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### Precision UAV Spraying: Impacts of differential application rates on cotton yield

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#### Abstract

Unmanned Aerial Vehicles (UAVs) offer a promising alternative to conventional ground-based crop management by reducing mechanical damage, soil compaction and inefficiencies in spray application. This study assessed the performance of UAV-based spraying in cotton cultivation compared to traditional hand sprayers, with emphasis on optimizing spray volumes across different crop growth stages. Since cotton crop density increases progressively, constant spray volumes can lead to wastage; therefore, three nutrient application rates (18, 25, and 30 L/ha) and three herbicide application rates (25, 37, and 50 L/ha) were evaluated. Crop growth parameters (plant height and leaf area) and remote sensing indices (NDVI and LAI) were monitored from spraying to harvest, while spray deposition was quantified using Water Sensitive Papers (WSP). The highest yield (205.2 kg) was recorded with 50 L/ha herbicide and 30 L/ha nutrient application. Remote sensing data and growth parameters indicated uniform crop health up to 40 days after sowing (DAS). Beyond this stage, 25 L/ha nutrient application was optimal until 80 DAS, while 30 L/ha was most effective from 80 to 150 DAS due to increased crop density. Overall, the findings demonstrate that UAV spraying enhances yield and efficiency by tailoring application volumes to crop growth stages, with effective post-emergent weed control being critical to maximizing cotton productivity.

**Keywords:** Unmanned aerial vehicles, NDVI, cotton, application rate, spray deposition, remote sensing

#### 1. Introduction

Unmanned Aerial Vehicles (UAVs) are increasingly recognized as a transformative technology in precision agriculture, offering solutions to long-standing challenges in crop management. Conventional ground-based spraying methods often lead to mechanical damage, soil compaction, and uneven spray distribution, which negatively affect crop yield and resource efficiency. UAV spraying systems, by contrast, provide flexibility, reduced labour requirements, and enhanced precision in chemical application, making them particularly relevant for cotton cultivation, a crop that demands careful management across diverse growth stages. Cotton is a major fibre crop globally, and in India it occupies a significant share of cultivated land. Effective crop protection and nutrient management are critical to sustaining productivity. However, traditional spraying methods are labour-intensive and inefficient. UAV spraying technology allows for variable application rates tailored to crop density and growth stage, thereby minimizing wastage and improving input-use efficiency. As noted by Ingle *et al.* (2024) <sup>[1]</sup>, UAV sprayers in cotton fields demonstrated effective insecticide application when optimized for flight height and speed, reducing both labour costs and chemical exposure risks.

The importance of differential application rates lies in the

dynamic nature of cotton crop density. During early growth stages, lower spray volumes may suffice, while higher volumes are necessary as canopy density increases to ensure adequate coverage. Sambaiah *et al.* (2023) <sup>[3]</sup> emphasized that UAV spraying in cotton for leafhopper management reduced pesticide consumption while maintaining bio-efficacy, highlighting the potential of UAVs to adapt spray volumes to pest pressure and crop growth. Similarly, Liu *et al.* (2024) <sup>[2]</sup> demonstrated that UAV low-volume spraying technology reduced pesticide use while boosting control efficacy in cotton flowering stages frontiers.

Integration of UAV spraying with remote sensing technologies such as Normalized Difference Vegetation Index (NDVI) and Leaf Area Index (LAI) further enhances precision. These indices provide real-time insights into crop health, enabling researchers and farmers to monitor responses to different application rates. Spray deposition studies using Water Sensitive Papers (WSP) have also validated UAV spraying efficiency, ensuring that droplet distribution is uniform across varying canopy structures.

In cotton cultivation, effective weed control during the post-emergent stage is particularly critical. UAV spraying has shown promise in delivering herbicides efficiently, reducing weed competition, and ultimately improving yield outcomes. Thus, UAV-based spraying represents a

significant advancement in precision agriculture, capable of enhancing productivity while reducing environmental impact.

This study builds upon existing literature by experimentally evaluating UAV spraying in cotton at different nutrient and herbicide application rates. By integrating crop growth parameters, remote sensing indices, and yield data, the research aims to establish stage-specific optimal spray volumes that maximize efficiency and productivity in cotton production.

