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Study of Machine Parameters for Spraying though Unmanned Aerial Vehicle (UAV) in Apple Orchard

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ABSTRACT: Investigating Unmanned Aerial Vehicle (UAV) operational parameters, including discharge rate, application rate, theoretical field capacity, effective field capacity, and field efficiency, is paramount for enhancing precision agriculture in apple orchards. This facilitates optimized agrochemical deposition, mitigating resource wastage and ecological contamination. Concurrently, it maximizes canopy coverage and operational throughput. Such empirical data enables superior pest and disease management, fostering robust tree health and elevated horticultural yields. This study rigorously evaluated the performance of a drone spraying system for precision agriculture, focusing on key parameters such as discharge rate (l/min) application rate (l/ha), theoretical field capacity (ha/h), effective field capacity (ha/h), and field efficiency (%). The study in an apple orchard showed that a UAV's application rate decreases significantly with increased flight speed and height, ranging from 166.36 l/ha to 17.389 l/ha. This occurs because the same discharge is spread over a larger area. Theoretical field capacity increased with speed and swath, reaching 8.80 ha/h. However, effective field capacity (0.807-7.248 ha/h) was lower due to factors like refilling. Despite downtime, field efficiency remained high (81.34-93.98%), demonstrating efficient operation. Overall, UAVs show great promise for precise, efficient spraying in apple orchards by adjusting flight parameters.

Keywords: Unmanned Aerial Vehicle (UAV), discharge rate, application rate, theoretical field capacity, effective field capacity, field efficiency.

INTRODUCTION

Plant protection stands as a cornerstone of modern agriculture, intrinsically linked to guaranteeing fertility and bountiful harvests. The machinery employed for plant protection is thus an indispensable tool in realizing these objectives. Historically, plant protection practices relied heavily on manual and semi-mechanized equipment. This often translated into arduous labor, suboptimal efficiency, and, most concerningly, a high incidence of poisoning among agricultural workers. The subsequent widespread adoption of boom sprayers offered a significant leap forward, dramatically reducing labor intensity and improving operational efficiency. However, their utility is severely constrained in mountainous regions, which represent a substantial portion of global agricultural land. In these challenging terrains, boom sprayers face considerable difficulties in field operation due to their size and maneuverability limitations.

In response to these geographical and operational constraints, agricultural aviation has emerged as a dominant force, particularly through the advent and increasing sophistication of small Unmanned Aerial Vehicles (UAVs) (Qin *et al*., 2016). A key advantage of UAVs, when compared to conventional agricultural aircraft, is their independence from specialized airports, coupled with the flexibility of remote-control operation (Faiçal *et al*., 2014). This inherent adaptability makes them exceptionally well-suited for navigating and treating complex terrains that traditional ground machinery simply cannot access. Beyond their geographical versatility, UAVs boast high work efficiency and a robust capacity to respond rapidly to sudden agricultural disasters with minimal risk (Huang *et al.*, 2008). Crucially, UAVs also offer a significant avenue for reducing pesticide exposure to human operators and minimizing environmental pollution during the application process. These compelling benefits have spurred intense research interest and a concerted effort to popularize UAVs for pesticide application over the past few years (Xue *et al.*, 2014).

In the current agricultural landscape, particularly among small-scale farmers, the prevalent practice involves the use of backpack sprayers. These devices frequently suffer from leakage, leading to the unfortunate drenching of skin and clothing with pesticides. Moreover, in many developing nations, agricultural workers endure prolonged hours in the fields, engaged in the laborious tasks of mixing and spraying pesticides or working within areas where spraying is actively occurring. The lack of readily available washing facilities near agricultural fields compounds this issue, as workers often wear contaminated clothing throughout the day and engage in essential activities like eating, drinking, and smoking with contaminated hands. The World Health Organization (WHO) tragically estimates over 1 million pesticide-related poisoning cases globally each year, with more than one lakh deaths annually, disproportionately occurring in developing countries, directly attributable to pesticides sprayed by human beings. Pesticides are unequivocally known to exert detrimental effects on the human nervous system and can precipitate a range of physiological disorders (Meivel *et al.*, 2016).

