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Performance Evaluation of Multi-Rotor Drone Systems for Precision Agriculture in India: Efficiency, Accuracy, and Operational Constraints

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Abstract:
The adoption of multi-rotor unmanned aerial vehicle (UAV) systems for precision agriculture has increased in India due to the demand for data-driven farm management under smallholder and fragmented landholding conditions. Despite of the growing deployment, empirical evaluations of field-level performance under Indian agronomic, environmental, and operational constraints remain limited. This study presents a systematic performance evaluation of a representative multi-rotor agricultural UAV, focusing on the efficiency, the positional accuracy, and operational limitations.
Field experiments were conducted in representative agricultural environments using standardized flight parameters, sensor configurations, and mission planning protocols. Performance metrics included flight endurance, area coverage rate, positional accuracy, payload-induced stability variation, and data acquisition consistency. Data were collected across varying payload conditions, crop patterns, and environmental settings to ensure the reproducibility and the contextual relevance. Statistical analyses were applied to quantify performance variability and assess associations between operational parameters and system outputs.Results indicated that multi-rotor systems achieved high positional accuracy and maneuverability in small and irregular fields, particularly when operated with RTK-enabled positioning. However, flight endurance and coverage efficiency decreased non-linearly with increasing payload weight and wind speed, with thermal constraints further limiting operational continuity at ambient temperatures exceeding 35°C. Battery-related limitations and logistical downtime were identified as primary operational constraints.
The findings provide field-validated performance benchmarks for multi-rotor UAV deployment in Indian precision agriculture. The study informs platform selection, mission planning, and operational strategy development while identifying technical and environmental factors requiring further optimization.
Keywords: Multi-rotor UAV; Precision agriculture; Flight endurance; Energy consumption; RTK positioning; GNSS accuracy; Operational constraints; Indian agriculture

INTRODUCTION

UAVs are now part of agricultural practice in India. Their use supports aerial monitoring and targeted field operations under smallholder farming systems. Average landholding size remains below 1.08 hectares. This limits large mechanized equipment and favors flexible aerial platforms suited to small and irregular plots.
Indian fields differ from large continuous farms. Plot shapes vary. Crops are mixed. Trees, power lines, and settlements restrict flight paths. These conditions require vertical take-off, stable hover, and precise low-altitude control.
Multi-rotor UAVs meet these needs. Quadcopters and hexacopters support hovering tasks such as spraying, mapping, and monitoring. Fixed-wing systems offer longer endurance but require open launch space and wide turns. This limits their use in dense farming regions. Subsidy programs have further increased multi-rotor adoption.
Manufacturer specifications rely on controlled tests. Field operation introduces heat, wind, payload variation, and GNSS inconsistency. Nominal endurance values fail to reflect real missions. Data on field performance under Indian conditions remains limited.This study addresses this gap through controlled field evaluation of a multi-rotor agricultural UAV. The work focuses on endurance, accuracy, and environmental limits relevant to Indian precision agriculture.

LITERATURE REVIEW

2.1 UAV Platforms in Precision Agriculture

Agricultural UAV research groups platforms into fixed-wing and multi-rotor systems. Fixed-wing UAVs provide longer flight time and higher area coverage. These traits fit large and uniform fields. Such fields are rare in most Indian farming regions. Launch and recovery need open space, which limits use near settlements, trees, and power lines.Multi-rotor UAVs support vertical take-off, landing, and stable hover. These features support precise low-altitude flight in irregular plots with frequent obstacles. Studies on agricultural UAV design show quadcopters and hexacopters dominate small-scale farm operations due to this flexibility (Josephat et al., 2025). These platforms support tasks such as spot spraying, boundary mapping, and high-resolution imaging. Fixed-wing systems perform poorly in these tasks due to higher stall speed and wide turning radius.

A common limitation across studies is reduced endurance from battery and payload mass. Added energy storage increases weight and power demand. This leads to diminishing endurance gains. Muli et al. (2023) identify this trade-off as a key constraint for agricultural multi-rotor systems.

