International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 6s, 2025
https://www.theaspd.com/ijes.php

Efficiency Analysis Of Unmanned Aerial Vehicle (UAV) Spraying For Potato Cultivation In The Hilly Region Of Uttarakhand

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Abstract

This study investigated the effectiveness of unmanned aerial vehicle based spraying, focusing on application rate, theoretical field capacity, effective field capacity, and field efficiency. Treatments systematically varied drone operational speeds (1, 3, or 5 m/s) and spray heights (2, 3, or 4 m). Findings revealed a clear inverse relationship between flight parameters and application rate; with a constant nozzle discharge (2.5 l/min), the highest rate (167.026 l/ha) occurred at the lowest speed and height, while the lowest rate (15.955 l/ha) was at the highest speed and height. This confirms that increasing flight speed or height directly reduces the application rate, aligning with fluid dynamics principles.

Conversely, theoretical field capacity, representing maximum potential coverage, increased significantly with higher speeds and heights, ranging from 0.9 ha/h to 8.80 ha/h. Effective field capacity, a more realistic measure accounting for non-productive time like refilling and battery changes, varied from 0.807 ha/h to 7.248 ha/h for drones. Field efficiency, reflecting operational time utilization, ranged from 81.34% to 93.98%. While theoretical capacity highlights potential, effective capacity underscores practical efficiency, heavily influenced by operational downtime and operator skill. These results emphasize that optimizing drone flight parameters and minimizing non-productive time are crucial for maximizing the efficiency and productivity of agricultural spray applications.

Keywords : *Unmanned Aerial Vehicle, application rate, theoretical field capacity, effective field capacity, field efficiency.*

1. INTRODUCTION

Potato (Solanum tuberosum L.) is a globally important crop and historically a staple in the hills of Uttarakhand, India. However, potato production in this region has sharply declined over the past five years (2020-2024). This drop is primarily due to unpredictable weather, reduced snowfall, and rising temperatures. Traditional farming practices in the challenging, steep terrains of the Himalayan foothills exacerbate these issues. Manually applying fertilizers and pesticides is inefficient, labor-intensive, and often results in uneven distribution of chemicals. This also exposes farmers to health risks. Conventional hand-operated spraying methods lead to excessive chemical use, environmental pollution, and higher production costs, especially in orchards, paddy fields, and dense crop areas.

Unmanned Aerial Vehicles (UAVs), or drones, offer a transformative solution. Equipped with spray tanks, these drones can precisely apply agrochemicals and nutrients, overcoming the limitations posed by difficult terrain. Drones fly at optimal heights, ensuring pesticides penetrate crops effectively, even reaching plant parts inaccessible through manual spraying. This targeted application not only enhances the efficacy of chemicals but also helps in reducing overall pesticide use and minimizing chemical waste. Agricultural drones are becoming increasingly popular among modern farmers due to their efficiency. With rising food demand, farmers are looking for ways to boost production and efficiency. Drones help evaluate factors like soil quality, rainfall patterns, temperature, climatic changes, wind speed, and the presence of weeds and insects to identify areas for improvement (Lee et al., 2021).

Farmers now prefer precision variable spraying systems on UAVs over ground-based vehicles due to their speed and ability to limit pesticide use while preserving soil nutrient content. Researchers are focused on developing innovations that meet farmers' needs (Morley et al., 2017). The goal is to promote highly efficient, safe, resource-efficient, and environmentally friendly pesticide spraying technology, ultimately aiming for zero growth in overall pesticide use by the end of 2020. While highly beneficial, UAV spraying faces challenges such as droplet drift and uneven spraying due to external factors like wind and the drone's own propeller wash (Laou et al., 2018). Research shows that smaller droplet sizes (e.g., 200.34 to 253.01 μm) can lead to significantly higher droplet density throughout the crop canopy, resulting in better pest control, such as a greater reduction in whitefly incidence (Parmar et al., 2022). Optimizing nozzle type, pressure, and height is crucial for uniform spray distribution. For instance, a cone nozzle at 8 kg/cm^2 pressure and 600mm height can achieve optimal volumetric distribution and a low coefficient of variation (Kailashkumar et al., 2023). Similarly, a flat fan nozzle at 6 kg/cm^2 pressure, 600 mm height, and a 62.24° angle can also yield excellent results.