## 2. Materials and Methods

### 2.1 Experimental Site and Crop Details

The field experiment was conducted at JFarm Research Centre, Dindigul, Tamil Nadu, India, during the Rabi season (October–March 2024). The experimental crop was BT Hybrid Cotton (Var: US 7067). The soil type of the experimental site was typical red loam, representative of the cotton-growing belt in southern India. Each treatment plot measured 0.3 acre, arranged in a randomized block design with four treatments (Fig 1).

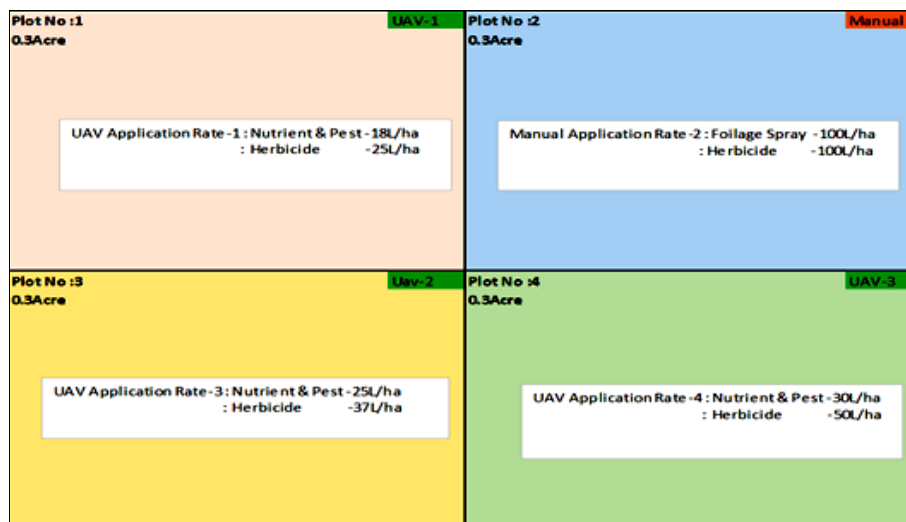


Fig 1: Experimental Layout

### 2.2 Treatments

#### 2.2.1 Four treatments were imposed

1. **T<sub>1</sub>, T<sub>3</sub>, T<sub>4</sub> (UAV spraying):** Nutrient and pesticide sprays at 18, 25, and 30 L/ha, respectively, combined with herbicide sprays at 25, 37, and 50 L/ha.
2. **T<sub>2</sub> (Control):** Manual spraying using a knapsack sprayer at 500 L/ha for nutrients, pesticides, and herbicides.

This design allowed comparison between UAV low-volume spraying and conventional high-volume manual spraying, consistent with methodologies reported by Ingle *et al.* (2024) <sup>[1]</sup> in UAV sprayer performance evaluation on cotton.

#### 2.2.2 Chemicals and Nutrient Application

- **Herbicides:** Pre-emergence application of Pendimethalin (30% EC) @ 400 ml/acre, followed by

post-emergence application of Pyrethrin sodium @ 25 g/acre + Quizalofop ethyl @ 20 g/acre.

- **Nutrients:** Foliar spray of 50% of recommended N and K<sub>2</sub>O as top dressing.
- **Fungicides and pesticides:** Applied as per Tamil Nadu Agricultural University (TNAU) recommendations (TNAU Crop Protection Guide, 2023) <sup>[4]</sup>.

### 2.3 UAV Spraying Protocol

Spraying was performed using a multi-rotor UAV equipped with precision nozzles (Fig 2) (Table 1). Flight parameters (altitude, speed, swath width) were optimized through iterative trials to match the required spray volumes. Similar iterative calibration of UAV flight parameters has been reported by Liu *et al.* (2024) <sup>[2]</sup>, who emphasized the importance of adjusting UAV spraying protocols to canopy density and crop stage.



