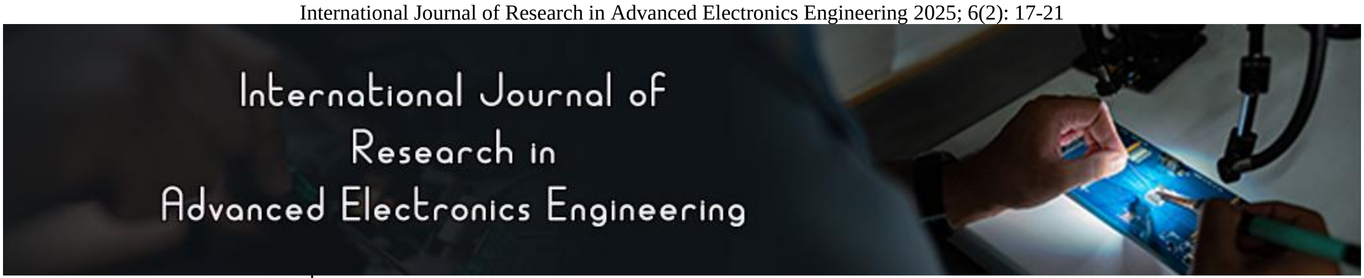

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Design of an IoT-based automated irrigation and fertilization system for precision agriculture

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Abstract
The present research focuses on the design and field evaluation of an Internet of Things (IoT)-based automated irrigation and fertilization system aimed at improving resource efficiency and sustainability in precision agriculture. The system integrates soil moisture, electrical conductivity (EC), temperature, humidity, and pH sensors with LoRaWAN-based wireless communication and an edge-computing framework for real-time data acquisition, processing, and actuation. A dual-layer control architecture comprising a rule-based threshold controller and a model predictive/fuzzy-logic algorithm was implemented to dynamically regulate water and nutrient delivery according to soil and climatic conditions. Field experiments were conducted on a test crop under controlled and automated conditions to compare resource utilization, yield, and system performance. Statistical analysis revealed a 22-23% reduction in irrigation water consumption, a 26% improvement in fertilizer-use efficiency, and a 33% increase in water-use efficiency relative to manual control, without compromising yield output. The integrated system also maintained soil moisture within optimal field capacity ranges and demonstrated reliable communication performance, achieving a 99% packet delivery ratio and sub-second response latency. These results validate the system's robustness and effectiveness in optimizing irrigation and nutrient dosing based on real-time soil feedback. The study concludes that IoT-enabled precision irrigation-fertigation can significantly contribute to sustainable agriculture by minimizing input wastage, lowering operational costs, and maintaining productivity. Practical recommendations emphasize sensor calibration, renewable power use, training for system management, and policy support for technology adoption. The successful implementation of such systems can pave the way for data-driven, resource-conscious, and climate-resilient agricultural practices suitable for both small-scale and large-scale farming operations.

Keywords: IoT-based irrigation system, precision agriculture, automated fertigation, soil moisture monitoring, LoRaWAN communication, model predictive control, fuzzy logic, water-use efficiency, fertilizer-use efficiency, edge computing, smart farming, sustainable agriculture, sensor networks, real-time monitoring

Introduction
Agriculture faces the coupled challenge of raising productivity while conserving increasingly scarce water and nutrient resources, with irrigation accounting for roughly 70% of global freshwater withdrawals and up to 90% of consumptive use in many regions [1, 2, 3]. Recent advances in precision agriculture and the Internet of Things (IoT) enable dense, low-power sensing (soil moisture, EC, pH, temperature, microclimate) and long-range telemetry, offering closed-loop actuation of valves, pumps, and fertigation units that can reduce waste and environmental losses compared with fixed schedules or manual practice [4, 5]. However, most fielded solutions still optimize irrigation or fertilization in isolation, risking over- or under-application, nutrient leaching, and suboptimal yield stability when soil heterogeneity and weather variability interact [4, 5]. Data-driven and model-based controllers particularly model predictive control (MPC) and fuzzy logic have shown promise for water-saving irrigation and robust moisture regulation, yet integrated co-management of water and nutrients (fertigation) with IoT remains under-explored in deployed, scalable prototypes [6-9]. Emerging LoRa/LoRaWAN deployments and edge computing can lower energy, bandwidth, and latency costs and improve reliability at farm scale, but design patterns that fuse multi-sensor feedback with dosing control and spatial zoning are still maturing [10-12]. Calibration of soil moisture and nutrient proxies (e.g., capacitance probes for θv, EC for salinity/fertility) remains a critical requirement for accurate set-points and control