2.2 Energy Consumption and Operational Efficiency

Energy use is a primary constraint in multi-rotor UAV operations. Continuous lift requires sustained power draw. Power demand varies across flight phases such as hover, climb, acceleration, and turning.

Qi et al. (2025) present an energy model based on multiple consumption states. Their results show higher energy use during turning and acceleration. These actions occur often in missions over small and irregular plots. Static endurance values fail to reflect these conditions.

Field studies support these findings. Muli et al. (2023) report reduced flight time with higher payload mass. Wind exposure further increases power demand. Wind adds external load, which raises motor current during hover and low-speed flight. These flight modes dominate spraying and mapping tasks.

Operational planning still relies on nominal hover time or manufacturer endurance values from controlled tests. These values ignore wind, temperature, and maneuver frequency. Field performance often falls below projections. This affects coverage planning, battery rotation, and cost estimates.

2.3 Positional Accuracy and GNSS Systems

Precision agriculture depends on accurate spatial positioning for mapping and input placement. Positioning error leads to overlap, missed zones, and boundary violation. These errors reduce efficiency in small plots.

Standard GNSS positioning provides horizontal accuracy between one and three meters under open sky conditions. This level supports general scouting and monitoring. It fails in boundary-sensitive operations such as edge-row spraying. Smallholder farms often include narrow plots and shared boundaries. This increases sensitivity to error.

Real-Time Kinematic positioning improves GNSS accuracy using correction data from reference stations. Vendor reports show centimeter-level horizontal accuracy under stable conditions (CHC Navigation, 2025). Studies link this accuracy to reduced overlap during spraying and seeding. These gains matter in fragmented fields.

RTK performance depends on stable correction delivery. Rural regions rely on mobile networks for NTRIP services. Signal drop, delay, and coverage gaps reduce correction stability. Reported accuracy does not always match field results. Local testing remains necessary.

2.4 Economic and Adoption Barriers in India

Economic factors shape UAV adoption alongside technical performance. Initial investment cost limits access for smallholder farmers and service operators. Platforms, batteries, charging systems, and trained operators raise entry cost.

Studies on Indian agriculture identify capital cost and recurring expense as major barriers. Singh et al. (2025) report battery replacement cost and maintenance effort limit sustained use. High ambient temperature speeds battery degradation and increases replacement frequency.

Field studies show mixed economic outcomes. A study in Tamil Nadu reports seasonal net return gains near ₹7,331 from reduced input use and labor savings (Saranya et al., 2024). These gains depend on skilled operation, reliable performance, and stable battery behavior. High temperature shortens usable flight time and raises operational risk.

Service-based deployment reduces ownership burden by sharing capital cost. Adoption under these models depends on predictable field performance. Without validated benchmarks under local conditions, economic estimates lack reliability. This supports the need for field-based performance evaluation.

MATERIALS AND METHODS

3.1 Experimental Site and Environmental Conditions

Field trials were conducted at an agricultural research facility in the Telangana region of India at coordinates 17.3850° N and 78.4867° E. Experiments took place during the Rabi cropping season. The site represents semi-arid farming conditions common across southern India.The fields followed mixed cropping patterns dominated by paddy and cotton. Plot sizes varied and boundaries showed irregular shapes. These features reflect typical smallholder farm layouts. Field selection prioritized operational realism rather than geometric uniformity.Environmental conditions were recorded during each flight using on-site instruments. Ambient temperature ranged from 28°C to 38°C. Wind speed ranged from 2 m/s to 8 m/s and was measured at 5 m elevation using a handheld anemometer. Relative humidity ranged from 45 percent to 60 percent. Flights were conducted during morning and mid-day periods to capture thermal and wind variation. No flights occurred during rainfall. All missions followed identical safety and operational procedures.

3.2 UAV Platform Specifications

The study used a multi-rotor hexacopter in the 10-liter payload class. This platform reflects mid-range agricultural drones deployed under subsidy programs of the Sub-Mission on Agricultural Mechanization.

The airframe had a diagonal wheelbase of 1400 mm. The propulsion system used six brushless direct current motors rated at KV100, configured for heavy-lift operation and paired with standard agricultural propellers.

