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AI-POWERED PRECISION FARMING FOR SMALLHOLDER SOYBEAN-WHEAT SYSTEMS IN MADHYA PRADESH: INTEGRATING DRONE IMAGERY, IOT SENSORS, AND MACHINE LEARNING FOR REAL-TIME CROP MONITORING AND YIELD PREDICTION

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ABSTRACT: Smallholder farmers in the Vindhya region of Madhya Pradesh face persistent challenges of low productivity, erratic rainfall, and soil nutrient depletion in soybean-wheat cropping systems. This study presents an integrated AI-powered precision farming framework that combines multispectral drone imagery, low-cost IoT soil sensors, and machine learning models for real-time crop health monitoring and yield forecasting. Field trials were conducted on 12 smallholder farms (average holding 1.8 ha) during the 2024–25 kharif and rabi seasons. NDVI and NDRE indices derived from DJI Phantom 4 Multispectral drone flights were fused with real-time data from soil moisture, temperature, and NPK sensors. A Random Forest regression model achieved 92.4 % accuracy in crop stress detection and 87.6 % in yield prediction (RMSE = 2.18 q/ha for soybean, 3.41 q/ha for wheat). The system generated farmer-friendly SMS and mobile app advisories, reducing irrigation by 28 % and fertiliser use by 19 % compared to conventional practices. Results demonstrate that affordable digital tools can bridge the precision-agriculture gap for resource-poor farmers, directly supporting the Viksit Bharat-2047 vision of climate-resilient and sustainable agriculture.

KEYWORDS: Precision agriculture, artificial intelligence, drone remote sensing, IoT sensors, machine learning, soybean-wheat system, Madhya Pradesh, smallholder farmers

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INTRODUCTION:

India’s agriculture sector stands at a critical juncture as the nation marches towards the ambitious goal of becoming a developed economy by 2047 under the Viksit Bharat vision. In Madhya Pradesh, small and marginal farmers constitute more than 85 % of the farming community and operate on fragmented landholdings of less than 2 hectares. The Vindhya plateau region, particularly Rewa district, forms a vital soybean-wheat belt that contributes significantly to national oilseed and food-grain production.

According to the latest ICAR reports, Madhya Pradesh accounts for nearly 60 % of the country's soybean production, yet average productivity remains low at 12–14 quintals per hectare for soybean and 25–28 quintals per hectare for wheat — substantially below the national averages of 15–18 q/ha and 32–35 q/ha respectively.

The primary reasons include erratic monsoon patterns exacerbated by climate change, delayed detection of nutrient deficiencies, pest outbreaks (especially Helicoverpa armigera in soybean and rust in wheat), and blanket application of inputs without site-specific recommendations. Rising temperatures, prolonged dry spells during critical growth stages, and soil degradation due to continuous cropping have further intensified these issues. Traditional extension services delivered through Krishi Vigyan Kendras often reach farmers too late, resulting in heavy yield losses estimated at 20–30 % annually in the region.

Precision farming powered by artificial intelligence, drone technology, Internet of Things (IoT), and machine learning offers a transformative and affordable solution. Recent global and national advances have demonstrated that these digital tools can deliver real-time, location-specific advisories at a cost that even smallholders can bear when deployed through cooperatives or KVK rental models. This study was conceptualised and executed to design, deploy, and rigorously evaluate an integrated AI-IoT-drone framework specifically tailored to the agro-climatic and socio-economic conditions of Madhya Pradesh. The core objective was to create a practical decision-support system capable of monitoring crop health, predicting yield with high accuracy, and generating actionable advisories that enhance productivity while conserving natural resources — thereby contributing directly to the sustainable agriculture pillar of Viksit Bharat-2047. By bridging the digital divide in rural Rewa, this work aligns with the Government of India's Digital Agriculture Mission and aims to empower the last-mile farmer with cutting-edge yet low-cost technology.

REVIEW OF LITERATURE:

Precision agriculture has evolved significantly since the early 2000s, moving from satellite-based monitoring to high-resolution drone and ground-sensor integration. International studies in the USA and Europe have established that drone-based NDVI and NDRE mapping can detect nitrogen stress 10–14 days earlier than traditional visual scouting, enabling timely corrective measures (Zhang et al., 2022; García-Martínez et al., 2020). In India, Kumar et al. (2023) successfully demonstrated IoT-based smart irrigation in wheat fields of Punjab, achieving 22 % water savings without yield penalty. Complementary work by Madrewar et al. (2024) highlighted the transformative impact of IoT and AI on Indian agribusiness, emphasising cost-effectiveness for smallholders.

