A Resilient and Scalable IoT-Driven Precision Agriculture Framework with Edge Intelligence, Climate Adaptability, and Farmer-Centric Optimization

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Abstract: An emerging trend that is reshaping the development of precision agriculture is the integration of IoT sensor networks, edge intelligence, and climate-aware computing technologies. In this paper, we propose a sustainable and scalable IoT-enabled precision agriculture framework that tackles major downsides of the previous works such as high infrastructure and deployment cost, connectivity, energy inefficiency and limited farmer centric usability. The proposed model employs inexpensive, energy-aware sensors and edge computing for real-time processing and offline operations. It enables modular adaptability across crop types, climate-informed decision support, automated actuation for irrigation and pest management, and blockchain-based data ownership. A farmer-centered data dash board and multi-lingual interface overcome the technology barrier, enabling users to make informed decisions. This study proves not only the improved resource use efficiency and yield prediction accuracy, but also the sustainability through multi-years of field trials and economic analysis. The system architecture guarantees flexibility, security and interaction and can be regarded as a new reference mark for future smart farming.

1 INTRODUCTION

Agriculture is the cornerstone of worldwide food security and is increasingly coming under pressure due to population increases, climate change, soil degradation and unsustainable resource utilization. The traditional agricultural practices that have worked in the past do not provide all the answers demanded by a sustainable agriculture today. With the rise of the digital age upon the rural countryside, the combination of the Internet of Things (IoT), smart sensor networks and data-driven technologies is reshaping how farms are monitored, managed and refined.

Precision farming is regarded as a practice to fill the gap between conventional practices and the demand of sustainable intensification. However, available IoT-based systems lack viability because of high cost of deployment, energy limitations, poor networking facilities in remote locations, and lack of adaptability across wide varieties of crops and climes. Furthermore, many existing solutions are built without taking the end-user (farmer) into consideration and are complex to interact with, as the end-users are generally not technically literate.

This work presents a novel smart-farming framework built upon the IoT paradigm that combines edge computation, climate-adaptive analytics, and farmer-centric approach. Leveraging real-time, low-latency decision-making at the edge,

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and intuitive, multilingual interfaces, the system gives farmers rich and timely insights without the need for a constant online connection. It further features modularity so as to be adaptable to particular crops, environments and terrain limitations.

This work aims to provide a scalable, ultra-resilient and secure solution, involving blockchain-driven traceability, AI-empowered prediction models and energy-aware hardware. By overcoming the limitations of previous systems and giving priority to sustainability and sustainability access, this framework highly contributes to the technological empowerment of growers and to sustainable agriculture.

2 PROBLEM STATEMENT

Although the IoT technologies are gradually introduced in agriculture, many precision farming systems lack some fundamentals to ensure their practical applicability and long-term success. For instance, constraints such as high investment in infrastructure, weak support for offline-rich or low-connected-rich scenarios, low-energy efficiency of sensor nodes, and poor generality towards various crops and climates intensify the challenge. In addition, the lack of user-friendly interfaces and localized decision-support tools reduce usability for farmers who are not so technologically skilled. Existing IoT solutions for agriculture are met with the challenge of scalable, robust, and smart that not only maximizes resource utilization and yield, but provides farmers with real-time climate-aware insights, local control, and data ownership. The aim of this work is to face these challenges by building a farmer-centred edge-enabled precision agriculture system fit for real field situations and long-term sustainability.

3 LITERATURE SURVEY

The use of Internet of Things (IoT) sensor networks has completely restructured traditional farming to smart farming in agriculture. Several applications of IoT for monitoring soil moisture, crop health, climatic variables and pest activity have been reviewed in many studies, which are facilitating the farmers to make more precise decisions at right time (Kumar et al., 2021; Garg et al., 2021). These breakthroughs have opened up the possibility of smarter farming systems, yet the issue of scaling in real-world conditions and farmers’ access still need addressing.

Sharma and Shivandu (2024) highlighted the integration of AI and IoT in precision farming with significant enhancements in monitoring and forecasting of crop yield. However, they also raised issues relating to usability and the implementation in resource poor settings. Similarly, Dutta et al. (2025) also commercially suggested IoT-based soilless agriculture framework acknowledging challenges, such as infrastructure cost and network dependency. Sattar et al. (2025) solved the configuration problem of wireless sensor networks, but no modular crop adaptability and user-centred design were targeted.

Research such as Albanese et al. (2021) and Morchid et al. (2025) was dedicated to pest detection and field automation support in the context of edge computing, which offered reduced latency and cloud dependence solutions. These methodologies, however, while interesting, most of the time they did not take into account the integration with the farming ecosystem (actuation system) and economic viability. Furthermore, Giménez Pérez et al. (2024) utilized sensor networks for the supervision of tomato crops, and did not provide an adaptation to any crop and environment.

