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Unmanned Aerial Vehicle (UAV) for spraying in field and Orchard Crops

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Abstract
Traditional plant protection methods, burdened by arduous labor, inefficiency, and significant operator exposure, are increasingly inadequate, especially in challenging terrains like mountainous regions. While boom sprayers offered improvements, their limitations in such environments remain. This research explores the transformative potential of Unmanned Aerial Vehicles (UAVs) for precise and efficient pesticide application in field and orchard crops. UAVs offer unparalleled advantages, including independence from specialized infrastructure, remote operation flexibility, rapid response capabilities to agricultural disasters, and significantly reduced human exposure to harmful chemicals.
Despite their promise, ensuring uniform spray coverage and optimal droplet penetration remains a key challenge, particularly in dense canopies. This study meticulously evaluates the performance and feasibility of UAVs for pesticide application, focusing on critical parameters such as spray distribution, droplet analysis, uniformity coefficient, droplet density, working efficiency, and comparative performance against conventional manual and power-operated sprayers. Economic viability is also thoroughly assessed. By providing crucial empirical data and technical guidance, this research aims to optimize UAV operational parameters, promoting safe and effective aerial spraying practices to enhance agricultural productivity and sustainability.
Keywords
Unmanned Aerial Vehicle, Spray Coverage, pesticide application, Spray distribution, droplet analysis working efficiency, uniformity coefficient, droplet density.

1. INTRODUCTION

Agriculture's ability to feed the world relies heavily on plant protection, which means keeping crops healthy to ensure good yields. The machinery used for this is essential. Historically, farmers protected their plants using basic tools or by hand. This was incredibly hard work, often ineffective, and, most concerningly, led to many farmers getting sick from pesticide exposure.
Over time, boom sprayers became common, significantly reducing physical effort and improving spraying efficiency. However, they struggle in hilly or mountainous areas, which form a large portion of global farmland. Their size and limited movement make them impractical in these challenging environments.

The Rise of Agricultural Drones

To overcome these difficulties, agricultural aviation has become a key solution, especially with the development of smaller Unmanned Aerial Vehicles (UAVs), or drones (Qin et al., 2016). Drones have several advantages over traditional agricultural aircraft: they don't need special airports and can be controlled remotely (Faiçal et al., 2014). This adaptability makes them ideal for reaching and treating difficult terrains that ground machines cannot access. Besides their versatility, drones are highly efficient and can quickly respond to agricultural problems like disease outbreaks with minimal risk (Huang et al., 2008). Crucially, drones also reduce human exposure to pesticides and minimize environmental pollution during spraying. These significant benefits have spurred extensive research and efforts to popularize drones for pesticide application (Xue et al., 2014).

The Need for Targeted Application

Effective pest management requires applying pesticides precisely where pests, diseases, or weeds are present. A major criticism of pesticide use is environmental pollution from chemicals drifting beyond target areas. Current spraying methods are often inefficient, leading farmers to spray more frequently and use larger quantities of chemicals, further contaminating soil and the environment. This highlights a critical need for technologies that can deliver agricultural chemicals more precisely and effectively. Pesticide application is a vital part of integrated pest management, a strategy combining various methods to control pests. The success of pest control depends significantly on the correct application technique and equipment effectiveness. In many farming economies, such as India, farmers face a severe shortage of skilled labor and rising wages for spraying. Additionally, traditional ground-based solutions have major limitations; for example, tractor-operated boom sprayers are unsuitable for wet paddy fields, and manual spraying is labor-intensive and inefficient. This underscores an urgent need for drone-mounted sprayers for precise and efficient chemical application in various crops, including paddy and apple orchards.

Human Health Risks and Outdated Practices

Currently, many small-scale farmers primarily use backpack sprayers, which often leak, causing pesticides to soak the operator's skin and clothes. In many developing countries, farm workers spend long hours mixing and spraying pesticides or working in sprayed areas. The lack of washing facilities near farms means workers often wear contaminated clothes all day and perform essential activities like eating and drinking with contaminated hands. The World Health Organization (WHO) estimates over 1 million pesticide poisoning cases globally each year, with more than 100,000 annual deaths, mostly in developing countries, directly linked to human-sprayed pesticides. Pesticides are known to harm the human nervous system and can cause various physiological disorders.