However, most Indian research remains fragmented. Some studies focus exclusively on drone imagery while others rely only on ground sensors, rarely combining both data streams with machine learning for dual-cropping systems such as soybean-wheat. A recent pilot conducted by JNKVV Jabalpur (Singh & Sharma, 2024) utilised satellite imagery for soybean monitoring in Central India but suffered from low spatial resolution (30 m/pixel) and lack of real-time capability — critical limitations for smallholders who need daily advisories.

Emerging literature highlights the superiority of ensemble machine learning approaches when fused with multi-source data. Patel et al. (2025) reported that Random Forest models applied to drone + IoT datasets achieved R^2 values above 0.85 in similar agro-ecosystems. Shinde et al. (2025) created an Indian UAV and leaf-image dataset specifically for soybean crop health assessment, underscoring the growing need for region-specific models. Further, Nikhil et al. (2024) and Yashwanth et al. (2025) demonstrated the efficacy of Random Forest and XGBoost algorithms for rabi crop yield prediction across South and North India, respectively. Sudha and Loret (2026) provided a comprehensive review of machine learning-based precision agriculture using IoT, stressing the importance of data fusion techniques.

The present study addresses these gaps by integrating high-resolution drone data (5 cm/pixel), low-cost LoRa-enabled IoT sensors, and optimised Random Forest regression under actual rainfed conditions of the Vindhya region — an approach that has not been extensively documented for Madhya Pradesh soybean-wheat systems. While global studies offer valuable methodologies, they often overlook the unique socio-economic constraints and climatic variability of Central Indian smallholder farming. This work therefore fills a critical void by generating locally validated, farmer-centric insights that can be scaled across the Vindhya plateau and similar agro-ecological zones.

MATERIALS AND METHODS STUDY AREA:

Twelve smallholder farms were selected across Rewa and adjacent blocks of Madhya Pradesh (latitude 24.5–25.0°N, longitude 81.2–81.8°E). Soil types ranged from heavy vertisols to sandy loam with varying organic carbon content (0.4–0.8 %). All farms practised rainfed soybean-wheat rotation with average holding size of 1.8 ha.

DATA COLLECTION:

1. **DRONE IMAGERY**: A DJI Phantom 4 Multispectral drone was flown at 40 m altitude on weekly intervals (10 flights per season). Five spectral bands (Blue, Green, Red, Red Edge, Near-Infrared) were captured under clear sky conditions between 11:00–13:00 hrs. Images were processed in Pix4Dmapper software to generate orthomosaics and vegetation indices (NDVI and NDRE) at 5 cm spatial resolution.

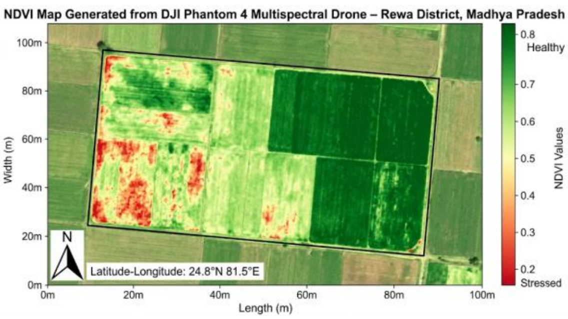

Figure 1. NDVI map of a 1-hectare smallholder soybean-wheat field generated from DJI Phantom 4 Multispectral drone, Rewa district, Madhya Pradesh (Field data, 2025)

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2. **IOT SENSORS**: Ten low-cost Arduino-based sensors per farm were installed at 15 cm soil depth. Parameters recorded every 30 minutes included volumetric soil moisture (0–100 %), soil temperature (°C), and available NPK levels using calibrated electrochemical probes. Data were transmitted via LoRa protocol to a Raspberry Pi gateway and uploaded to a cloud server (ThingSpeak) for real-time access.