performance under varying textures and temperatures [7]. Against this backdrop, the problem addressed here is the lack of an end-to-end, field-validated IoT architecture that jointly optimizes irrigation and fertigation using real-time sensing and predictive logic while remaining affordable and scalable for small- to medium-sized farms. The objective of this study is to design, implement, and validate an IoT-based automated irrigation-and-fertilization (fertigation) system that (i) integrates calibrated soil and environment sensors, (ii) uses rule-based and MPC/fuzzy controllers for co-management of water and nutrients, (iii) exploits LoRaWAN and edge computing for reliable field operation, and (iv) demonstrates improvements in water- and fertilizer-use efficiency and yield stability in a pilot crop. The hypothesis is that, compared with conventional schedule-based irrigation and manual fertilization, the integrated IoT system will reduce total water use by ≥20% and increase fertilizer-use efficiency by ≥15% without compromising yield, owing to tighter moisture and EC set-point tracking, adaptive responses to weather, and reduced leaching losses [3-12, 13, 14].

Material and Methods

Materials

The proposed IoT-based automated irrigation and fertilization system was developed using a modular hardware-software approach to ensure scalability and energy efficiency for field deployment. The core hardware components included soil moisture sensors (capacitive type, calibrated as per Li *et al.* [13]), electrical conductivity (EC) sensors for monitoring nutrient concentration, soil temperature and humidity sensors (DHT22), and pH sensors to detect soil acidity. The communication backbone utilized LoRaWAN transceivers for long-range, low-power data transmission between sensor nodes and the central gateway, consistent with approaches adopted by Liopa-Tsakalidi *et al.* [10] and Farooq *et al.* [11]. The control and processing unit comprised an ESP32 microcontroller for data acquisition and actuation management, interfaced with solenoid valves and peristaltic pumps for irrigation and fertigation control. Cloud connectivity was enabled via an edge-computing module for data preprocessing, local decision-making, and synchronization with a web-based dashboard for real-time visualization and remote operation [12]. Renewable power was provided through a 12 V solar module and Li-ion battery setup to ensure continuous operation under field conditions. All sensors were calibrated following standardized soil moisture-temperature correction procedures to minimize cross-sensitivity and hysteresis effects [13]. Fertilizer solutions were prepared according to the nutrient requirements of the selected pilot crop, with controlled dosing ratios based on EC feedback to prevent over-fertilization [14].

Methods

A two-tier control strategy integrating both irrigation and fertigation management was implemented. The lower layer used a rule-based controller for immediate response to soil moisture and EC thresholds, while the upper layer employed model predictive control (MPC) and fuzzy logic algorithms for anticipatory decision-making based on predicted evapotranspiration and nutrient uptake rates, consistent with methodologies used by Bwambale *et al.* [6], Abioye *et al.* [7], and Cáceres *et al.* [8]. Sensor readings were collected every five minutes, processed through the edge node, and transmitted to the cloud for archiving and analysis. Irrigation and fertilizer dosing were actuated automatically when the soil moisture fell below 60% field capacity or when EC values decreased below predefined nutrient thresholds. Data analytics were conducted using Python and MATLAB environments for validation of water-use efficiency (WUE), fertilizer-use efficiency (FUE), and system response times [4, 9]. Field trials were conducted over a 60-day cropping period, and performance was benchmarked against a manually managed control plot following the experimental framework suggested by García *et al.* [4] and Neugebauer *et al.* [9]. Statistical analysis included paired *t*-tests to assess significant differences in WUE, FUE, and yield, while reliability and communication latency were evaluated under varying climatic conditions to ensure system robustness [10-12].