The Push for Modernization in Agriculture

In India, agriculture is a cornerstone of the national economy. However, its productivity and efficiency lag behind Western countries, particularly in adopting advanced technologies. There is an urgent need to embrace modern methods to ensure agricultural profitability and competitiveness. Precise and timely application of crop protection materials is crucial for effective pest management. Fertilizers and chemicals often need to be applied at specific times and locations for accurate, site-specific pest control. While traditional ground sprayers and piloted aerial equipment work well for large-area cropping systems, their efficiency diminishes for smaller plots. Although piloted aircraft can cover vast areas, their widespread prevalence is not universal, necessitating viable alternatives. This is where Unmanned Aerial Vehicles (UAVs) become essential. Smaller fields, in particular, benefit immensely from drones, which have been specifically developed to support precision agriculture.

Despite these advancements, ensuring effective and proper spraying remains a major concern in chemical application, especially with growing global worries about environmental and health risks. Most spraying systems in India, for instance, apply chemicals from the top of the plant canopy. This often results in suboptimal spray penetration into lower crop canopy layers and overall low spraying effectiveness. Traditional manual spraying invariably leads to excessive chemical use and is particularly challenging in dense environments like orchards and paddy fields. This significantly contributes to environmental pollution and uneven application, increasing production costs. Drone-mounted spray tanks, capable of precisely spraying pesticides over crops, directly address these challenges. These drones operate at carefully calibrated heights, facilitating optimal pesticide penetration, thereby enhancing effectiveness by reaching previously inaccessible plant parts, a feat often impossible with manual methods.

Given their proven effectiveness, agricultural drones are rapidly becoming an indispensable tool for modern farmers. In a world with high food demand, agricultural producers must re-evaluate and optimize strategies to boost production and efficiency for farm success and profitability. Accurately identifying areas for improvement requires a detailed evaluation of environmental and agricultural parameters like soil quality, rainfall, temperature, climate change, wind speed, and the presence of weeds and insects (Lee et al., 2021). While chemicals and pesticides are crucial for managing pests and diseases, their judicious use is essential due to diverse crop-specific requirements. It is noteworthy that over 88% of manually operated sprayers in China are knapsack air-pressure or electric sprayers (Yang et al., 2018), highlighting the continued reliance on labor-intensive methods.

Manual pesticide spraying exposes personnel to numerous harmful side effects, from mild skin irritation to severe conditions like birth defects, organ damage, and even death. The WHO estimates about one million annual cases of illness directly attributable to manual pesticide spraying (Shaw K K & Vimal Kumar R, 2020), underscoring the urgent need for safer application methods.

The Path Forward: Precision, Efficiency, and Research Gaps

Consumers and agricultural stakeholders increasingly prefer precision variable spraying systems mounted on UAV-based sprayers over traditional ground vehicles due to their superior speed and precision. Farmers are considering limiting indiscriminate pesticide use and regulating the agricultural environment to preserve land health, especially with drones' high operational speed and targeting capabilities. As researchers, we must introduce innovations that meet farmers' evolving demands (Morley et al., 2017). The use of pesticides by UAVs holds immense promise for precise, targeted chemical application. However, external factors like wind and the UAV's propeller downwash can lead to issues like droplet drift and uneven spray patterns (Laou et al., 2018). UAV variable-rate spraying offers a precise and adaptable strategy to overcome these challenges. Future research should advance variable-rate spraying precision by combining it with detailed cropland mapping to accurately determine site-specific pesticide needs. Despite high quality and precision benefits, strict spraying limits can make uniform field coverage challenging (Hanif et al., 2022). While previous studies focused on working parameters' effect on droplet deposition and biological efficacy, a significant gap remains: a comprehensive report evaluating UAV working efficiency for plant protection, a critically important index. As an emerging technology, UAV spraying still faces practical issues needing thorough investigation, such as droplet distribution uniformity, crucial droplet coverage ratio, pesticide penetrability into dense canopies, and overall system working efficiency. This research meticulously chosen to systematically assess UAV pesticide application performance and feasibility, particularly in fields and orchards.

LITERATURE SURVEY

Recent research on Unmanned Aerial Vehicles (UAVs) for agricultural applications has largely focused on understanding how operating parameters affect spray droplet deposition and biological effectiveness. 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.

