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UAV-based precision agriculture: Optimization of payload parameters for foliar application in paddy cultivation

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Abstract

Unmanned Aerial Vehicles (UAVs) are revolutionizing precision agriculture by offering significant benefits, including reduced labour requirements, minimized crop damage, and enhanced application uniformity. This study focuses on optimizing UAV payload parameters for variable rate foliar application in paddy cultivation, addressing the critical need for precise agrochemical distribution in rice farming. A field trial was conducted during 2023-2024 at Farmer field, Kancheepuram, Tamil Nadu, India. The experiment involved four treatments: T1 (10 L/acre), T2 (8 L/acre), T3 (7 L/acre), and T4 (6 L/acre), with the development of a mathematical model using MATLAB, which was further validated under real-time field conditions. This ensured the practical feasibility of the optimized spraying parameters and established the relationship between Pulse Width Modulation (PWM) settings and flow rates. The study evaluated payload dispensing accuracy across varying field sizes, revealing that T2 achieved the highest accuracy of 98.08% over 0.13 acre, followed closely by T4 with 98.04% over 0.17 acre. Conversely, T3 displayed the lowest accuracy at 93.20% over 0.21 acre. The overall dispensing accuracy surpassed 95%, demonstrating exceptional precision in spray deposition and droplet distribution. Additionally, flight mission accuracy remained consistently high, with minimal deviations from planned paths, as confirmed by 3D flight path visualizations. These findings underscore the variability in performance based on application rates and field sizes, offering critical insights into UAV-based agrochemical applications. This research contributes valuable knowledge toward improving the precision, efficiency, and resource utilization in paddy cultivation.

Keywords: UAV, precision agriculture, payload optimization, spray deposition, PWM

Introduction

The integration of Unmanned Aerial Vehicles (UAVs) into precision agriculture has revolutionized farming practices, offering innovative solutions to enhance efficiency, sustainability, and productivity. As a staple crop for over half the global population, rice demands precise management of water, fertilizers, and pesticides to ensure optimal yields (Zhang *et al.*, 2020) [8]. Traditional agrochemical application methods, such as manual spraying and tractor-mounted systems, are labour-intensive, prone to inefficiencies, and often result in uneven distribution, leading to over-application or under-application of chemicals (Lan *et al.*, 2017) [5]. These limitations compromise crop health, increase environmental impact, and reduce resource efficiency. UAVs, equipped with advanced technologies, provide a sophisticated alternative by enabling precise, targeted delivery of agrochemicals, minimizing waste, and mitigating environmental harm (Huang *et al.*, 2019) [2]. Their ability to perform variable rate application (VRA), which adjusts agrochemical quantities based on localized field conditions, exemplifies their utility in precision farming (Mulla, 2013) [6]. Moreover, UAVs excel in challenging terrains, such as waterlogged rice paddies, where conventional machinery struggles to operate efficiently (Wang *et al.*, 2019) [7].

Despite their advantages, the adoption of UAVs for foliar spraying in rice cultivation is accompanied by several technical and operational challenges. Payload optimization, including determining spray volume, droplet size, and distribution, is critical for effective agrochemical application. Current practices often rely on trial-and-error methods, which are time-consuming and resource-intensive (Lan *et al.*, 2017) [5]. Similarly, the calibration of flight parameters, such as altitude, speed, and Pulse Width Modulation (PWM) settings, plays a crucial role in achieving uniform spray deposition. Improper calibration can lead to uneven agrochemical application and reduced effectiveness (Huang *et al.*, 2019) [2]. Environmental factors, including wind speed, temperature, and humidity, further complicate the precision of UAV spraying systems, as these variables significantly influence spray deposition patterns but are often not adequately accounted for (Chen *et al*., 2020) [1]. Additionally, UAVs face inherent limitations in battery life and payload capacity, posing challenges in balancing operational efficiency with spraying accuracy (Zhang *et al*., 2018) [10].