UAVs with variable-rate spraying capabilities offer a precise and adaptable strategy for crop management. Future research should integrate this technology with cropland mapping to accurately determine pesticide needs (Hanif et al., 2022). Drones are already proving invaluable for data acquisition and payload delivery across various industries (Jayanth & Yadav 2023). Studies have evaluated UAV spray distribution in crops like cotton, suggesting optimized flight speeds (e.g., 4.0 m/s) and heights (e.g., 1.5 m) for satisfactory liquid delivery to all parts of the plant (Ingle et al., 2024). Droplet size tends to increase with flight height and decrease with flight speed, while droplet density decreases as both flight height and speed increase.

While extensive research exists on how UAV parameters affect droplet deposition and biological efficacy, there's a critical need for more reported evaluations of UAV working efficiency as a key performance indicator in plant protection. Despite their high efficiency and ability to quickly address plant diseases and insect infestations with low risk, practical challenges remain. To systematically identify and comprehensively assess the performance and feasibility of UAVs, especially for potato crops, the topic was meticulously chosen. This study aims to provide crucial empirical data and insights into the operational parameters of UAVs for precision spraying, specifically focusing on application rate, theoretical field capacity, actual field capacity, and overall efficiency.

LITERATURE SURVEY

Recent research on Unmanned Aerial Vehicles (UAVs) for agricultural applications has largely focused on understanding how operating parameters affect application rate and overall efficiency. This provides a crucial foundation for the use of agricultural aviation. This literature review categorizes in following relevant studies, including both direct and indirect influences.

The studies, aligning with contemporary findings, clearly demonstrates an inverse relationship between drone flight speed/height and the resulting application rate. For instance, maintaining a constant nozzle discharge of 2.5 l/min, our data showed the highest application rate of 167.026 l/ha at the lowest speed (1 m/s) and height

(2 m), whereas the lowest rate, 15.955 l/ha, was observed at the highest speed (5 m/s) and height (4 m). This phenomenon is scientifically justifiable, as slower speeds allow more liquid deposition per area, and greater heights lead to wider spray patterns. Various studies corroborate this: Wang et al. (2019) explored how spray volume influences deposition and control efficacy, noting that coarser nozzles at higher volumes were optimal. Ferguson et al. (2020) confirmed that increasing volume rates significantly boosts coverage, while Wang et al. (2023) highlighted that flight height has a more significant effect on droplet deposition and penetration than speed, with higher altitudes generally leading to poorer penetration and increased drift. Lopes et al. (2023) further demonstrated enhanced spray deposition and canopy penetration in soybean crops using specific nozzle types on UAVs.

Beyond application rate, the efficiency of UAV operations is quantified by theoretical and effective field capacities. Theoretical field capacity, representing the maximum potential area a UAV could cover per hour without downtime, is directly proportional to operating speed and effective spray width. Our investigation revealed a highest theoretical capacity of 8.80 ha/h at 5 m/s speed and 4 m height, contrasting with a low of 0.9 ha/h at 1 m/s and 2 m height. The effective spray width ranged from 2.5 m to 5 m. More practically, effective field capacity accounts for non-productive time, such as refilling, battery changes, and operator delays. Our drone treatments showed effective capacities varying from 0.807 ha/h to 7.248 ha/h. This reduction from theoretical to effective capacity is a consistent finding in recent literature. Verma et al. (2021) reported actual UAV field capacities between 2.0-2.3 ha/h, emphasizing the impact of operational downtimes. Yan et al. (2021) also noted that UAV spraying significantly reduced water consumption and overall working time compared to traditional methods, further underscoring the efficiency gains when accounting for these operational aspects.