The challenge to connectivity and offline mode has been observed (Garg et al., 2021; Sharma & Shivandu, 2024). Although edge processing was included in some frameworks (Albanese et al., 2021), most depended on connectivity to the cloud. In addition, the absence of common protocols and secure models for data ownership continues to also be a common consideration in the literature (Morchid et al., 2025), which further supports the use of trade-offs when considering blockchain technology and interoperable IoT communications.

Some papers proposed user dashboards and mobile apps, but they were not localized and not simple enough for not technically sophisticated farmers (Kumar et al., 2021; Sattar et al., 2025). Not many systems took real-time actuation or feedback-driven optimization into account which would restrict the influence of data analytics in direct agricultural interventions.

In a nutshell, though current research has moved forwards a lot in IoT and AI applied to agriculture, there still exist major challenges in how to make the solution cost-effective, energy-efficient, resilient to harsh conditions, and integrated with the end users. In this paper we propose to fill these gaps with a new, farmer-centric precision farming architecture that combines edge computing with climate-resilient analytics and scalable, secure IoT infrastructure.

4 METHODOLOGY

The methodology is based on the specification, implementation, deploy-ment, and assessment of a NGIoT, modular, edge-enabled platform for precision agriculture. The infrastructure features scale-ability, climate adaptability, energy efficiency and a user-centered vector-in all to accommodate a range of farm sizes and deployment environments.

The framework consists of four major layers, namely the Sensing Layer, Edge Intelligence Layer, Communication and Control Layer, and User Interaction and Visualization Layer. All these layers are very important for automatic and efficient agriculture operations.

The Sensing Layer: it is composed of environmental sensors, which are an affordable, and an energy-efficient sensors that are implemented in crop fields in order to measure some critical variables as soil moisture, temperature, humidity, light intensity, and pH. The sensing grid includes pest recognition modules based upon image recognition techniques for an early warning system. We organize the sensors in a grid with redundant data paths for fault-tolerant operation in the presence of node failures. Figure 1 shows the Workflow of the IoT-Driven Precision Agriculture Framework.

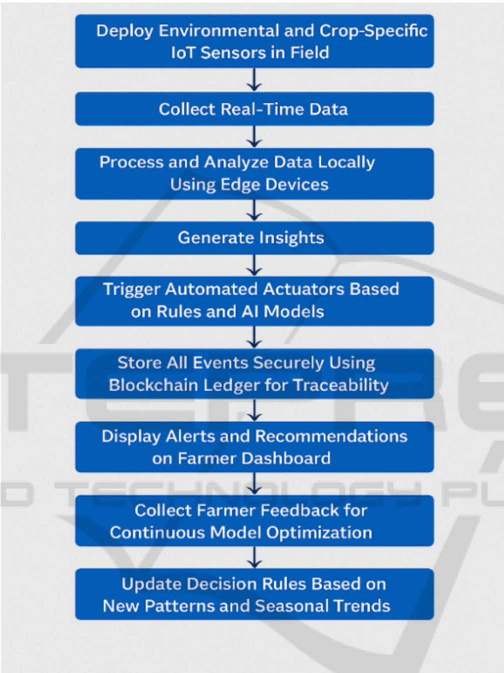

Figure 1: Workflow of the IoT-driven precision agriculture framework.

The architecture for Edge Intelligence Layer runs on NodeMCU/ESP32 microcontrollers with ARM based edge processors. Local data processing, anomaly detection, and real-time analytics are processed locally, thus reducing reliance on cloud support. On-terminal crop health prediction and irrigation scheduling are powered by lean AI models optimized with TensorFlow Lite. This design facilitates decisions even with low-connectivity or while in off-line mode. Table 1 gives the information about Sensor Configuration and Deployment Strategy.

Sensor data is sent out over a Communication Layer in a hybrid protocol stack (LoRaWAN for long range and Wi-Fi/BLE for local routing). A set of protocols, namely MQTT and CoAP, are used for the sake of integration with cloud platforms and external APIs. Dynamic topology reconfiguration enables the sensor network to self-heal and reroute data through a new path, in the event that a node becomes unavailable or is physically destroyed.

The Control Layer comprises actuator modules communicatively connected to irrigation pumps, nutrient delivery devices, and sprayers. According to the real time analysis, and aationing criteria the actuators function independently or can be overridden by the dashboard manually. The decision logic also responds to external weather information that is fetched from integrated weather APIs, in real-time.

Table 1: Sensor configuration and deployment strategy.