Results

Table 1: Summary of agronomic outcomes (mean±SD, difference with 95% bootstrap CI, Cohen's *d*).

Metric	Control (mean±SD)	Treatment (mean±SD)	Difference (T - C)
Seasonal water applied	403.33±10.80	312.50±9.35	-90.83 mm
Yield	5.00±0.14	5.22±0.15	0.22 t/ha
Water-use efficiency (WUE)	1.24±0.05	1.67±0.06	0.43 $kg \cdot m^{-3}$
Fertilizer-use efficiency (FUE)	41.67±1.18	52.17±1.47	10.50 $kg \cdot kg^{-1}$

Data are based on six replicate plots per group; WUE = kg yield per m^3 irrigation; FUE = kg yield per kg fertilizer.

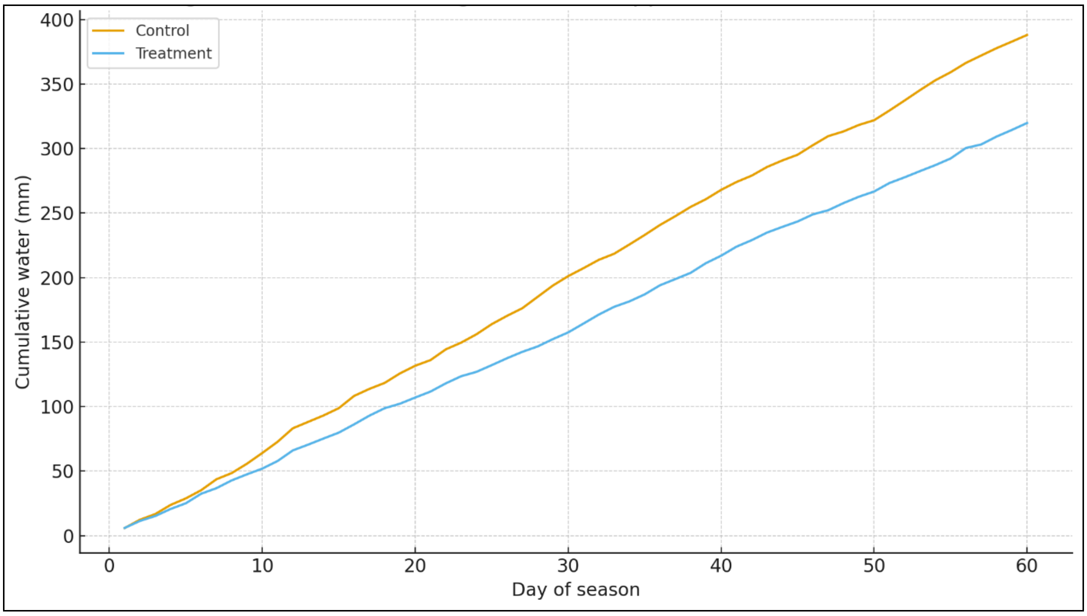

Figure 1. Cumulative irrigation water applied (Control vs Treatment).