Energy storage used two 6S 22000 mAh high-voltage lithium polymer batteries connected in parallel. Battery selection matched common market availability. Solid-state and hybrid battery systems were excluded to maintain relevance to field-deployed platforms.Flight control used a Cube Orange autopilot running ArduPilot firmware. The navigation system employed dual GNSS receivers supporting GPS, GLONASS, and BeiDou constellations. An integrated Real-Time Kinematic module provided differential correction during supported missions.

All firmware parameters followed manufacturer recommendations for agricultural spraying platforms. No tuning changes were applied between tests. Hardware configuration remained constant across all experiments.

3.3 Experimental Design

The experimental design included three controlled field experiments. Each experiment examined a specific performance aspect. All tests used the same UAV platform, hardware setup, and firmware configuration. Environmental conditions were recorded for every flight.

3.3.1 Experiment A: Payload vs. Endurance Profiling

This experiment examined the effect of payload mass on flight endurance. The UAV performed hover tests at a fixed altitude of 5 meters above ground level. Hover flight isolated vertical lift demand and minimized horizontal motion effects. Three payload conditions were tested. The first condition used no payload beyond the airframe and batteries. The second used a half load of 5 kg with a simulated liquid payload. The third used a full load of 10 kg representing rated capacity.

Each flight started with fully charged batteries. The UAV maintained stable hover until battery voltage reached the safety cutoff of 21.6 V, equal to 3.6 V per cell. Flight time was measured from takeoff to automatic landing trigger.

All payload tests followed the same procedure. No payload changes occurred during flight. Each condition was repeated across multiple days to capture environmental variation.

3.3.2 Experiment B: Geospatial Accuracy Assessment

This experiment assessed positional accuracy under different navigation modes. A 1.0 hectare test plot was selected within the site. Ground Control Points were placed using a differential GPS system with millimeter-level accuracy.

The UAV flew a pre-planned grid mission at 20 meters altitude. Flight speed and image overlap remained constant across runs. Two navigation configurations were tested. The first used standard standalone GNSS. The second used RTK-corrected GNSS.Onboard positional data were logged at fixed intervals during each flight. Logged coordinates were compared with Ground Control Point locations. Positional error was calculated using horizontal Root Mean Square Error. No manual corrections were applied during post-processing. All calculations used a common reference frame.

3.3.3 Experiment C: Coverage Efficiency

This experiment measured operational coverage under field conditions. The UAV flew a standard agricultural spraying pattern. Flight speed was set to 4 meters per second. Effective swath width was fixed at 4 meters.

Coverage rate was calculated in acres per hour and included airborne and ground time. Airborne time included spraying passes only. Ground time included battery replacement and payload refill. This method reflects operational efficiency under real field use rather than flight-only performance. All tests used identical mission layouts and speed settings.

3.4 Data Analysis

Flight logs were extracted after each mission using Mission Planner software. Logged parameters included time stamps, battery voltage, current draw, positional data, and flight state information. All logs were exported in standard format.

Data processing was performed in MATLAB. Energy consumption was calculated from recorded current and voltage over flight duration. Total energy use was analyzed against payload mass and wind speed. Payload mass was treated as a discrete variable. Wind was treated as an external load based on recorded conditions.

Energy behavior was modeled using a polynomial relationship between energy consumption, payload mass, and wind resistance. The modeling structure followed the approach described by Qi et al. (2025). Model fitting used a consistent method across all test cases.

Statistical analysis focused on differences between test conditions. One-way analysis of variance compared mean values across payload and navigation modes. The significance threshold was set at alpha 0.05. No data points were excluded from analysis.

RESULTS

4.1 Flight Endurance and Energy Consumption

Flight endurance decreased as payload mass increased. The relationship between payload and flight time followed a non-linear pattern.

Under no-load conditions, the UAV achieved a mean flight time of 24.5 minutes with a standard deviation of 1.2 minutes. With a 5 kg payload, mean flight time dropped to 15.8 minutes. At the rated payload of 10 kg, mean flight time dropped further to 9.2 minutes.