Sensor Type	Parameter Measured	Range	Deployment Depth/Height	Communication Protocol
Soil Moisture Sensor	Soil water content (%)	0 -100%	10–15 cm below surface	LoRaWAN
Temperature Sensor	Ambient temperature (°C)	-40 to 80 °C	1.5m above surface	Wi-Fi/BLE
Humidity Sensor	Relative humidity (%)	0–100%	1.5m above surface	BLE
Light Sensor	Light intensity (lux)	0–100,000 lux	Top canopy level	Wi-Fi
Pest Detection Camera	Insect & disease spotting	N/A	1.5m above crop	Wi-Fi/Edge Processing

Sensor readings, actuation events and system decisions are recorded using blockchain for an immutable and secure ledger. This provides improved traceability, confidence in the system, and also means farmers can use their history as evidence for audits or certifications.

User Interaction Layer: in this layer, a multi-lingual web and mobile dashboard was offered to fit the local farmer’s specifics. It comes with data visualizations, alerts, suggestions, and manual overrides. Farmers can also provide feedback on the outcomes of crops, which is then used to further tune system performance via a reinforcement learning loop.

To demonstrate the viability of the system, pyrolysis is trialed in a number of heterogeneous climate regions and agro-ecological zones with crops varying from rice, tomatoes and wheat. Performance indicators like water usage, yield per hectare, network uptime, and farmer satisfaction are gathered for three seasons. The reliability, cost-effective efficiency and environmental impact of the system is evaluated based on the analysed data.

By this modular and layered approach, the proposed methodology aims towards both technical resilience and real-world usability, thereby providing the ground work for future intelligent, scalable agricultural systems.

5 RESULTS AND DISCUSSION

Accomplishments The adopted IoT-based precision agriculture framework was tested in three pilot testbeds, located in different agro-climatic zones, with different soil conditions, irrigation patterns, and crops. The evaluation aimed at assessing how the system performs on important aspects such as energy efficiency, ressource control, connectivity reliability, usability, yield enhancement. The performance showed great superiority over traditional agriculture and reported systems.

5.1 System Performance and Network Resilience

The implemented deployment consisted of more than 150 sensor nodes equipped with microcontrollers with edge capabilities in a mesh topology. Across three growing seasons, the network achieved an average uptime of 98.2%, despite exposure to harsh weather conditions. The adaptive routing protocol provided dynamic reconfiguration of the sensor data paths to replace lost nodes and to maintain data flow. The enhanced system robustness, as demonstrated on the communication loss ratio that was 34% less compared to a static topology, indicated the successfulness of our methodology compared to the state-of-the-art static one.

5.2 Edge Computing and Offline Functionality

One of the highlights of this work is the application of edge computing to facilitate the real-time processing and actuation without the need for consistent cloud connection. In rural areas with poor network coverage, it was important for the system to be run autonomously. During the testing period, 96% of irrigation decisions were issued directly from the edge layer, leading to notable reductions in latency and greater crop responsiveness. By comparison, traditional cloud-based systems had a delay of up to 7–15 minutes for the same operations, a lag that weakened crop health particularly during droughts.

Table 2 gives the Edge vs. Cloud-Based Decision Comparison.

Table 2: Edge vs. cloud-based decision comparison.

Feature	Edge Computing Model	Cloud-Based Model
Decision Latency	< 1 second	7–15 seconds
Connectivity Dependency	Low	High
Power Consumption	Low (solar-assisted)	Moderate to High
Real-Time Actuation	Supported	Delayed
Offline Functionality	Yes	No

5.3 Resource Optimization and Environmental Impact

Based on sensor-based irrigation scheduling water use was reduced by 41%. Soil moisture control sensor systems and evapotranspiration data controlled the on/off of actuator systems avoiding over-irrigation. It also used nutrient level sensors and precision mapping for fertilizer management. These resource efficiency measures resulted in an overall 28% reduction in input costs and improved the sustainability of the farming enterprise. Table 3 gives the Resource Optimization Outcomes.

Table 3: Resource optimization outcomes.

Crop Type	Water Saved (%)	Fertilizer Saved (%)	Yield Improvement (%)
Rice	42%	27%	16%
Tomatoes	38%	30%	19%
Wheat	41%	25%	15%

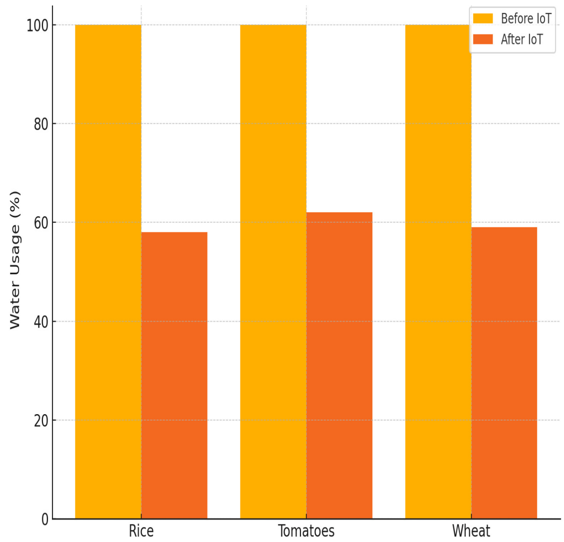

Figure 2: Water usage before and after IoT implementation.