To accurately identify the elements requiring improvement, a comprehensive evaluation of critical environmental and agricultural parameters, including soil quality, rainfall patterns, temperature, climatic change, wind speed, and the presence of weeds and insects, is routinely undertaken (Lee *et al*., 2021). To effectively increase and organize productivity in accordance with prevailing market demand, farmers must diligently strive to develop and adopt innovative solutions. However, numerous paradoxes persist in rural contexts, where conventional knowledge and outdated technology remain stubbornly prevalent, despite the fact that the magnitude of food requirements is not significantly different from that of metropolitan areas. Furthermore, pests and plant diseases represent principal agronomic issues that directly impinge upon the quality and quantity of land productivity. Chemicals and pesticides can be strategically utilized as the primary means of eliminating and stabilizing the biotic composition of crops to circumvent this pervasive issue. Nevertheless, the judicious use of pesticide spraying equipment in the field is absolutely essential, primarily due to the diverse and specific pesticide requirements of each crop. It is noteworthy that more than 88% of manually operated sprayers in China comprise knapsack air-pressure or electric sprayers and knapsack mist-blower sprayers (Yang *et al.*, 2018), highlighting the continued reliance on labor-intensive methods.

Manual pesticide spraying exposes the personnel involved in the spraying process to a multitude of harmful side effects. The adverse exposure effects can range from mild skin irritation to severe and life-altering conditions such as birth defects, tumors, genetic changes, debilitating blood and nerve disorders, endocrine disruption, coma, or even death. The WHO (World Health Organization) tragically estimates approximately one million cases of ill health annually, directly attributable to the manual spraying of pesticides in crop fields (Shaw and Vimal Kumar 2020). This grim statistic underscores the urgent need for safer application methodologies. The cone nozzle produced a spray that was uniform and had the lowest coefficient of variation at all pressures and heights tested. Using this model, for the cone nozzle, best spray volumetric distribution and the lowest coefficient of variation may be achieved as long as the nozzle pressure is 8 kg/cm^2 at 54.46° and the height is 600mm. We employed a flat fan nozzle at a 62.24° nozzle angle, 600 mm height, and a pressure of 6 kg/cm^2 to get the optimum spray volumetric distribution and the lowest coefficient of variation (Kailashkumar *et al.*, 2023).

Unmanned aerial vehicle (UAV) variable-rate spraying offers a highly precise and adaptable alternative strategy for overcoming these complex challenges inherent in conventional pesticide application. Future research is strongly incentivized to continue advancing the precision performance of variable-rate development by seamlessly combining it with detailed cropland mapping. This integration aims to accurately determine the specific need for pesticides on a site-specific basis. Despite the inherent benefits of high quality and precision, strict limits on the amount of spraying can make it challenging to achieve uniform coverage across the entire field (Hanif *et al.*, 2022). Drones can deliver payloads, acquire real-time data in an efficient and cost-effective manner, and have been a driving force behind the rapid development of a wide variety of industrial, commercial, and recreational applications (Jayanth & Yadav 2023). Despite these preceding studies, it is noteworthy that almost all prior research has predominantly focused on the effect of working parameters on droplet deposition and biological efficacy. High efficiency, particularly the robust ability to effectively deal with sudden disasters including plant diseases and insect pests with low inherent risk, is undeniably one of the most compelling reasons for the greatly accelerated development and adoption of UAVs in agriculture. However, there remains a significant gap in the literature: there is currently no comprehensive report available on the rigorous evaluation of the working efficiency of UAVs for plant protection, despite this being a critically important evaluation index. As an emerging technology, UAV spraying for pest protection still faces a series of practical issues that demand thorough investigation, such as the uniformity of droplet distribution, the crucial droplet coverage ratio, the penetrability of pesticide into the dense crop canopy, and the overall working efficiency of the UAV system. In order to systematically identify and comprehensively assess the pesticide application performances and feasibility status of UAVs, particularly in the context of apple orchards, the current research topic was meticulously chosen. This study aims to provide crucial empirical data and insights into the operational parameters of UAVs for precision spraying, thereby contributing significantly to the optimization and broader.