Use of Unmanned Aerial Vehicle (UAV) in Agriculture

Early studies laid the groundwork for understanding UAV spraying performance. For instance, Qiu et al. (2013) explored how flight height and velocity influenced the spraying performance of a CD-10 UAV, finding that both factors significantly affected droplet density and uniformity. Gao et al. (2013) demonstrated the effectiveness of a single-rotor electric UAV with a centrifugal nozzle for low-altitude bifenthrin application on wheat midge. Qin et al. (2014) showed that UAV spraying of insecticides on maize canopy improved insecticidal efficacy and persistence compared to hand-lance methods. However, challenges in achieving optimal efficiency were noted. Wang et al. (2017) observed inconsistencies in deposition and liquid coverage and reported a high proportion of total working time spent on ground service (50%), preparation (10%), and route planning (10%), with only 30% for actual operation. This highlighted that the full efficiency potential of UAVs was not yet realized. Yallappa et al. (2017) developed a hex-copter capable of carrying 5.5 L of liquid with a 16-minute endurance, while focused on a cost-effective quadcopter design. Balaji et al. (2018) developed a hexacopter for pesticide spraying and monitoring, predicting 20%-90% savings in water, chemicals, and labor with proper UAV implementation. found that a low operation height (1.2 m) and specific flight speed (3.5 m/s) maximized droplet density and coverage in citrus trees. Desale et al. (2019) presented a cost- and weight-optimized UAV architecture for both spraying and field monitoring using cameras and GPS.

More recent studies continue to refine operational parameters. Parmar et al. (2021) investigated aerial spraying at different speeds (2.0, 3.0, 4.0 m/s) and heights (0.50, 0.75, 1.0 m), finding that both flying height and forward speed significantly affected the bio-efficacy against whitefly and brown plant hopper across three crops. Verma et al. (2021) reported an on-flight field capacity of 3.0-3.3 ha/h for UAV spraying, with actual capacity at 2.0-2.3 ha/h. They observed maximum coverage (2.67-10.67%) and droplet density (14.67-28.33 droplets/cm^2) at the top of the canopy. While knapsack sprayers sometimes showed slightly higher aphid population reduction, the study provided valuable data on droplet size distribution for UAVs. Kumar et al. (2022) found that UAV sprayer droplets, especially with adjuvants, were larger than those without. They observed that a UAV sprayer with adjuvant led to the least Phalaris minor weed density, and UAV sprayer treatments resulted in higher yields compared to knapsack sprayers. Parmar et al. (2022) further detailed that UAV-based sprayers produced significantly smaller droplets (200.34 to 253.01 µm) compared to knapsack sprayers (463.88 to 738.80 µm), leading to higher droplet density and a remarkable reduction in whitefly incidence in green gram. Meng et al. (2022) suggested that systemic chemicals should be used with UAVs due to poor droplet distribution uniformity in cotton canopies, emphasizing the need for optimizing application parameters at different growth stages.

Lopes et al. (2023) highlighted that specific nozzle types (AirMix 11001 air-induction flat fan and COAP 9001 hollow cone) achieved the highest spray deposition on the upper part of soybean crops when using UAVs, even outperforming ground applications on the lower plant parts, indicating superior spray penetration. Their process control charts also showed consistent, high-quality spray patterns. Wang et al. (2023) found that flight height had a more significant effect on droplet deposition than speed and Leaf Area Index (LAI), with higher heights leading to worse overall droplet penetration. They noted that reducing speed from 2.5 m/s to 1.5 m/s could increase coverage by over 70%. Ground loss was about twice as high at 1.5 m/s compared to 2.5 m/s, and drift distance increased significantly with higher operating height and wind speed. This study provided comprehensive data for multi-rotor UAV application in tall trees, emphasizing the need for more plant protection-focused data and further exploration of droplet deposition patterns within specific canopies. Sreenivas et al. (2024, Note: Published in 2024, but included as it directly follows the specified review period's trends) observed uniform droplet deposition and density, along with higher application rates and field capacity with minimal spray drift when a drone-mounted sprayer operated at 1.2 m above the crop canopy. They also found that certain drone-applied pesticide treatments were as effective as recommended doses applied by power sprayers.

Pesticide Application through Unmanned Aerial Vehicle (UAV)

Research has extensively examined the characteristics and effectiveness of pesticide application via UAVs. Lou et al. (2018) studied droplet distribution, drift, control efficiency on cotton aphids and spider mites, and leaf absorption during UAV spraying. They found that a 2 m flight height improved droplet uniformity, coverage, deposition, and drift, achieving 63.7% control on cotton aphids and 61.3% on spider mites, though slightly inferior to boom spraying. Meng et al. (2018) showed that adding aerial spraying adjuvants improved UAV spray efficiency, reducing imidacloprid dosage by 20% without significantly affecting initial residue compared to manual knapsack spraying. Wang et al. (2019) assessed the effect of spray volume on deposition and control efficacy for wheat aphids and powdery mildew using UAVs and electric air-pressure knapsack (EAP) sprayers. They found that optimal control was achieved with coarser nozzles at higher spray volumes for systemic insecticides. The UAV showed comparable deposition and efficacy to EAP at higher spray volumes but was inferior at lower volumes with fine nozzles.