The overall operational productivity of UAV spraying is encapsulated by field efficiency, which is the ratio of effective to theoretical field capacity. In our study, drone spraying achieved field efficiencies ranging from 81.34% to 93.98%, with the highest efficiency at 5 m/s speed and 2 m height. These high efficiency values (over 80%) suggest well-managed operations, although variations highlight the influence of specific flight parameters and management practices. Recent research aligns with these observations, emphasizing the factors that impact efficiency. Biglia et al. (2022) demonstrated that different flight modes critically affect spray application efficiency, with band spray increasing canopy deposition and reducing ground losses. Changfen et al. (2022) found that control efficacy increased with water application volume, recommending 22.5 L/ha for optimal efficiency in corn fall armyworm control. Furthermore, several studies from 2019-2024, including Park et al. (2019), Xiaofeng et al. (2021), and Sambaiah et al. (2022), show that UAVs often achieve comparable, or even superior, pest control efficacy to traditional methods while offering benefits like reduced chemical dosage, lower water consumption, and minimized operator exposure. Sreenivas et al. (2024) specifically highlighted uniform droplet deposition and higher field capacity with minimal drift when drone sprayers operated at an optimal height of 1.2 m, proving their efficacy on par with power sprayers.

METHODOLOGY

This field experiment was conducted in 2024 at two villages, Museti and Kaparoli, and the College of Horticulture, Veer Chandra Singh Garhwali Uttarakhand University of Horticulture and Forestry, Bharsar, Pauri Garhwal. The villages are geographically located between 30.0253° N latitude and 79.0116° E longitude, with an elevation ranging from 1800 to 2100 meters above mean sea level.

Meteorological and Crop Parameter Monitoring

During spraying operations, crucial meteorological parameters such as wind velocity, air temperature, humidity, and rainfall were recorded. These parameters significantly influence spray quality, and their monitoring helped mitigate adverse climatic effects on sprayer performance. Additionally, various biometric crop parameters were noted as they directly affect the spraying techniques employed in the field trials. These included, type of crop and variety, crop growth stage, row-to-row spacing, plant-to-plant spacing, Leaf Area Index (LAI), date of sowing.

UAV Sprayer Application and Droplet Analysis

A UAV sprayer was utilized to analyze droplet distribution at three different heights (2m, 3m, 4m) and three different speeds (1 m/s, 3 m/s, 5 m/s). To assess droplet deposition, glossy papers were strategically attached to plant leaves across three distinct zones: Upper, Middle, and Lower. A blue dye was mixed with water to create a colored spray solution. Following spraying, the collected glossy papers were meticulously sorted by their respective zones. All experiments were replicated thrice for each treatment to ensure robust data.To thoroughly evaluate the spray system's performance, the several key metrics like application rate, theoretical field capacity, effective field capacity, and field efficiency are calculated.

Application Rate

The application rate (R), measured in liters per hectare (L/ha), was determined according to the ASABE standard (S386.2, 2018). The mean values for the discharge rate, travel speed, and effective spray width was measured. The application rate was then calculated using the following formula:

$$\text{Application rate (R)} = \frac{Q \times K}{S \times W}$$

Where:

- R = Application rate (L/ha)
- Q = Output rate (L/min)
- K = Constant (600)
- S = Travel speed (km/h)
- W = Effective spray width (m)

Theoretical Field Capacity

Theoretical field capacity (TFC) represents the maximum rate at which the implement could cover the field, assuming 100% operational time at the rated speed and covering 100% of its rated width. It's expressed in hectares per hour (ha/h) and calculated as:

$$\text{Theoretical Field Capacity (TFC)} = \frac{W \times S}{10}$$

Where:

- TFC = Theoretical field capacity (ha/h)
- W = Spray width (m)
- S = Forward speed (km/h)

Effective Field Capacity

Effective field capacity (EFC) reflects the actual area covered by the system, taking into account both total time consumed and the spray width (Mehta et al., 2024). This metric is also expressed in hectares per hour (ha/h) and is calculated using the formula:

$$\text{Effective Field Capacity (EFC)} = \frac{A}{T_p + T_l}$$

Where:

- EFC = Effective field capacity (ha/h)
- A = Area (ha)
- Tp = Productive time (h)
- Tl = Non-productive time (h)

Field Efficiency

Field efficiency (FE) quantifies the operational effectiveness of the spraying system. It is defined as the ratio of effective field capacity to theoretical field capacity, expressed as a percentage (Kepner et al., 1978). The field

$$\text{Field Efficiency (FE)} = \frac{EFC}{TFC} \times 100$$

Where:

- FE = Field efficiency (%)
- EFC = Effective field capacity (ha/h)
- TFC = Theoretical field capacity (ha/h)

RESULTS AND DISCUSSION

This study evaluated application effectiveness across different treatments for spraying through drone focusing on application rate, theoretical field capacity, effective field capacity, and field efficiency. The treatments were designed by combining various drone operational speeds (1, 3, or 5 m/s) with different spray heights (2, 3, or 4 m).