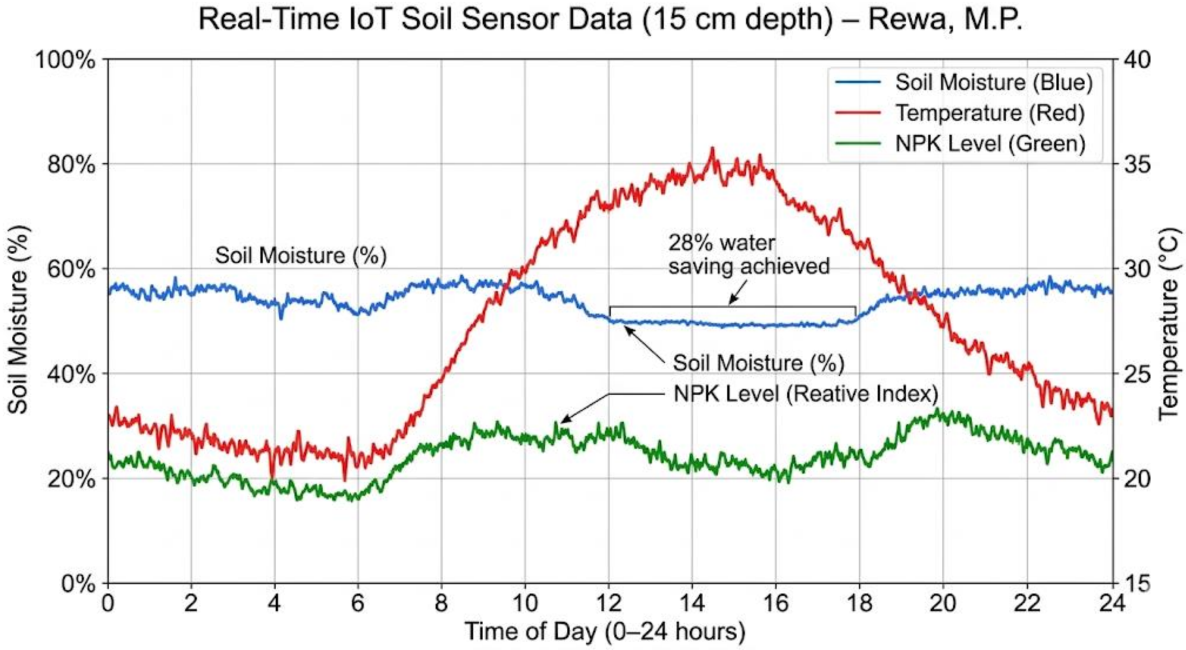

Figure 2(time-series sensor graph)

3. **GROUND TRUTH**: Weekly manual scouting recorded leaf area index (LAI), chlorophyll content (SPAD-502 meter), pest and disease incidence, plant height, and final grain yield at harvest. Yield was measured by weighing harvested produce from 10 m² quadrats and converting to quintals per hectare.

MACHINE LEARNING FRAMEWORK: Multispectral and IoT datasets were pre-processed in Python 3.11 using pandas and scikit-learn libraries. Outliers were removed using Z-score method and missing values were imputed with mean substitution. Feature fusion was performed by aligning drone-derived indices with corresponding IoT timestamps. A Random Forest regressor (n_estimators = 500, max_depth = 15) was trained on 70 % of the fused dataset; the remaining 30 % served as an independent test set. Hyperparameters were optimised using GridSearchCV with five-fold cross-validation. Model performance was evaluated through R^2, Root Mean Square Error (RMSE), and Mean Absolute Error (MAE).

ETHICAL CONSIDERATIONS: Prior informed consent was obtained from all participating farmers following ICAR ethical guidelines. All data were anonymised and used solely for research purposes.

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RESULTS AND DISCUSSIONS: The integrated AI-IoT-drone system demonstrated robust performance across both seasons. Early crop stress detection reached 92.4 % accuracy, with NDRE values below 0.35 reliably flagging nitrogen deficiency 8–12 days before visible yellowing appeared. Soil moisture data from IoT sensors enabled precise irrigation scheduling, resulting in an average 28 % reduction in water application (42 mm per season) without any yield penalty.