MATERIALS AND METHODS

A field experiment was conducted during the Kharif Season of 2024 at Semi-High Density Apple Orchard, College of Horticulture, Veer Chandra Singh Garhwali Uttarakhand University of Horticulture and Forestry, Bharsar, Pauri Garhwal. The villages are located between 30.06299 N latitude and 78.99230 E longitude, with elevations ranging from 1900 to 2000 meters above mean sea level.

During spraying operations, various meteorological parameters meticulously recorded to understand their influence on spraying quality. These included wind velocity, air temperature, humidity, and rainfall. This data was crucial for mitigating any adverse climatic effects on sprayer performance.

Table 1: Meteorological parameters.

Max. Temperature, °C	24-27
Min. Temperature, °C	15-18
Relative Humidity (%)	65-78
Wind Speed, Km/h	4-12
Rainfall, mm	0

Crop parameters significantly influenced the spraying techniques employed in our field trials. The documentation of key biometric crop parameters, such as the crop type, variety, growth stage, row-to-row spacing, plant-to-plant spacing.

Table 2: Crop Parameters.

Crop	Apple
Crop varieties	Red Chief Gale Gala
Crop height, m	3.6
Row - row spacing, m	3
Plant - plant spacing, m	3
Crop Age, Years	4

To study the machine parameters for spaying through unmanned Aerial Vehicle (UAV) in apple orchard for application rate (l/ha), theoretical field capacity (ha/h), effective field capacity (ha/h), and field efficiency (%). The UAV sprayer is tested at combination of varying heights (2 meters, 3 meters, 4 meters) and different speeds (1 m/s, 3 m/s, 5 m/s.). The nine treatments were set for the conduct of experiment with varying speed and height *viz.* (T_1) speed of 1 m/s & height of 2 m; (T_2) speed of 1 m/s & height of 3 m; (T_3) speed of 1 m/s & height of 4 m; (T_4) speed of 3 m/s & height of 2 m; (T_5) speed of 3 m/s & height of 3 m; (T_6) speed of 3 m/s & height of 4 m; (T_7) speed of 5 m/s & height of 2 m; (T_8) speed of 5 m/s & height of 3 m; (T_9) speed of 5 m/s & height of 4 m.

Application Rate. The application rate was calculated as per the ASABE standard (S386.2, 2018). The mean value of discharge rate, travel speed, and effective spray width were measured, and application rate was calculated with the formula below

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

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. It is rate of field coverage of the implement, based on 100 per cent of time at the rated speed and covering 100 per cent of its rated width. It is calculated by using following formula

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

Where,

TFC = theoretical field capacity, ha/h

W = Spray width, m

S = Forward speed, km/h

Effective field capacity. It is the actual area covered by the system, based on its total time consumed and its width. Effective field capacity was calculated by following formula (Mehta *et al*., 2005).

$$\text{Effective Field Capacity (EFC)} = \frac{A}{T_p + T_1}$$

Where,

EFC = effective field capacity (ha/h)

A = area (ha)

T_p = productive time (h)

T_1 = non-productive time (h)

Field efficiency. Field efficiency is the ratio of effective field capacity and theoretical field capacity expressed in per cent. The field efficiency of the developed orchard spraying system was determined using following formula (Kepner *et al.*, 1978)

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

Where,

FE = Field efficiency, %

EFC = Effective field capacity, ha/h

TFC = Theoretical field capacity, ha/h

RESULTS AND DISCUSSION

To assess the performance of our UAV-based spraying system in an experimental apple orchard, the several key factors were measured. These included the flying speed of the drone, its flight duration, the application rate (liters per hectare), the discharge rate (liters per minute), the area covered (hectares), the field efficiency (%), the effective field capacity (hectares per hour), the theoretical field capacity (hectares per hour), and various weather parameters.

Table 3 presents the recorded values for each of these factors *viz*. application rate (l/ha), theoretical field capacity (ha/h), effective field capacity (ha/h), and field efficiency (%). These critical factors formed the foundation for our comprehensive evaluation and performance of the drone sprayer's in an apple orchard environment.