Application Rate

Our findings show a clear inverse relationship between these drone flight parameters and the application rate. Keeping the nozzle discharge rate constant at 2.5 l/min, the application rate changed significantly with different settings. Specifically, the highest application rate for drones was 167.026 l/ha (Treatment T_1), achieved at the lowest speed (1 m/s) and lowest height (2 m). Conversely, the lowest application rate was 15.955 l/ha (Treatment T_9), observed at the highest speed (5 m/s) and greatest height (4 m).

This demonstrates that increasing either flight speed or flight height directly reduces the application rate. This is scientifically sound: a slower drone deposits more liquid per area, and a higher spray creates a wider pattern, spreading the same volume over a larger area. These observations are consistent with existing research (Gaadhe et al., 2025) on fluid dynamics in aerial application.

Theoretical Field Capacity

Theoretical field capacity measures the maximum area a UAV could spray per hour, assuming continuous operation without any breaks. This is determined by the drone's operating speed and its effective spray width (swath). Our results showed that the highest theoretical field capacity was 8.80 ha/h when the UAV operated at its fastest tested speed of 5 m/s and a height of 4 m. Conversely, the lowest theoretical field capacity recorded was 0.9 ha/h at the slowest flight speed of 1 m/s and a height of 2 m. The effective spray width observed during operations ranged from 2.5 m to 5 m.

Scientifically, theoretical field capacity directly relates to both flight speed and swath width. A faster drone covers more ground over time. Additionally, increasing flight height can sometimes widen the spray swath due to greater droplet dispersion, covering a larger area per pass. Therefore, the observed increase in theoretical field capacity with higher speed and wider coverage (achieved at greater heights) aligns with the engineering principles of sprayer performance.

Table 1: Average application rate (l/ha), theoretical field capacity (ha/h), effective field capacity (ha/h), and field efficiency (%).

Treatments	Application Rate (l/ha)	Theoretical Field Capacity (ha/h)	Effective Field Capacity (ha/h)	Field Efficiency (%)
T_1	167.026	0.900	0.840	93.296
T_2	131.978	1.152	1.083	93.970
T_3	102.880	1.476	1.365	92.451
T_4	50.827	3.024	2.786	92.127
T_5	37.977	3.888	3.417	87.888
T_6	33.122	4.752	4.390	92.386
T_7	23.016	5.940	5.018	84.480
T_8	18.927	7.740	6.766	87.420
T_9	15.955	8.820	7.285	82.600

Effective Field Capacity (ha/h)

Effective field capacity offers a more realistic look at how much area can actually be covered per hour. This metric considers all the non-productive time during spraying, such as refilling the tank, swapping batteries, making turns at the end of rows, and any delays caused by the operator's skill or decisions. In our study, the effective spray width (swath) ranged from 2.3 m to 4.5 m across different treatments. For drone treatments (T_1-T_9), the effective field capacity varied from 0.807 ha/h to 7.248 ha/h. This range was observed with speed variations from 1 m/s to 5 m/s and height variations from 2 m to 4 m. On average, the effective field capacity for treatments T_1 to T_9 fell between 0.84 ha/h and 7.285 ha/h.

While theoretical field capacity shows what's possible, effective field capacity reveals the actual, practical efficiency. The difference between these two figures primarily comes down to unavoidable operational downtime. Key factors influencing this include how quickly tanks are refilled, how long drone batteries last, and how skilled the operator is at minimizing unproductive maneuvers. For example, frequent battery changes or inefficient turning sequences will reduce the total area covered in an hour, even if the drone is spraying at a high speed.