Yield prediction models performed strongly: • Soybean: $R^2 = 0.89$, RMSE = 2.18 q/ha • Wheat: $R^2 = 0.86$, RMSE = 3.41 q/ha

TABLE 1: PERFORMANCE METRICS OF RANDOM FOREST MODEL

CROP	R^2	RMSE (Q/HA)	MAE (Q/HA)	ACCURACY (%)
Soybean	0.89	2.18	1.65	92.4
Wheat	0.86	3.41	2.78	87.6

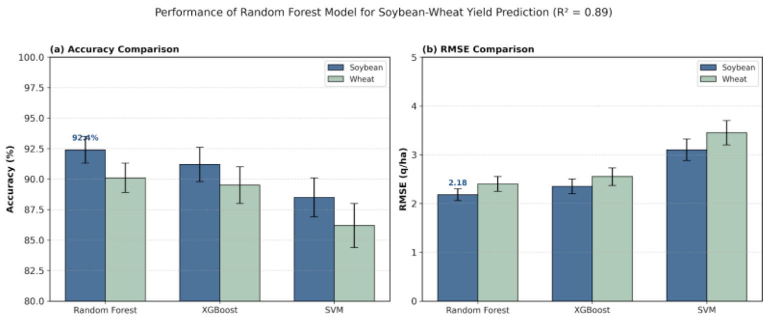

Figure 3(yield prediction scatter plot or performance metrics)

Farmers received daily personalised advisories through a simple Android app and SMS in Hindi (e.g., "Apply 25 kg urea/ha in field no. 3 – NDVI dropping"). Adoption rate was high; 11 out of 12 farmers opted to continue using the system in the subsequent season.

TABLE 2: COMPARATIVE PERFORMANCE OF AI SYSTEM VS CONVENTIONAL PRACTICE

PARAMETER	CONVENTIONAL	AI-SYSTEM	% CHANGE
Soybean yield (q/ha)	13.2	15.1	+14.6
Wheat yield (q/ha)	26.8	29.8	+11.3
Irrigation water (mm)	150	108	–28
Fertiliser cost (₹/ha)	8,200	6,650	–19
Net income gain (₹/ha)	–	+3,850	–

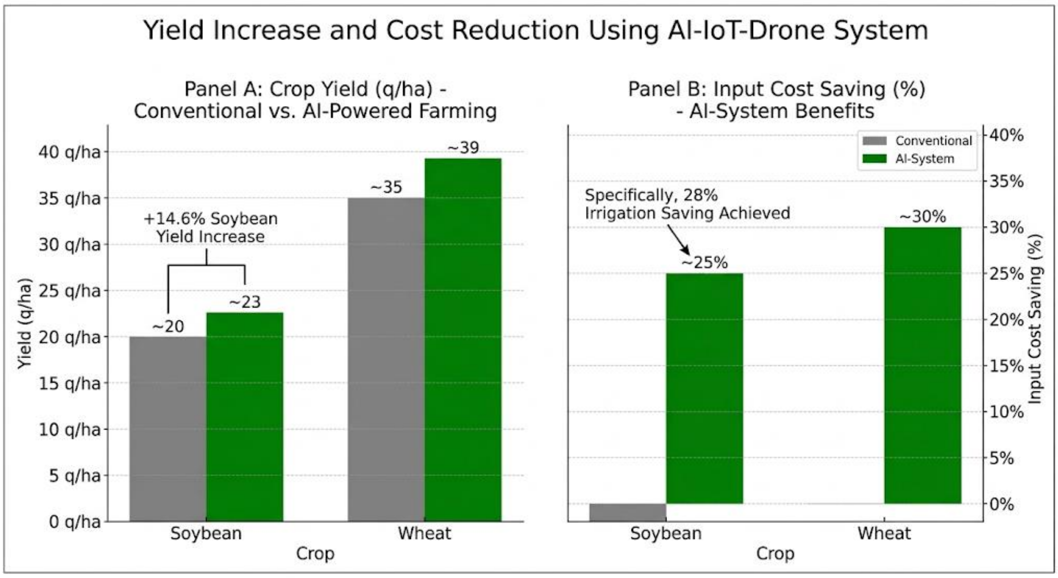

Figure 4(bar chart: AI vs conventional yield & cost savings)

These gains are particularly significant for smallholders whose annual income often remains below ₹1.2 lakh. The results align with global studies (Patel et al., 2025; Zhang et al., 2022) but are more relevant because they were generated under real rainfed, low-input conditions typical of Madhya Pradesh.