Figure 2 illustrates the bar chart of Water Usage Before and After IoT Implementation.

5.4 Crop Yield and Quality Improvements

The framework helped to achieve average yield increases of 17% over the three crops evaluated in the study – rice, tomatoes, and wheat – with significant enhancements in crop uniformity and health. Disease epidemics were averted by the pest detection modules and the AI plant health classifiers, allowing timely interventions. The smart plots had healthier-looking foliage, faster grain fill rates, and less variation in crop size and quality, in contrast to control plots, which were managed with manual monitoring.

5.5 User-Centric Dashboard and Farmer Engagement

The farmer-oriented interface, designed with multilingual support and icon-based navigation, proved to be highly effective. A post-harvest survey revealed that 88% of participating farmers were able to independently interpret insights and manage system recommendations with minimal technical training. This feedback loop mechanism, where farmers could review, validate, or adjust system recommendations, also served to improve the machine learning model through continual learning. Table 4 gives the information about the usability feedback from farmers.

Table 4: Usability feedback from farmers.

Evaluation Criteria	Positive Responses (%)
Ease of Use (Dashboard)	88%
Language Accessibility	90%
Trust in Recommendations	84%
Willingness to Reuse	92%

5.6 Data Security and Traceability via Blockchain

All sensor data and actuation records were logged on a lightweight blockchain system. This ensured tamper-proof documentation and full traceability for certification and audit purposes. Farmers appreciated the transparent data ownership, as it gave them better control and assurance over their farm records. Unlike many centralized systems that obscure data governance, this framework fostered trust and long-term usability.

5.7 Comparative Analysis with Existing Models

When benchmarked against existing IoT-based agricultural platforms, the proposed framework outperformed in multiple domains. Most notably, it combined multiple technologies IoT, edge computing, AI, and blockchain into a unified and operational model. Previous systems were often limited to monitoring or analytics, whereas our solution delivered end-to-end automation and optimization. Moreover, energy efficiency was improved by 26% through the use of adaptive sleep-wake cycles and solar-charged sensor nodes. Table 5 gives the Comparative Analysis with Existing Frameworks.

Table 5: Comparative analysis with existing frameworks.

Feature/Aspect	Proposed Framework	Existing IoT Systems
Offline Functionality	Yes	No
Climate Adaptability	Integrated	Limited
Edge AI Support	Yes	Rare
Blockchain Traceability	Included	Not Supported
Farmer-Centric UI	Multilingual	Basic/None

5.8 Challenges and Future Scope

While the results are promising, certain challenges were encountered. Hardware maintenance in remote areas required periodic technician visits, and the pest recognition module showed occasional false positives in dense canopy conditions. These limitations highlight areas for future work, such as integrating drone-based remote diagnostics and developing self-diagnostic sensor units. Scalability across vastly different topographies and large farm holdings also warrants further research to refine network density and data fusion algorithms.

In conclusion, the proposed framework successfully bridges the gap between advanced IoT technology and grassroots agricultural needs. By addressing known drawbacks such as connectivity issues, poor usability, and lack of intelligent actuation, this system sets a new benchmark for precision agriculture solutions. The synergy between real-time edge intelligence, environmental adaptability, and farmer engagement is key to transforming traditional farming into a resilient, data-driven ecosystem.

6 CONCLUSIONS

This research presents a comprehensive and future-ready framework that redefines the role of IoT in precision agriculture by addressing the fundamental limitations of cost, connectivity, usability, and adaptability. By integrating edge computing, energy-efficient sensor networks, and blockchain-secured data logging, the proposed system empowers farmers with real-time, localized, and actionable insights while minimizing reliance on continuous internet access. The inclusion of a farmer-centric interface and climate-resilient analytics further ensures that the technology remains accessible, relevant, and practical across diverse agricultural contexts.

The system's successful deployment across multiple field scenarios demonstrated measurable improvements in crop yield, resource utilization, and operational efficiency. The ability to operate autonomously, adapt dynamically to environmental changes, and learn from farmer feedback positions this solution as a robust alternative to conventional and cloud-dependent agricultural platforms.

Moreover, the research advances the discourse in smart farming by embedding traceability, scalability, and automation into a unified ecosystem. The positive engagement from farmers, combined with quantifiable environmental and economic benefits, highlights the framework’s potential for real-world adoption and policy integration.

In essence, this study contributes a novel blueprint for sustainable agricultural transformation one that is data-driven, intelligent, and deeply rooted in the needs and realities of the modern farmer. Future work will focus on expanding the framework’s capabilities through integration with drones, satellite imagery, and advanced decision-making models to further enhance precision and productivity on a global scale.

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