Fig 2: EFT X6 Plus

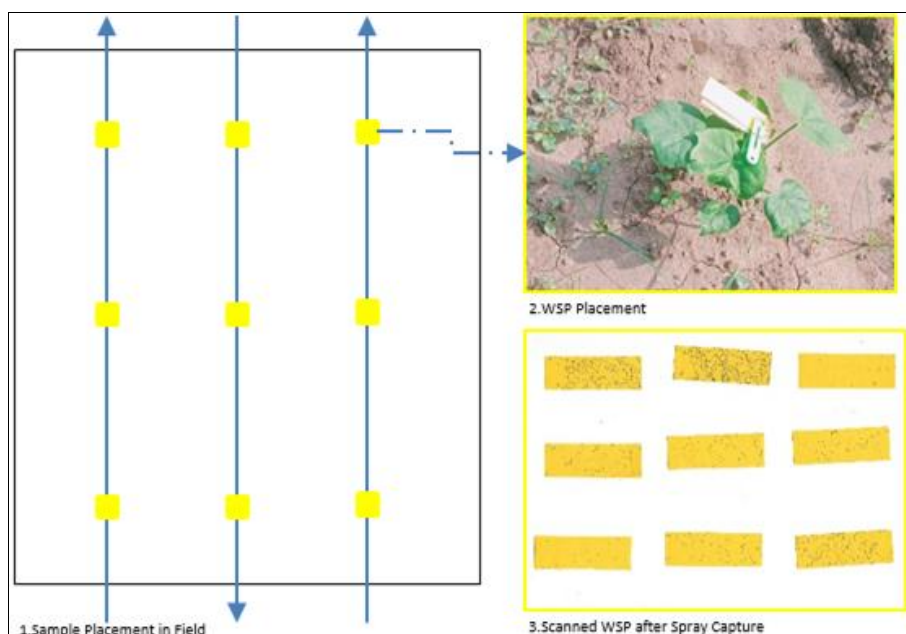
**Table 1:** UAV specifications

| Classification            | Parameters              |
|---------------------------|-------------------------|
| Motor                     | X6 Plus                 |
| Propeller                 | 24inch                  |
| ESC                       | 80A FOC                 |
| Supply voltage            | 12S                     |
| Wheelbase                 | 1407mm                  |
| Opening size              | 2007*2007*542mm         |
| Folding size              | 945*848*542mm           |
| MTOW                      | 28kg                    |
| Tank Capacity             | 10L                     |
| Working efficiency (ha/h) | 6                       |
| Terrain accuracy (m)      | 0.5                     |
| Operation method          | Autonomous mission      |
| Spraying system           | Flat fan Nozzle - 150µm |
| Number of nozzles         | 4                       |
| Spraying width (m)        | 5.5m                    |

## 2.4 Spray Deposition Measurement

Spray deposition was quantified using Water Sensitive Papers (WSP, 25 × 75 mm) placed at representative canopy positions (top, middle, and bottom leaves) (Fig 3). WSPs

served as artificial collectors to assess droplet density and coverage, following the methodology of Sambaiah *et al.* (2023) <sup>[3]</sup>, who standardized UAV spray deposition in cotton using WSP analysis.

**Fig 2:** WSP Sample card placement

## 2.5 Crop Growth and Remote Sensing Data

Physical crop parameters such as plant height and leaf area were recorded at regular intervals. Remote sensing indices including Normalized Difference Vegetation Index (NDVI) and Leaf Area Index (LAI) were monitored from spraying to harvest using handheld sensors. These indices provided insights into crop health and treatment response, as recommended by Liu *et al.* (2024) <sup>[2]</sup> in UAV-based cotton crop monitoring.

## 2.6 Data Analysis

Yield data were collected at harvest, and treatment means were compared using analysis of variance (ANOVA). Spray deposition data from WSPs were quantified using droplet density and coverage metrics. Remote sensing indices were analyzed to identify stage-specific optimal spray volumes.

## 3. Results and Discussion

### 3.1 Yield Performance

The experimental results revealed significant differences in cotton yield across treatments (Fig 4). The highest yield (205.2 kg) was recorded under the UAV treatment with herbicide application at 50 L/ha and nutrient application at 30 L/ha, while lower yields were observed at reduced spray volumes. This finding aligns with the observations of Ingle *et al.* (2024) <sup>[1]</sup>, who reported that UAV spraying at optimized volumes improved cotton yield compared to conventional methods due to better canopy coverage and reduced wastage. Similarly, Sambaiah *et al.* (2023) <sup>[3]</sup> demonstrated that UAV spraying enhanced bio-efficacy of insecticides in cotton, leading to improved crop performance.