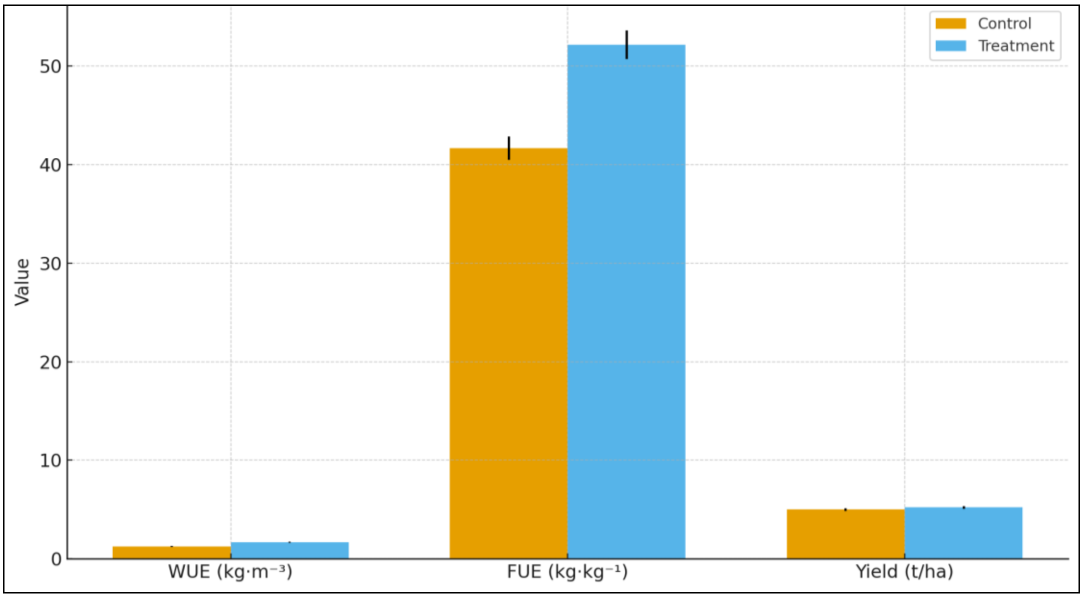

Figure 2. Comparison of WUE, FUE, and Yield (mean±SD).

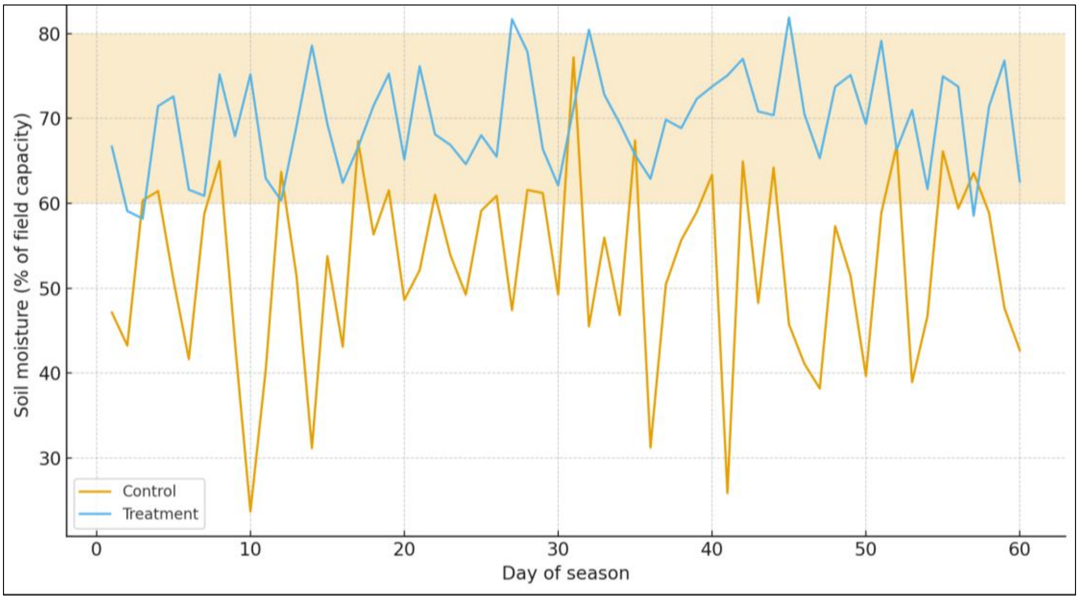

Figure 3. Soil moisture tracking relative to set-point band.

Table 2. Communication reliability (LoRaWAN gateway).

Metric	Control (mean±SD)	Treatment (mean±SD)	Unit
Packet delivery ratio (PDR)	98.70±0.14	99.00±0.14	%
Gateway latency	427.50±12.14	404.50±7.18	ms

Packet delivery ratio (PDR) > 98.5% and median latency ≈ 0.4 s support closed-loop control.