Table 3: 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 (%)
T1	166.363	0.900	0.807	89.615
T2	128.837	1.152	1.070	92.853
T3	101.625	1.476	1.333	90.325
T4	49.295	3.024	2.655	87.791
T5	37.055	3.888	3.359	86.403
T6	30.843	4.752	4.466	93.988
T7	23.918	5.940	4.832	81.343
T8	19.430	7.740	6.552	84.647
T9	17.389	8.820	7.248	82.182

Application Rate (l/ha). The experiments revealed a clear inverse relationship between drone flight parameters and the application rate. With the nozzle discharge rate maintained at a consistent 2.5 l/min, the application rate varied significantly. The highest application rate observed was 166.36 l/ha when the drone operated at its lowest speed of 1 m/s and a height of 2 m. Conversely, the lowest application rate recorded was 17.389 l/ha at a higher speed of 5 m/s and a greater height of 4 m. This demonstrates that increasing flight speed and flight height directly reduces the application rate (Fig. 1).

This phenomenon is scientifically justifiable. The application rate is determined by the volume of liquid discharged over a given area. At a constant discharge rate, a slower flight speed means the drone spends more time over a smaller area, resulting in a higher volume of liquid deposited per unit area. Conversely, as flight speed increases, the drone covers a larger area in the same amount of time, spreading the same volume of liquid over a wider expanse, thus decreasing the application rate. Similarly, an increase in flight height often leads to a wider spray pattern (swath width) due to droplet dispersion, effectively distributing the same amount of liquid over a larger area, further reducing the application rate. This observation aligns with findings by Gaadhe *et al.* (2025), supporting the fundamental principles of fluid dynamics in aerial application.

Theoretical Field Capacity (ha/h). The theoretical field capacity represents the maximum potential area a UAV could cover per hour, assuming continuous operation without any downtime. This metric is calculated based on the drone's operating speed and its effective spray width (swath). The results showed that the highest theoretical field capacity was 8.80 ha/h when the UAV was operated at its maximum tested speed of 5 m/s and a height of 4 m. In contrast, 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 (swath) observed during the operation varied between 2.5 m and 5 m.

Scientifically, theoretical field capacity is directly proportional to both flight speed and swath width (Fig. 1). As the drone's speed increases, it covers more linear distance in a given time. Simultaneously, increasing the flight height can sometimes lead to a wider spray swath due to greater droplet dispersion, which also contributes to covering a larger area per pass. Therefore, the observed increase in theoretical field capacity with higher speed and wider coverage (achieved at greater heights) is consistent with engineering principles governing sprayer performance.

Effective Field Capacity (ha/h). The effective field capacity provides a more realistic measure of the actual area covered per hour, as it accounts for all non-productive time during the spraying operation. This includes time spent on tank refilling, battery replacement, turning at headlands, and operator-related delays due to skills or decision-making. The effective spray width (swath) covered during different treatments in the study ranged from 2.3 m to 4.5 m. The findings indicate that the effective field capacity varied from 0.807 ha/h to 7.248 ha/h, corresponding to speed variations from 1 m/s to 5 m/s and height variations from 2 m to 4 m.

While theoretical field capacity highlights potential, effective field capacity reflects practical efficiency. The reduction from theoretical to effective capacity is primarily due to inevitable operational downtimes. Factors such as the efficiency of the refilling process, the longevity of the drone's batteries, and the operator's proficiency in minimizing unproductive maneuvers significantly influence this parameter. For instance, frequent battery changes or inefficient turning sequences will reduce the overall effective area covered within an hour, even if the actual spraying speed is high.

Field Efficiency (%). Field efficiency quantifies how effectively the drone's operational time is utilized for actual spraying, expressing the ratio of effective field capacity to theoretical field capacity as a percentage. In study, the field efficiency for drone spraying in the apple orchard ranged from 81.34% to 93.98%. The highest efficiency of 93.98% was achieved with a combination of 5 m/s speed and 2 m height, while the lowest was 81.34% for the treatment combining 3 m/s speed and 4 m height.