Xiao et al. (2020) found that UAV sprayers had slightly lower control efficacy on Phytophthora capsici and aphids in processing pepper fields compared to EAP sprayers but could reduce pesticide dosage while maintaining control. They emphasized the need for further study on high-concentration pesticide residues. Zeng et al. (2020) investigated UAV application against fall armyworm in sugarcane, recommending a specific insecticide mixture (chlorfenapyr–chlorantraniliprole–lufenuron) for best control (94.94% efficacy).

Droplet Size Analysis of Unmanned Aerial Vehicle (UAV)-Based Spraying

Understanding droplet characteristics is crucial for effective UAV spraying. Zhang et al. (2014) showed that effective swath widths and uniformity of droplet deposition were significantly influenced by wind speed and direction, emphasizing the need for adjustments based on weather conditions. Qin et al. (2016) further investigated how UAV operation height and velocity affected droplet deposition on rice canopies and efficacy against plant hoppers. They found that a spraying height of 1.5 m and velocity of 5 m/s maximized lower-layer droplet deposition and achieved the most uniform distribution (CV = 23%), resulting in high insecticidal efficacy (92%–74% from 3 to 10 days post-spray), which was superior to hand-lance methods. This work provides a basis for optimizing UAV design and application. Wang et al. (2016) found that chlorantraniliprole 18.5% SC applied by UAVs at flight heights of 2-4 m and velocities of 3-4 m/s achieved significantly high control efficacy (over 90%) against rice stem borer.

Laou et al. (2018) reiterated that UAV spraying at 2m height improved droplet distribution, drift, and deposition, achieving significant control against cotton aphids and spider mites. Ferguson et al. (2020) compared various application volume rates and nozzle types, along with different collector types for measuring spray coverage. They found that increasing volume rates significantly increased coverage across nozzle types and that Mylar washed (MW) and water-sensitive paper (WSP) provided higher coverage measurements than other methods. Parmar et al. (2022) further confirmed that UAV-based sprayers produced significantly smaller droplets and higher droplet density compared to knapsack sprayers, leading to a notable reduction in whitefly incidence in green gram. These studies consistently emphasize the critical interplay between UAV operational parameters, environmental conditions, and the resulting droplet characteristics for effective and uniform pesticide application.

METHODOLOGY

The fundamental system and components of the unmanned aerial vehicle. The airframe consisted of the fuselage, landing gear, and arms. The propulsion system included the battery, motors, electronic speed controllers (ESCs), and propellers. The command and control system encompassed the radio-controlled (RC) transmitter and receiver, flight controller unit (FCU), global positioning system (GPS), ground control station (GCS), and radio telemetry as given in figure 1.