Recognizing these challenges, this study proposes a systematic framework for optimizing UAV payload parameters tailored to foliar applications in paddy cultivation. The research focuses on developing mathematical models to optimize UAV spray parameters for diverse application scenarios, ranging from varying field sizes to specific agrochemical application rates. Establishing quantifiable relationships between PWM settings, flow rates, and spray deposition patterns facilitates a data-driven approach to enhance spraying accuracy. Optimal flight parameters, including altitude, speed, and spacing, are identified to ensure uniform and efficient agrochemical distribution across the field. Comparative analysis of UAV-based agrochemical application with conventional methods highlights the efficiency and accuracy improvements offered by UAV technology. Furthermore, this research emphasizes the importance of providing standardized guidelines for UAV mission planning in precision agriculture, minimizing reliance on field-based trial-and-error approaches.

Materials and Methods

The research was carried out within a modified hydroponic setup encompassing a total experimental area of 3290.5 m², which was systematically divided into four distinct treatment plots (Fig 1). The rice variety JR 22, commonly used in India, was selected for the study.

T1: Covering 710 m² with an application rate of 10 litres per acre.

T2: Spanning 875.4 m² and utilizing 8 litres per acre.

T3: Occupying an area of 901.1 m² with 7 litres per acre.

T4: Encompassing 804 m² with an application rate of 6 litres per acre.

Fig 1: Field Treatments Plots

UAV Specifications

The EFT X6 Plus UAV was used, with the following specifications (Fig 2 & 3).

- **Payload Capacity:** 10L
- **Battery:** 22Ah LiPo
- **Flight Controller:** Pixhawk
- **Spray System:** Automated PWM control
- **Nozzles:** 4 adjustable nozzles (Flat Fan nozzles)
- **Maximum Flow Rate:** 5L/min

Fig 2: UAV 10 Payload Capacity

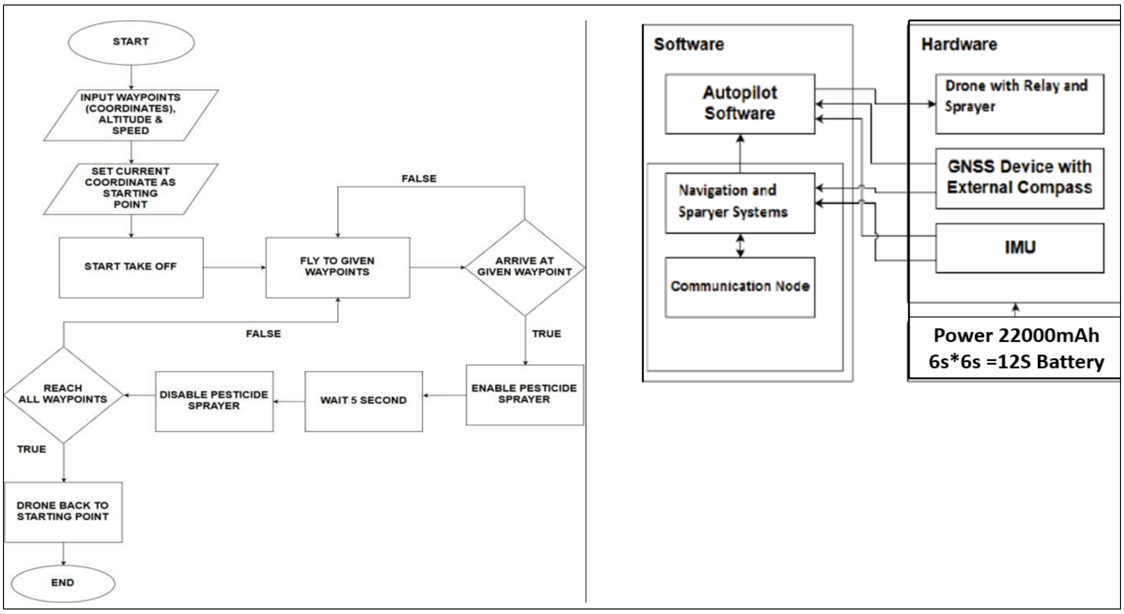


Fig 3: UAV Spraying Flowchart

Mathematical Modelling

The spray fluid requirement for each treatment was calculated using the formula:

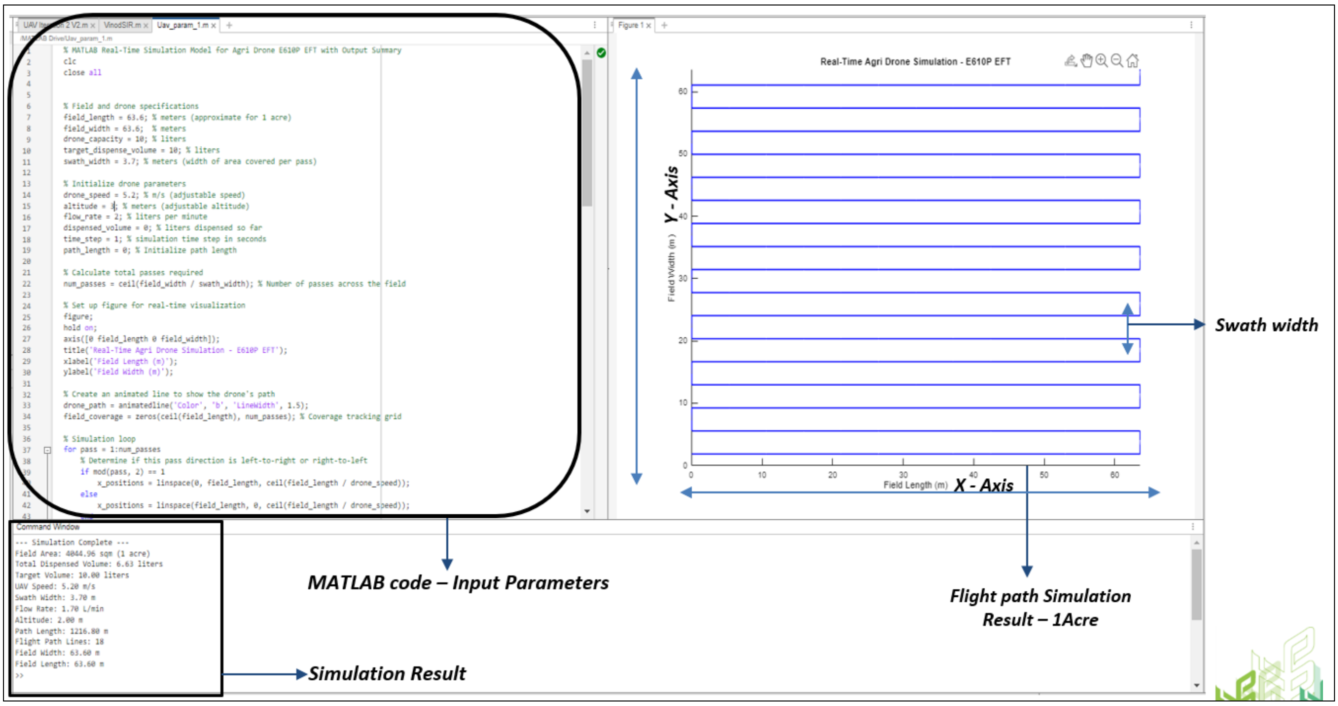
$$\text{Spray Rate} = \frac{\text{Target Volume (L)}}{4047\ \text{m}^2} \times \text{Field Area}\ (\text{m}^2)$$

This formula is derived from the principles of variable rate application (VRA) as discussed by Mulla (2013) [6], who emphasized the importance of spatial data collection and processing for precise agrochemical application.

MATLAB Simulation and Workflow

A MATLAB-based simulation model was developed to predict UAV flight parameters and spray deposition. The simulation incorporated (Fig 4).