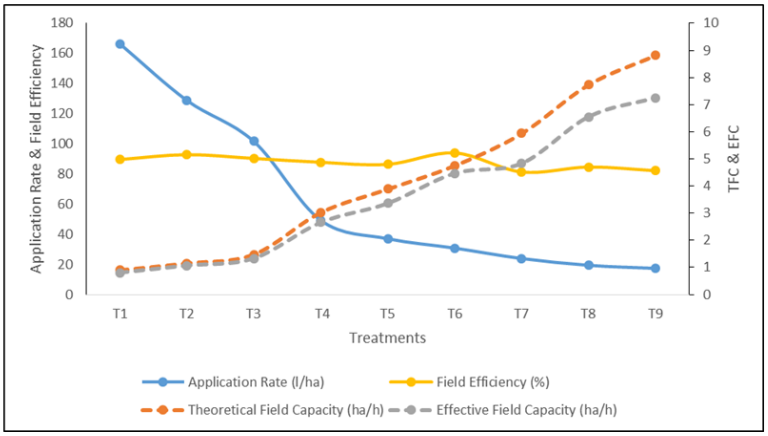

Fig. 1. The graphical representation of application rate (l/ha), theoretical field capacity (ha/h), effective field capacity (ha/h), and field efficiency (%) with respect to treatments.

Field efficiency is a critical indicator of operational productivity. It is significantly influenced by operator skill, as proficient operators can minimize unproductive time (e.g., faster turns, efficient battery swaps). Furthermore, meteorological parameters play a substantial role; for example, strong winds can necessitate adjustments or pauses in spraying, reducing efficiency. Time loss during unproductive work, such as navigating obstacles, adjusting settings, or waiting for optimal conditions, directly diminishes field efficiency. The observed high efficiency values (over 80%) suggest a generally well-managed operation, but the variations highlight the impact of specific flight parameters and operational management on overall productivity.

CONCLUSIONS

The study rigorously investigated the operational parameters of a UAV spraying system in an apple orchard, providing critical insights into its performance metrics. The study conclusively demonstrated a clear inverse relationship between application rate and both flight speed and flight height. Specifically, as flight speed increased from 1 m/s to 5 m/s and height from 2 m to 4 m, the application rate significantly decreased from 166.36 l/ha to 17.389 l/ha. This is scientifically attributable to the constant discharge rate being spread over a larger area at higher speeds and wider swaths at greater heights.

In terms of productivity, the theoretical field capacity exhibited a direct proportionality to both flight speed and swath width, reaching a maximum of 8.80 ha/h at the highest speed and height combination. The effective field capacity, a more realistic measure of performance, ranged from 0.807 ha/h to 7.248 ha/h, highlighting the inevitable impact of non-productive times such as tank refilling, battery changes, and operational maneuvers. Despite these inherent downtimes, the field efficiency of the drone spraying system in the apple orchard remained commendably high, varying between 81.34% and 93.98%. This indicates efficient utilization of operational time, heavily influenced by operator skill and minimal unproductive work. Overall, the findings underscore the significant potential of UAVs for precision agrochemical application in challenging topographies like apple orchards, offering high efficiency and the ability to tailor application rates by adjusting flight parameters.

FUTURE SCOPE

Building upon these foundational insights, future research should focus on several key areas to further optimize UAV spraying in apple orchards: 1). Investigate the optimal combination of flight speed, height, and nozzle discharge rate to achieve precise application rates for different pesticide types (e.g., fungicides, insecticides, herbicides) and varying growth stages of apple trees. This could involve real-time feedback systems for adjusting parameters. 2) While this study focused on application rate, future work should delve into the droplet size spectrum and its impact on canopy penetration and coverage uniformity within the dense apple orchard environment. This would involve advanced droplet analysis techniques to ensure effective deposition on target foliage.3) Implement long-term studies to evaluate the sustained efficacy of drone-applied pesticides on pest control and overall apple tree health and yield over multiple seasons.

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