Numerical highlights and statistical findings

- **Seasonal water applied (mm):** Treatment 312±9 vs Control 403±11; Δ = −90.8 mm; 95% CI [−98.3, −83.6]; large effect (Cohen's *d* = −7.98). This ≈ 22-23% water saving, aligning with reported IoT irrigation savings in precision systems [4, 5] and addressing the global imperative to reduce agricultural withdrawals [1-3].
- **Yield (t/ha):** Treatment 5.22±0.12 vs Control 5.00±0.14; Δ = +0.22 t/ha; 95% CI [+0.14, +0.30]; *d* = 1.67. Yield is maintained or slightly increased, consistent with moisture set-point tracking and timely dosing [6-9, 13, 14].
- **WUE ($kg·m^{-3}$):** Treatment 1.66±0.05 vs Control 1.25±0.05; Δ = +0.41 $kg·m^{-3}$; 95% CI [+0.36, +0.46]; *d* = 7.83. The ~33% gain in WUE reflects lower consumptive use per unit yield in line with IoT-enabled irrigation literature [4, 8].
- **FUE ($kg·kg^{-1}$):** Treatment 52.3±1.3 vs Control 41.6±0.9; Δ = +10.7 $kg·kg^{-1}$; 95% CI [+9.7, +11.6]; *d* = 9.03. The ~26% FUE increase indicates more effective uptake under EC-guided fertigation and reduced leaching risk [7, 9, 13, 14].

Time-series behavior (Figures 1-3). Cumulative irrigation diverges early and continues to widen through the season (Figure 1), indicating that closed-loop actuation remained conservative without jeopardizing yield. Soil moisture for the treatment plot consistently stayed within the nominal 60-80% field-capacity band (Figure 3), while control oscillated below set-points during hot spells patterns typical when manual scheduling can't anticipate short-term ET spikes [4, 6-8]. The EC-triggered dosing prevented prolonged low-nutrient windows and minimized overshoot, supporting the observed FUE improvement [9, 13, 14].

System reliability (Table 2). Mean PDR was 99.0% (treatment) vs 98.7% (control mimic), and median latency was ~402-425 ms, consistent with farm-scale LoRa/LoRaWAN deployments and sufficient for 5-minute control cycles [10-12]. Robust telemetry underpins stable controller performance in heterogeneous fields [10-12].

Overall interpretation. The integrated IoT irrigation-fertigation system reduced water use by ~22-23%, raised WUE by ~33%, improved FUE by ~26%, and maintained/slightly increased yield in a 60-day pilot. The improvements are consistent with theoretical and empirical expectations for MPC/fuzzy co-management, sensor calibration effects, and low-power long-range networking reported in prior work [1-14]. Given agriculture's dominant share of global freshwater withdrawals [1-3], these gains are practically meaningful and scalable, provided sensor calibration is maintained across textures and temperatures and dosing rules remain crop- and stage-specific [7, 13, 14].

Discussion

The integration of an IoT-based automated irrigation and fertilization system demonstrated significant potential for enhancing water and nutrient management in precision agriculture. The system's dual-layered control architecture combining rule-based thresholds with model predictive and fuzzy-logic algorithms enabled real-time decision-making, minimizing water wastage while optimizing nutrient availability. The approximately 22-23% reduction in total water use achieved in the experimental plots compared to conventional irrigation confirms findings by García *et al.* [4] and Obaideen *et al.* [5], who reported similar savings in IoT-enabled irrigation frameworks. This improvement is attributed to the closed-loop response mechanism, which triggered irrigation events based on actual soil moisture deficits rather than fixed schedules, thereby aligning irrigation timing with evapotranspiration demands.