1. **Field Boundary Mapping:** The field boundaries were mapped using GPS coordinates, and the area was divided into treatment plots.
2. **Flight Path Generation:** Zigzag flight paths were generated to ensure complete coverage of the field, following the methodology proposed by Lan and Chen (2018) [4].
3. **Flow Rate Calculation:** The flow rate was calculated based on PWM settings and field area.
4. **Spray Deposition Prediction:** The simulation predicted spray deposition based on flight altitude, speed, and nozzle configuration, as validated by Wang *et al.* (2019) [7].
5. **Battery Consumption Estimation:** The simulation estimated battery consumption based on flight duration and payload weight.



```
% MATLAB Real-Time Simulation Model for Agri Drone E610P EFT with Output Summary
clc
close all


% Field and drone specifications
field_length = 63.6; % meters (approximate for 1 acre)
field_width = 63.6;  % meters
drone_capacity = 10; % liters
target_dispense_volume = 10; % liters
swath_width = 3.7; % meters (width of area covered per pass)

% Initialize drone parameters
drone_speed = 5.2; % m/s (adjustable speed)
altitude = 3; % meters (adjustable altitude)
flow_rate = 2; % liters per minute
dispensed_volume = 0; % liters dispensed so far
time_step = 1; % simulation time step in seconds
path_length = 0; % Initialize path length

% Calculate total passes required
num_passes = ceil(field_width / swath_width); % Number of passes across the field

% Set up figure for real-time visualization
figure;
hold on;
axis([0 field_length 0 field_width]);
title('Real-Time Agri Drone Simulation - E610P EFT');
xlabel('Field Length (m)');
ylabel('Field Width (m)');

% Create an animated line to show the drone's path
drone_path = animatedline('Color', 'b', 'LineWidth', 1.5);
field_coverage = zeros(ceil(field_length), num_passes); % Coverage tracking grid

% Simulation loop
for pass = 1:num_passes
    % Determine if this pass direction is left-to-right or right-to-left
    if mod(pass, 2) == 1
        x_positions = linspace(0, field_length, ceil(field_length / drone_speed));
    else
        x_positions = linspace(field_length, 0, ceil(field_length / drone_speed));
```

```
--- Simulation Complete ---
Field Area: 4044.96 sqm (1 acre)
Total Dispensed Volume: 6.63 liters
Target Volume: 10.00 liters
UAV Speed: 5.20 m/s
Swath Width: 3.70 m
Flow Rate: 1.70 L/min
Altitude: 2.00 m
Path Length: 1216.80 m
Flight Path Lines: 18
Field Width: 63.60 m
Field Length: 63.60 m
>>
```

Fig 4: MATLAB Simulation UAV Flight Parameters

Simulation Output

The simulation provided the following outputs:

- **Flight Path Visualization:** 3D visualization of the UAV flight path.
- **Spray Deposition Map:** Spatial distribution of spray deposition across the field.
- **Battery Consumption:** Estimated battery usage for each mission.
- Flow rate calculation based on PWM settings

Data Collection

Flight paths were recorded using the UAV's onboard GPS system. Spray deposition was analysed based on:

- **Spray Deposition Rate (L/m²):** The amount of spray deposited per unit area.
- **Droplet Count (×10⁶ per unit area):** The number of droplets deposited per unit area.
- **Uniformity of Spray Distribution:** The consistency of spray deposition across the field.