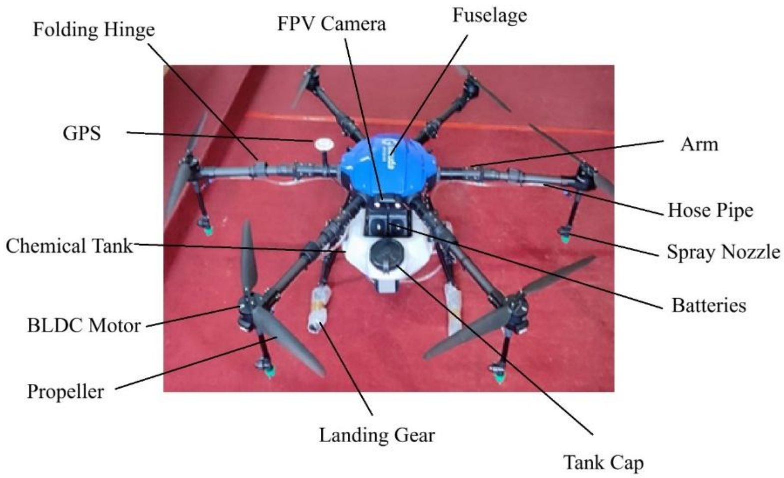

Fig:1 Components of Unmanned Aerial Vehicle

Experimental Sites and Crop Details

Field experiments were conducted at two distinct locations within Pauri Garhwal to evaluate the performance of a drone-mounted spraying system on potato and apple crops. Agricultural fields in Museti and Kaproli villages: These fields are located at 30.0253° N latitude and 79.0116 ∘ E longitude. Instructional farm and semi-high density apple orchard at the College of Horticulture, VCSGUUHF, Bharsar: This site is situated at 30.06299 ∘N latitude and 78.99230 ∘ E longitude. Before initiating spraying operations, comprehensive data on crop and tree parameters were meticulously recorded. This included the crop type, variety, row-to-row spacing, plant-to-plant spacing, and tree height. Throughout the experiments, meteorological conditions such as relative humidity, wind velocity, rainfall, and temperature were consistently monitored to account for their influence on spray application.

Drone Spraying System and Parameters

The UAV sprayer was tested under various combinations of flight parameters to assess their impact on spray characteristics and application efficiency. The following flight parameters were systematically varied: Flight heights: 2 meters, 3 meters, and 4 meters and Flight speeds: 1 m/s, 3 m/s, and 5 m/s

Laboratory and Field Data Collection

Laboratory experiments were conducted for calibration and testing purposes. Droplet analysis was performed using specialized software to accurately measure the number and area of collected droplets. During the field trials, several critical operational parameters were meticulously recorded. These included: Forward speed, Spraying height from the top of the orchard canopy, Time lost during turns, Refilling time,Total spraying time, Labor requirements

Observations were systematically recorded to enable the calculation of key spray and field performance indicators, including: Volume Median Diameter (VMD), Number Median Diameter (NMD), Uniformity Coefficient (UC), Droplet density, Application rate (L/ha), Theoretical field capacity (ha/h), Effective field capacity (ha/h), Field efficiency (%). All calculations, observations, and analyses were performed based on standard procedures established for each specific parameter. Furthermore, a comprehensive cost analysis was conducted, taking into account both fixed and variable costs associated with the drone spraying system.

RESULTS AND DISCUSSION

The investigation of impact of UAV flight parameters on spray characteristics revealed several key findings concerning droplet size, uniformity, density, and overall application efficiency.

Droplet Characteristics: VMD, NMD, and Uniformity

We observed a consistent trend across Volume Median Diameter (VMD) and Number Median Diameter (NMD): as both flight height and flight speed increased, droplet sizes also increased. This outcome is particularly beneficial for drift reduction. Larger droplets, due to their greater mass, are less susceptible to environmental wind drift, enhancing their likelihood of accurately depositing within the target area. Conversely, smaller droplets are more prone to drifting away from the intended zone, leading to off-target contamination and reduced efficacy.

Furthermore, our analysis of the Uniformity Coefficient (UC) showed that an increase in both flight height and flight speed tended to improve the uniformity of the spray. This suggests that while larger droplets are produced at higher speeds and heights, their distribution across the spray pattern remains relatively consistent.

Droplet Density and Application Rate

In contrast to droplet size, droplet density decreased with increased flight height and flight speed. This phenomenon occurs because the spray disperses over a larger area more quickly, reducing the amount of spray per unit area. Additionally, the increased propensity of smaller droplets to drift means that only a fraction of the larger, more effective droplets ultimately reach the plant canopy, further contributing to reduced density.

The application rate, defined as the volume of liquid discharged over a given area, is critically influenced by flight parameters. At a constant discharge rate, slower flight speeds result in higher application rates because the drone spends more time over a smaller area, depositing a greater volume of liquid per unit area. Conversely, increasing flight speed covers a larger area in the same amount of time, spreading the same volume of liquid over a wider expanse, thereby 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 and 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.

Field Capacity and Operational Efficiency

Our analysis of theoretical field capacity confirmed its direct proportionality to both flight speed and swath width. 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.

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 serves as 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.

CONCLUSION

Our findings demonstrate that UAV flight parameters significantly influence Volume Median Diameter (VMD), Number Median Diameter (NMD), Uniformity Coefficient (UC), and droplet density. Increasing flight height and speed generally leads to larger VMD and NMD, which is beneficial for reducing spray drift. However, this also results in reduced droplet density. Conversely, lower flight heights and speeds yield higher droplet densities, which is crucial for achieving effective coverage. Therefore, optimizing UAV spraying requires a careful balance of these interdependent factors to achieve efficient deposition, uniform coverage, and minimal drift while maximizing effective field capacity and operational efficiency.

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