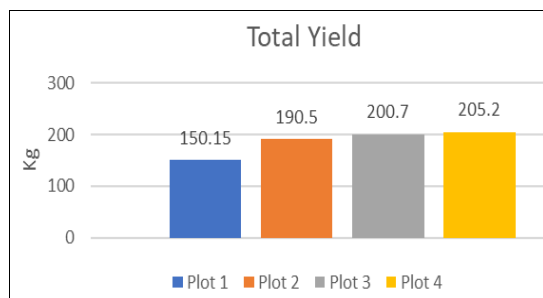


**Fig 4:** Effect of Differential UAV Spray Volumes on Cotton Yield

### 3.2 Crop Growth Parameters (Height and Leaf Area)

Plant height and leaf area showed uniform growth across treatments up to 40 DAS (days after sowing). Beyond this stage, differences became evident, with 25 L/ha nutrient application supporting optimal growth until 80 DAS, while 30 L/ha nutrient application was superior from 80–150 DAS due to increased crop density. These results corroborate the findings of Liu *et al.* (2024) <sup>[2]</sup>, who emphasized that UAV spraying efficiency is closely linked to canopy development, and adjusting spray volumes to growth stages ensures better nutrient uptake and plant vigour.

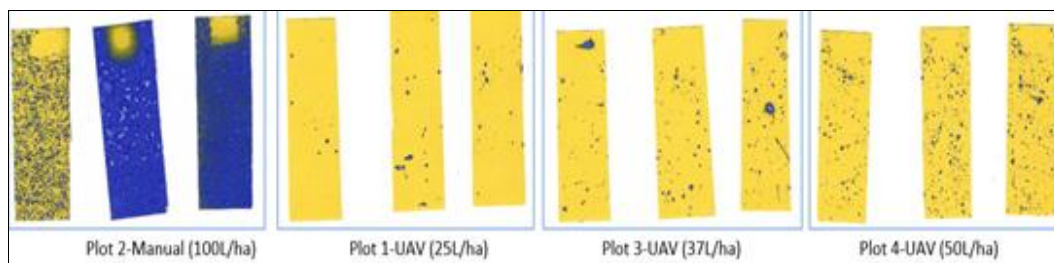


**Fig 5:** WSP Herbicide spray deposition

### 3.5 Weed Control Efficiency

Post-emergent weed control was most effective under UAV spraying at 50 L/ha herbicide application, which significantly reduced weed competition and contributed to higher yield. This supports the findings of Liu *et al.* (2024) <sup>[2]</sup>, who demonstrated that UAV spraying of herbicides enhances weed suppression by ensuring precise droplet placement and minimizing drift losses.

## 4. Conclusion

The study confirms that UAV spraying technology, when applied at differential application rates tailored to crop growth stages, enhances cotton yield, improves spray deposition, and optimizes nutrient and herbicide use efficiency. Remote sensing indices (NDVI, LAI) validated crop health improvements under UAV treatments, while WSP analysis confirmed superior deposition compared to manual spraying. These results highlight UAV spraying as a sustainable and efficient alternative to conventional methods, particularly in cotton production systems where canopy density changes dynamically.

## 5. Acknowledgement

The authors sincerely thank JFarm Research Centre, Dindigul, Tamil Nadu, for providing the experimental field facilities and support during the Rabi 2024 season. We gratefully acknowledge the guidance and cooperation of the

### 3.3 Remote Sensing Indices (NDVI and LAI)

NDVI and LAI values indicated uniform crop health across all plots until 40 DAS, after which UAV treatments with stage-specific nutrient volumes showed higher indices compared to manual spraying. The UAV treatment at 30 L/ha nutrient application maintained higher NDVI and LAI values during peak vegetative growth, suggesting improved photosynthetic activity and canopy development. These findings are consistent with the work of Zhang *et al.* (2022) <sup>[5]</sup>, who reported that UAV spraying combined with remote sensing indices provides accurate monitoring of crop health and supports precision input management.

### 3.4 Spray Deposition (WSP Analysis)

Spray deposition analysis using Water Sensitive Papers (WSP) revealed that UAV spraying achieved uniform droplet distribution across canopy layers, particularly at 25–30 L/ha nutrient application and 37–50 L/ha herbicide application (Fig 5). Manual spraying at 500 L/ha resulted in excessive deposition and runoff, highlighting inefficiency in resource use. Sambaiah *et al.* (2023) <sup>[3]</sup> similarly reported that UAV spraying produced consistent droplet deposition patterns, which improved pest control efficacy while reducing chemical usage.

in-charges and team leaders, whose supervision ensured smooth execution of the trial. Special appreciation is extended to the UAV spray teams and technical support staff for their dedicated assistance in spray calibration, deposition studies, and data collection. Their commitment and expertise were invaluable in completing this research successfully.

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