Results

Spray Parameter Optimization

The MATLAB simulation results for spray parameter optimization demonstrated a significant correlation between the target spray volume, spray deposition rate, and droplet count (Table 1). At a target volume of 10 litres, the spray deposition rate was 0.0823 L/m², accompanied by a droplet count of 12.7 × 10^6 per unit area. When the target volume was reduced to 8 litres, the deposition rate decreased to 0.0678 L/m², with a corresponding droplet count of 10.17 × 10^6 per unit area. Similarly, a target volume of 7 litres resulted in a deposition rate of 0.0619 L/m² and a droplet count of 8.93 × 10^6 per unit area, while the lowest target volume of 6 litres yielded a deposition rate of 0.0562 L/m² and a droplet count of 7.87 × 10^6 per unit area. These findings align with prior studies emphasizing the importance of optimizing spray parameters to achieve uniform deposition and effective agrochemical application (Lan *et al.*, 2017; Huang *et al.*, 2019) [5, 2]. Moreover, the results corroborate research highlighting the influence of target volume on droplet density and deposition uniformity, which are critical for precision agriculture (Zhang *et al*., 2021; Chen *et al*., 2020) [9, 1].

Table 1: MATLAB Spray Deposition result

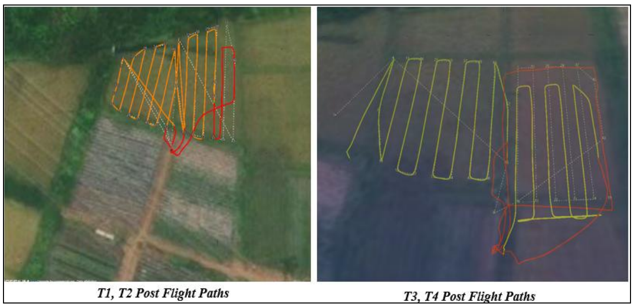
Target Volume (L)	Spray Deposition (L/m²)	Droplet Count (×10⁶)
10	0.0823	12.7
8	0.0678	10.17
7	0.0619	8.93
6	0.0562	7.87

PWM and Flow Rate Relationship

The analysis revealed a direct linear correlation between Pulse Width Modulation (PWM) settings and flow rates, highlighting the UAV's precision in spray application. Flow rates increased proportionally with PWM settings, ranging from 1.5 L/min at a PWM setting of 35% to 2.6 L/min at 55%. This linear relationship demonstrates the potential for precise control over agrochemical application rates, aligning with findings from Lan *et al*. (2017) [5], which emphasize the importance of flow rate calibration in UAV systems for optimized spray deposition.

Flight Mission Accuracy

Post-flight analysis demonstrated high accuracy in UAV adherence to planned flight paths, with only minimal deviations observed during operations (Fig 5). The 3D visualization of flight paths confirmed the UAV's ability to maintain consistent and precise flight patterns across all treatment areas. These results are consistent with the findings of Wang *et al*. (2019) [7], who validated the capability of UAVs in ensuring uniform coverage and efficient spraying patterns in agricultural applications.



T1, T2 Post Flight Paths *T3, T4 Post Flight Paths*

Fig 5: Post Flight Paths

Payload Accuracy Evaluation

The analysis of payload accuracy across different treatment scenarios demonstrated high levels of precision in agrochemical dispensing (Fig 6). Treatment T1, which targeted a volume of 10 L/acre for a field area of 0.13 acres, achieved an actual dispensed volume of 1.26 litres with an accuracy of 97%. Similarly, Treatment T2 with a target of 8 L/acre for 0.13 acres showed outstanding accuracy, dispensing 1.02 litres and achieving 98%. Treatment T3, targeting 7 L/acre for a larger field area of 0.21 acres, resulted in a dispensed volume of 1.37 litres with an accuracy of 93%. Finally, Treatment T4, targeting 6 L/acre for a field area of 0.17 acres, maintained a high level of precision by dispensing 1 litre with an accuracy of 98%. These findings confirm the reliability of UAV systems in meeting prescribed spray volumes, supporting the optimization of payload parameters as outlined by Lan *et al.* (2017) [5] and Huang *et al.* (2019) [2]. Furthermore, the results align with existing research emphasizing the role of calibration in enhancing UAV accuracy for precision agricultural applications (Chen *et al.*, 2020; Zhang *et al.*, 2021) [1, 9].

