09	60.80	0*	0.05
Factor S	2.00	3.40	0.12	0.03	5.11	0.003*	0.09	0.02	0.01	5.29	0.01154*	0.03
Int H X S	4.00	2.70	0.03	0.01	1.40	0.26	N/A	0.09	0.02	14.67	0*	0.05
Int D X S	4.00	2.70	0.02	0.01	1.65	0.21	N/A	0.08	0.02	12.68	0.001*	0.05
Int H X D X S	8.00	2.30	0.11	0.01	2.40	0.042*	0.15	0.31	0.04	25.45	0*	0.08
Error	27.00		0.15	0.01				0.04	0.00			
Total	53.00		1.26					1.69				

Table 12. ANOVA table for EFC at crop stage 1 (60 DAS) and crop stage 2 (70 DAS)

Source of Variation	DF	F- Cri	crop stage 1 (60 DAS)					crop stage 2 (70 DAS)				
			SS	MS	F-Cal	S	C.D.	SS	MS	F-Cal	S	C.D.
Factor H	2.0	3.4	2.0	1.0	7110.3	0*	0.0	1.9	1.0	9683.1	0*	0.0
Factor D	2.0	3.4	0.0	0.0	0.9	0.1	N/A	0.0	0.0	1.0	0.1	N/A
Int H X D	4.0	2.7	0.0	0.0	0.6	0.7	N/A	0.0	0.0	2.5	0.1	N/A
Factor S	2.0	3.4	7.8	3.9	28181.3	0*	0.0	8.2	4.1	41338.7	0*	0.0
Int H X S	4.0	2.7	0.0	0.0	42.4	0*	0.0	0.0	0.0	114.9	0*	0.0
Int D X S	4.0	2.7	0.0	0.0	5.7	0.0019*	0.0	0.0	0.0	4.0	0.0118*	0.0
Int H X D X S	8.0	2.3	0.0	0.0	5.7	0.0002*	0.0	0.0	0.0	5.0	0.0007*	0.0
Error	27.0		0.0	0.0				0.0	0.0			
Total	53.0		9.8					10.2				

Table 13. ANOVA table for FE at crop stage 1 (60 DAS) and crop stage 2 (70 DAS)

Source of Variation	DF	F- Cri	crop stage 1 (60 DAS)					crop stage 2 (70 DAS)				
			SS	MS	F-Cal	S	C.D.	SS	MS	F-Cal	S	C.D.
Factor H	2.0	3.4	3.1	1.6	12.5	0.0*	0.2	3.1	1.6	12.5	0.001*	0.2
Factor D	2.0	3.4	0.5	0.2	1.0	0.1	N/A	0.8	0.4	0.2	0.3	N/A
Int H X D	4.0	2.7	0.8	0.2	1.7	0.2	N/A	0.4	0.1	1.0	0.5	N/A
Factor S	2.0	3.4	1300.0	650.0	5154.5	0*	0.2	1243.4	621.7	6598.2	0*	0.2
Int H X S	4.0	2.7	3.7	0.9	7.4	0.0*	0.4	1.4	0.3	3.7	0.016*	0.4
Int D X S	4.0	2.7	3.3	0.8	6.5	0.0*	0.4	1.3	0.3	3.5	0.0207*	0.4
Int H X D X S	8.0	2.3	6.5	0.8	6.4	0.0*	0.7	3.2	0.4	4.3	0.0020*	0.6
Error	27.0		3.4	0.1				2.5	0.1			
Total	53.0		1321.8					1253.3				

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The peer review history for this paper can be accessed here:
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