Field Efficiency (%)

Field efficiency measures how well a drone's operational time is used for actual spraying. It's calculated as the percentage of effective field capacity compared to theoretical field capacity. In this study, drone spraying in the apple orchard showed field efficiencies ranging from 81.34% to 93.98%. The highest efficiency, 93.98%, was achieved with a speed of 5 m/s and a height of 2 m. The lowest, 81.34%, occurred with a 3 m/s speed and 4 m height. On average, the field efficiency for treatments T_1 to T_9 varied from 93.97% to 82.60%.

Field efficiency is a crucial indicator of how productive an operation is. It's heavily influenced by the operator's skill, as proficient operators can minimize non-productive time through quicker turns and efficient battery swaps. Weather conditions also play a big part; for example, strong winds might require pausing or adjusting spraying, which reduces efficiency. Any time lost to non-productive tasks like navigating obstacles, changing settings, or waiting for ideal conditions directly lowers field efficiency. The high efficiency values (over 80%) observed suggest that the operation was generally well-managed. However, the variations highlight how much specific flight parameters and operational management can impact overall productivity.

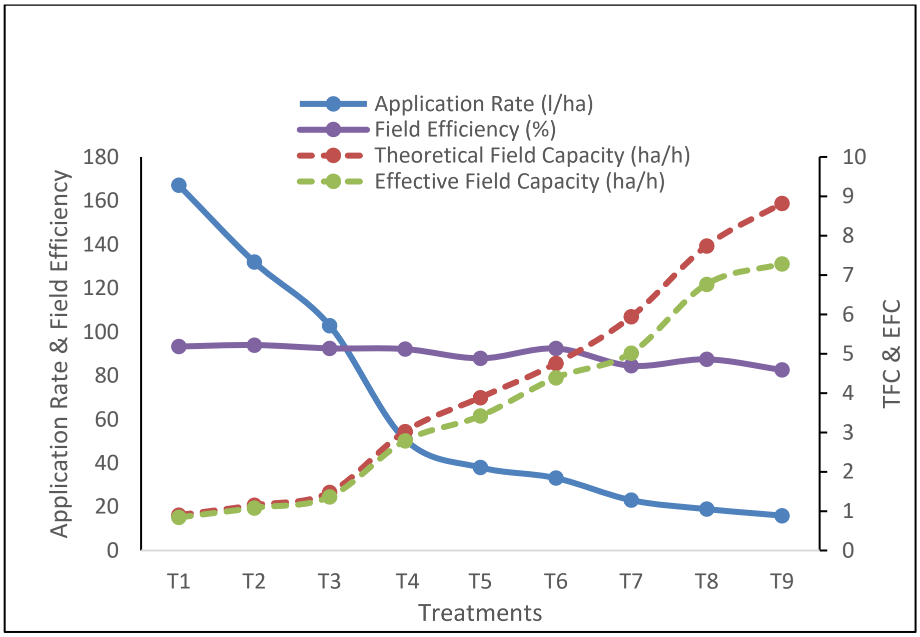

Fig. 1. The graphical representation of different parameters with respect to treatments.

CONCLUSION

This study clearly demonstrates the significant impact of drone operational parameters on spraying effectiveness. The study found an inverse relationship between flight speed/height and application rate, with the highest rates achieved at lower speeds and heights, aligning with fluid dynamics principles. Conversely, theoretical and effective field capacities increased with higher speeds and heights, highlighting greater area coverage potential. While theoretical capacity shows maximum potential, effective capacity offers a realistic measure by accounting for crucial non-productive time like refilling and battery swaps. High field efficiency (over 80%) generally indicates well-managed operations, yet variations underscore the importance of optimizing flight settings and minimizing downtime for maximizing overall productivity and resource utilization in drone-based agricultural applications.

Acknowledgement.
I sincerely thank Dr. Ramesh Pal (IFTM University, Moradabad), my major advisor, and my advisory committee for their invaluable guidance throughout my studies. I am also grateful to the villagers of Museti and Kaparoli, and to the College of Horticulture, VCSGUUHF, Bharsar, Uttarakhand, for their support in this research.

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