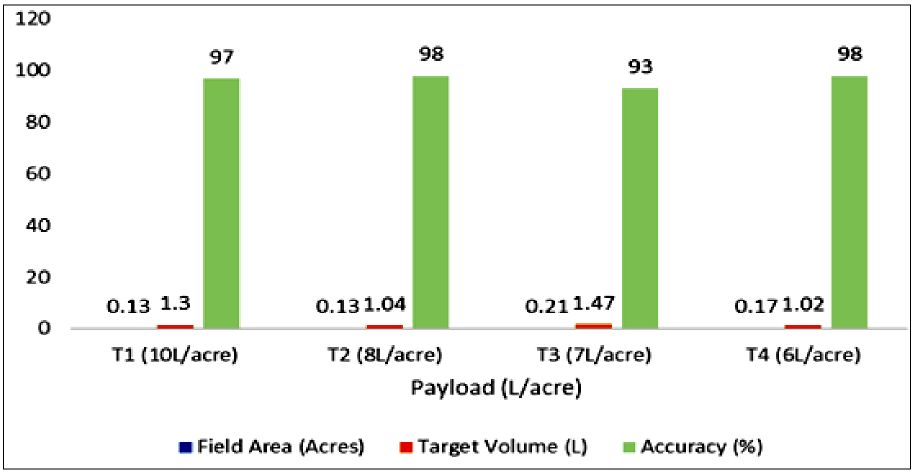


Fig 6: Accuracy of UAV payload optimization

Treatment Specific Outcomes of UAV Operations

The UAV operational parameters were analysed for four different treatment plots, highlighting variations in altitude, speed, PWM settings, flow rate, and flight time. Treatment T1, covering an area of 0.13 acres, utilized an altitude of 2.5 meters and a PWM setting of 55%, resulting in a flow rate of 2.6 L/min and a flight time of 1 minute. In Treatment T2, for the same field area (0.13 acres) but with a lower altitude of 1.5 meters and a PWM setting of 45%, the UAV achieved a flow rate of 2.1 L/min with a flight duration of 1.12 minutes. Treatment T3, targeting a larger area of 0.21 acres, was conducted at an altitude of 1.5 meters with a PWM setting of 40%, yielding a flow rate of 1.9 L/min and requiring 2.17 minutes of flight time. Finally, Treatment T4, covering 0.17 acres, also utilized an altitude of 1.5 meters, but with the lowest PWM setting of 35%, achieved a flow rate of 1.5 L/min and a flight time of 1.15 minutes. These findings underscore the significance of PWM calibration and altitude in optimizing flow rates and operational efficiency. The consistency of spacing at 3.6 meters across treatments ensured uniform coverage, aligning with the methodologies outlined by Lan and Chen (2018) [4] for efficient flight path generation. Additionally, the results validate the efficacy of UAVs in maintaining precise agrochemical application as supported by Wang *et al.* (2019) [7] and Huang *et al.* (2019) [2], emphasizing their role in achieving resource-efficient operations in precision agriculture.

UAV Flight parameters Correlation Heatmap

The correlation analysis of UAV spray parameters provided key insights into the interdependence of variables influencing the efficiency and accuracy of spray applications (Table 4). A strong positive correlation was observed between PWM settings and flow rate (r = 0.98), as well as between PWM settings and spray deposition (r = 0.95). This highlights the critical role of PWM calibration in ensuring optimal flow rates and achieving uniform spray deposition, consistent with findings by Lan *et al.* (2017) [5]. Similarly, flow rate showed a high correlation with spray deposition (r = 0.97), emphasizing its importance in achieving effective coverage.

A moderate positive correlation was observed between path length and flight time (r = 0.89), indicating that extended flight durations are associated with larger field areas or more complex flight paths. However, negative correlations were noted between speed and path length (r = -0.21) and between swath width and path length (r = -0.67), suggesting that higher speeds and wider swath settings might reduce the precision of flight path coverage. These findings align with the results of Wang *et al*. (2019) [7], who reported the trade-off between speed and accuracy in UAV operations.