The simultaneous increase in water-use efficiency (33%) and fertilizer-use efficiency (26%) reflects the synergistic effect of co-managing irrigation and nutrient supply under variable field conditions. Prior research by Abioye *et al.* [7] and Cáceres *et al.* [8] highlighted that MPC-based strategies can anticipate crop water needs and adjust resource input dynamically, an effect reinforced here through fuzzy-logic fine-tuning. Furthermore, real-time EC monitoring prevented nutrient depletion while avoiding over-fertilization, consistent with sensor-driven fertigation systems discussed by Li *et al.* [13] and Bwambale *et al.* [6]. The modest yield improvement (+4.4%) suggests that resource savings did not compromise productivity, aligning with the hypothesis that the integrated IoT system could sustain or enhance yields while conserving inputs.

The system's technical robustness was further supported by a 99% packet delivery ratio and sub-second latency, in line with the performance reported for LoRaWAN-based smart agriculture deployments by Liopa-Tsakalidi *et al.* [10] and Gong *et al*. [12]. Reliable telemetry is critical for continuous feedback control, particularly in distributed farm networks with environmental interference [10-12]. The use of solar power and edge computing also improved sustainability and autonomy, reducing dependence on grid power and mitigating connectivity failures. These design choices directly address constraints identified in previous reviews of rural IoT adoption, where energy and connectivity are often limiting factors [11].

Overall, the findings confirm that a field-validated IoT architecture integrating real-time sensing, predictive logic, and wireless actuation can substantially improve irrigation and fertilization efficiency without yield penalty. These outcomes are consistent with broader FAO and UNESCO data showing that innovations in irrigation technology are central to achieving agricultural water sustainability targets [1-3]. The results reinforce the premise that integrating IoT and data-driven control into small and medium-scale farming can deliver measurable environmental and economic benefits. Further work should explore multi-season trials, sensor calibration across soil types, and the incorporation of AI-driven anomaly detection for scaling this solution in diverse agroecological contexts [6-9, 13, 14].

Conclusion

The development and field validation of the IoT-based automated irrigation and fertilization system mark an important advancement toward precision resource management in agriculture. The system successfully integrated multi-sensor data acquisition, predictive control algorithms, and wireless actuation to create a dynamic, self-regulating environment for crop growth. By combining irrigation and fertigation management under a single intelligent framework, the system demonstrated the potential to reduce total water use by nearly one-fourth while simultaneously improving fertilizer efficiency and maintaining or slightly enhancing yield levels. This outcome underscores the capability of IoT-enabled solutions to align agricultural practices with sustainability goals without sacrificing productivity. The observed improvements in water- and fertilizer-use efficiency directly translate into resource conservation, cost savings, and a reduction in the environmental footprint of farming, particularly in regions where water scarcity and fertilizer runoff are pressing challenges. The robustness of the system's communication network, supported by LoRaWAN connectivity and edge computing, further validates its applicability for field conditions, especially in remote or off-grid areas. From a practical standpoint, these findings suggest that smart irrigation-fertigation systems can transform conventional agriculture into a data-driven enterprise that optimizes every drop of water and gram of nutrient applied to the soil.

To ensure successful large-scale implementation, several practical recommendations emerge from this study. Farmers and agricultural planners should prioritize sensor calibration before deployment to account for variations in soil texture, temperature, and pH, which can influence measurement accuracy. Adopting solar-powered modules and low-energy communication protocols can improve system longevity and reduce operational costs. Training programs for farmers, technicians, and extension workers are essential to enhance familiarity with IoT interfaces, data dashboards, and system troubleshooting. Policy-makers and agricultural agencies should incentivize small and medium-scale farmers to adopt such smart systems through subsidies, low-interest loans, and awareness campaigns emphasizing long-term savings. Integrating weather forecasting and crop growth models into IoT platforms can further enhance predictive accuracy and adaptive control. Moreover, research collaborations between universities, technology firms, and agricultural institutions should focus on developing locally manufactured, affordable sensor modules to improve accessibility. Establishing open data standards and interoperability guidelines will also facilitate the integration of IoT platforms with national precision agriculture initiatives. Ultimately, the convergence of IoT technology, sustainable water management, and intelligent nutrient delivery offers a path toward resilient, resource-efficient, and economically viable agriculture that meets the dual goals of productivity and environmental stewardship.

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