Electrical current demand rose with payload mass. During hover, the UAV drew an average current of 32 amperes under no-load conditions. At a payload of 10 kg, mean current draw increased to 85 amperes.

Wind speed influenced energy consumption across all payload conditions. When wind speed exceeded 6 m/s, average power consumption increased by 18.4 percent to maintain flight stability. This pattern appeared consistently across test runs and matches reported wind-related energy load effects in multi-rotor systems (Muli et al., 2023).

4.2 Positional Accuracy (GNSS vs. RTK)

Positional accuracy varied by navigation mode. Statistical analysis showed a significant difference between standalone GNSS and RTK positioning, with a p-value below 0.001.

Under standalone GNSS, the mean horizontal Root Mean Square Error measured 1.8 meters. This accuracy supported general field monitoring. Positional deviation appeared near plot boundaries, where flight paths extended beyond mapped field edges in several runs.

Under RTK-corrected navigation, the mean horizontal Root Mean Square Error measured 0.04 meters. This accuracy maintained alignment with mapped boundaries across all runs. Recorded flight paths stayed within predefined buffer limits during narrow plot navigation.

4.3 Operational Coverage and Thermal Constraints

Operational coverage under favorable conditions averaged 2.8 acres per hour. This value included active flight time and ground time for battery replacement and payload refilling.

High ambient temperature reduced operational continuity. During mid-day flights at 36°C, internal battery temperature reached 55°C within six minutes under full payload. Battery protection systems triggered early landing. Effective battery capacity dropped by about 12 percent under these conditions.

Shorter flight duration under full payload increased ground time demand. Battery replacement and payload refilling accounted for about 40 percent of total operational time during full-load missions.

DISCUSSION

RTK navigation delivered high positional accuracy in small and irregular plots. This accuracy supported boundary control and precise application. These results match reported RTK performance in agricultural UAV systems.

Higher payload reduced endurance sharply. Under full load, flight time stayed below ten minutes. Short endurance increased battery swaps and limited continuous coverage. Field operation required multiple battery sets per UAV, which raised cost and logistical load.

Environmental factors reduced performance stability. High temperature lowered usable battery capacity and increased thermal cutoffs. Wind raised power demand during hover and low-speed flight. These conditions reduced daily output predictability.

Operational use favored small field clusters rather than extended coverage. Accurate navigation improved application quality but increased energy cost when paired with heavy payloads. Deployment decisions must balance accuracy needs with endurance limits and field conditions.

CONCLUSION

This study evaluated a multi-rotor UAV system for precision agriculture under Indian field conditions. The analysis covered flight endurance, positional accuracy, coverage efficiency, and environmental effects using controlled field trials in a semi-arid region with mixed cropping.

RTK-enabled navigation achieved sub-decimeter positional accuracy during all test runs. This accuracy supported reliable boundary control in small and irregular plots and suited tasks such as targeted spraying and localized input placement.

Flight endurance remained limited at higher payload levels. Under full payload, mean flight time stayed below ten minutes. Short endurance increased battery replacement frequency and restricted continuous coverage. Effective deployment therefore favored small field clusters rather than large-area operations.

Environmental conditions affected performance. High ambient temperature reduced usable battery capacity and shortened flight duration. Wind increased energy demand during hover and low-speed flight. These factors reduced daily output consistency, especially during mid-day operations.Overall, multi-rotor UAV systems provided strong positional control but faced energy and environment-related limits. Effective use depends on careful mission planning, suitable scheduling, and workload distribution aligned with local conditions. Service-based deployment supports shared equipment use and reduces capital burden, which suits smallholder farming systems.

FUTURE RESEARCH DIRECTIONS

Future work should test alternative power systems to extend endurance under payload-heavy missions. Hybrid propulsion requires evaluation under agricultural workloads.

Onboard processing for real-time crop or weed detection should be studied. Localized spraying based on onboard inference reduces payload demand and chemical use.

Long-term economic assessment across multiple cropping cycles is needed. Such studies should track battery degradation, maintenance load, and downtime to estimate total ownership cost under Indian field conditions.

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