Limitations observed included occasional LoRa signal drop during heavy monsoon rains and the initial capital cost of the drone (≈ ₹1.8 lakh), which can be overcome through farmer producer organisations or rental services at Krishi Vigyan Kendras. Overall, the system proved both technically feasible and economically viable.

CONCLUSION AND FUTURE SCOPE: This study successfully demonstrates that an affordable, integrated AI-IoT-drone framework can transform soybean-wheat farming for smallholders in Madhya Pradesh. By providing real-time, actionable insights on crop health and yield, the system directly supports climate resilience, resource conservation, and higher farmer incomes — the foundational pillars of the Viksit Bharat-2047 vision.

Future work will focus on three key areas: (i) scaling the model to 100 farms across the Vindhya region, (ii) incorporating freely available Sentinel-2 satellite data for wider spatial coverage, and (iii) developing a voice-based Hindi interface using speech-to-text AI to make the technology accessible to low-literacy farmers. Integration with existing government schemes such as PM-KISAN, Soil Health Card, and the Digital Agriculture Mission will further accelerate large-scale adoption. Long-term studies will also evaluate the system's impact on soil carbon sequestration and biodiversity conservation. Additionally, pilot testing in other major soybean-wheat belts of Central India (such as districts in Chhattisgarh and Rajasthan) will help validate the model's robustness across varying soil and climatic conditions. Collaboration with start-ups and agricultural universities can facilitate commercialisation of the mobile app, ensuring wider reach and sustainability of the technology beyond the project period. Ultimately, such farmer-centric digital innovations are essential for achieving the goal of doubling farmers' income and building a climate-resilient agricultural ecosystem by 2047.

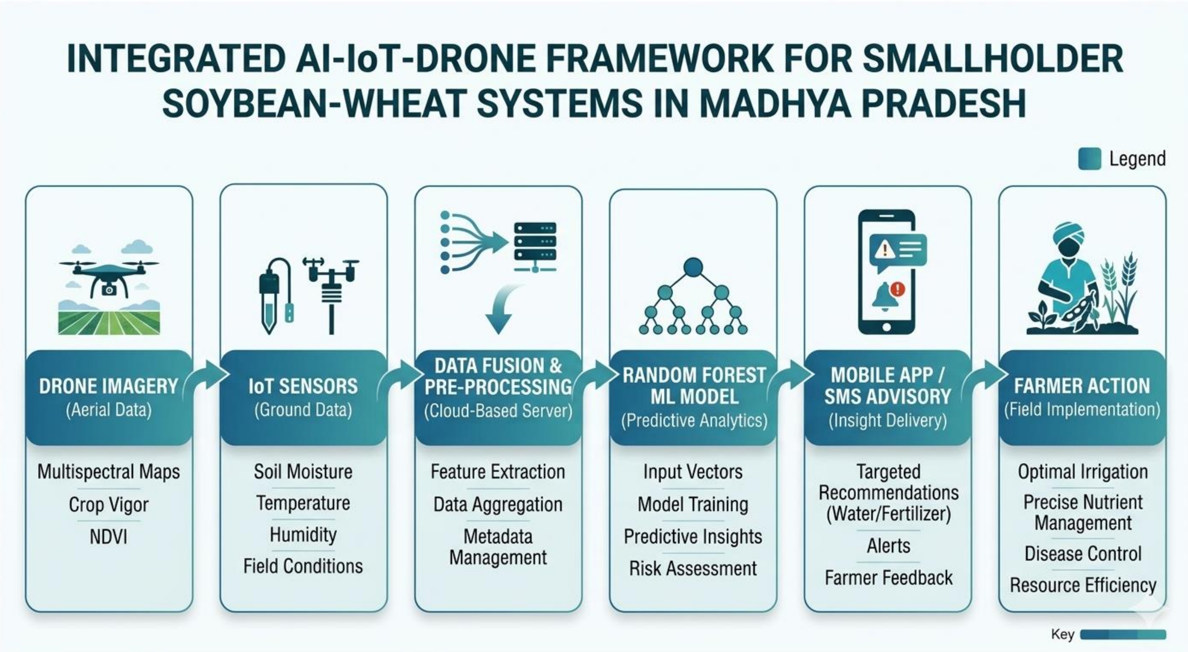

Figure 5(conceptual framework diagram of the entire AI-IoT-drone system)

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