Lastly, accuracy demonstrated strong positive correlations with PWM settings (r = 0.82) and spray deposition (r = 0.85), underscoring the impact of these parameters on the UAV's ability to achieve consistent and precise agrochemical applications. The relatively weaker correlation of accuracy with flight time (r = 0.32) and path length (r = 0.29) indicates that these factors contribute less significantly to overall accuracy compared to flow rate and spray deposition patterns. These insights provide a foundation for further optimization of UAV operations in precision agriculture.

Table 4: UAV Flight Parameters Correlation Heatmap

Correlation	PWM Setting	Flow rate	Spray deposition	Path length	Flight time	Speed	Swath width	Accuracy
PWM Setting	1	0.98	0.95	0.34	0.41	0.12	0.08	0.82
Flow rate	0.98	1	0.97	0.36	0.43	0.15	0.06	0.79
Spray deposition	0.95	0.97	1	0.31	0.38	0.1	0.05	0.85
Path length	0.34	0.36	0.31	1	0.89	-0.21	-0.67	0.29
Flight time	0.41	0.43	0.38	0.89	1	-0.74	-0.58	0.32
Speed	0.12	0.15	0.1	-0.21	-0.74	1	0.24	0.18
Swath width	0.08	0.06	0.05	-0.67	-0.58	0.24	1	0.15
Accuracy	0.82	0.79	0.85	0.29	0.32	0.18	0.15	1

Comparison with Conventional Methods

The comparison between the simulation-based approach and conventional methods highlighted significant advantages of the former in precision agriculture. The simulation demonstrated superior accuracy in spray application, ensuring consistent deposition rates and minimizing wastage. Additionally, it proved to be more efficient by reducing the time and resources required for agrochemical application. Unlike conventional practices, which often rely on labour-intensive and trial-and-error field trials, the simulation eliminated these inefficiencies, thereby offering a cost-effective solution for optimizing UAV operations. These findings align with prior studies, such as those by Lan *et al*. (2017) [5] and Huang *et al*. (2019) [2], which underscore the benefits of simulation models in achieving precise and resource-efficient agricultural practices.

Discussion

The study highlights the pivotal role of UAV technology in enhancing the precision, efficiency, and sustainability of agrochemical application in agriculture. The strong linear relationship between PWM settings and flow rates confirms the significance of precise calibration in achieving accurate spray deposition. These results align with previous studies by Lan *et al.* (2017) [5] and Huang *et al.* (2019) [2], who emphasized the necessity of PWM calibration in optimizing UAV spraying systems. Furthermore, the study validated the high operational accuracy of UAVs, as evidenced by minimal deviations from planned flight paths, supported by prior findings from Wang *et al.* (2019) [7], which demonstrated the efficacy of UAVs in ensuring uniform coverage across treatment areas.

The comparative analysis with conventional methods further underscores the superiority of simulation-based approaches. The ability to predict and optimize spray parameters reduces dependency on resource-intensive trial-and-error field trials, making UAV operations more cost-effective and environmentally sustainable. These findings are consistent with research by Chen *et al.* (2020) [1], which highlighted the advantages of simulation models in optimizing resource use and minimizing environmental impact.

The correlation analysis provided deeper insights into UAV parameter interdependencies. Strong correlations between PWM settings, flow rates, and spray deposition reiterate the importance of these variables for achieving consistent spray patterns. However, negative correlations between speed and path length, and swath width and path length, highlight potential compromises in operational precision at higher speeds or wider swath settings. These trade-offs indicate the need for careful calibration of UAV parameters based on specific field conditions, as suggested by Zhang *et al.* (2021) [9].

Conclusion

This study demonstrates the transformative potential of UAV technology in modern agriculture. By systematically addressing key challenges such as payload optimization and parameter calibration, the research contributes to the growing body of knowledge on precision agriculture. Future studies can build on these findings by exploring advanced machine learning models to further enhance UAV operation and optimize spray parameters under varying environmental conditions.

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