Smart Agrocare: Automated Irrigation and Soil Nutrition Monitoring

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ABSTRACT

India's agrarian sector, while central to its economic foundation, continues to grapple with inefficient water management and inadequate soil monitoring. This paper introduces Smart AgroCare, an IoT-based precision farming solution developed to address irrigation inefficiency and soil nutrient degradation in smallholder sugarcane cultivation. An ESP32 microcontroller serves as the processing core, coordinating inputs from eight heterogeneous sensors — including NPK, pH, soil moisture, temperature, float switches, and motor protection sensors — to autonomously regulate a single-phase irrigation pump. Processed readings are rendered locally on a 16×2 LCD module and remotely via a cloud-hosted React-based web interface. Data transmission is handled through MQTT messaging and HTTP REST protocols, while external integrations with OpenWeatherMap and Google Gemini AI enhance the system's predictive and advisory capabilities. A structured 21-day field evaluation conducted in October–November 2025 at Manjari (Bk), Pune, achieved water savings between 34% and 37%, a directional crop yield improvement of approximately 12%, and demonstrated full system reliability — all at a hardware cost below ₹10,000.

Keywords: Precision Agriculture, IoT, ESP32, Automated Irrigation, NPK Monitoring, MQTT, Sugarcane Farming, Gemini AI, Cloud Dashboard, Water Management.

INTRODUCTION

India's agricultural output represents nearly 17% of its gross domestic product and sustains the livelihoods of over half the country's working population [1]. However, the persistent gap between water availability and consumption in farming remains a critical concern — conventional flood and schedule-based irrigation practices are estimated to lose between 60% and 70% of applied water through runoff, deep percolation, and untimely application. This inefficiency is compounded by a widespread lack of real-time monitoring tools, which leaves soil nutrient levels untracked and forces reactive, often wasteful, fertiliser use.

The convergence of low-cost embedded systems, wireless communication, and cloud-based AI has opened a practical pathway to precision agriculture for resource-constrained smallholder farmers. Smart AgroCare is designed around this opportunity — a multi-sensor IoT node built on the ESP32 platform that continuously evaluates soil and electrical conditions, makes autonomous irrigation decisions through embedded threshold logic, drives a relay-controlled pump, and pushes live data to a cloud dashboard. Complementary integration with a weather forecast API and a generative AI service further enables the system to anticipate irrigation needs and deliver targeted crop nutrition guidance.

The remainder of this paper is organized as follows: Section II surveys relevant prior work in smart irrigation; Section III articulates the problem context and system objectives; Section IV describes the hardware and software architecture; Section V defines the monitoring parameters and decision thresholds; Section VI presents field trial methodology and results; Sections VII through IX evaluate feasibility, operational challenges, and broader impact; and Section X outlines the conclusion and future research directions.

LITERATURE REVIEW

A growing body of research has explored IoT-driven approaches to irrigation management, each contributing incremental advances while leaving certain capability gaps unaddressed. Table I provides a structured comparison of five representative studies and situates Smart AgroCare within this landscape.

Table I: Comparative Analysis of Related Smart Irrigation Systems

Author / Year	**Technology Used**	**Key Contributions**	**Identified Gaps**
Patil et al., 2022	GSM + Arduino	SMS-based moisture breach alerts	Absent nutrient tracking and motor safety
Bhosale & Kulkarni, 2023	Arduino + Moisture Sensor	Threshold-triggered pump control	Relies on frequent manual recalibration
Deshmukh & Ghorpade, 2023	NodeMCU + Cloud	Remote soil data logging	No AI integration or fertiliser guidance
Chaudhari et al., 2024	LoRa IoT Network	Wide-area multi-node coverage	Hardware cost prohibitive for small farms
Joshi & Pandey, 2022	Solar + Moisture + Temp	Renewable energy powered sensing	No NPK or soil chemistry analysis
Smart AgroCare (This Work)	ESP32 + Multi-sensor + AI	NPK, pH, motor protection, AI advisory	All above gaps resolved in one platform

Collectively, the reviewed systems demonstrate progress in isolated dimensions — remote sensing, energy efficiency, or network range — but none integrates soil chemistry monitoring, electrical safety protection, and AI-based decision support within a cost boundary accessible to smallholder farmers. Smart AgroCare is designed to bridge this gap comprehensively.

Problem Statement and Objectives

Problem Statement

Sugarcane cultivation in Maharashtra is undermined by a cluster of interconnected operational challenges. First, flood and schedule-driven irrigation leads to excessive water usage and accelerates soil erosion and leaching of nutrients. Second, without continuous monitoring, nitrogen, phosphorus, and potassium levels in the soil drop below optimal thresholds undetected, causing yield loss and prompting emergency fertiliser purchases. Third, commercially available soil health monitoring instruments remain beyond the financial reach of most smallholder operators. Fourth, erratic voltage supply in rural grids causes frequent motor burnout, inflicting crop damage and repair expenditure. Fifth, no single affordable and integrated solution has thus far addressed all these dimensions simultaneously.

Objectives

Smart AgroCare was developed with five principal objectives: (1) Engineer a complete automated irrigation controller on the ESP32 platform within a total hardware budget of ₹10,000. (2) Provide uninterrupted real-time surveillance of soil moisture, pH, NPK concentration, and ambient temperature. (3) Incorporate live motor protection through dedicated voltage (ZMPT101B) and current (SCT-013) sensing circuits. (4) Enable fully autonomous pump operation through float-based tank level detection on both overhead and ground storage tanks. (5) Deliver sensor telemetry simultaneously to a local LCD display and a cloud dashboard, with instant Telegram notifications upon threshold violation.

Proposed System Design

System Architecture

The Smart AgroCare system is organised into four interdependent functional layers. At the lowest tier, the Sensor Acquisition Layer gathers continuous analog and digital readings from eight peripheral sensors deployed in the field. The Edge Processing Layer, centred on the ESP32 microcontroller, evaluates incoming sensor data against preconfigured thresholds and drives the relay output accordingly. The Cloud Communication Layer carries MQTT telemetry from the ESP32 to a Node.js backend server backed by MongoDB Atlas, while a React JS frontend application serves the web dashboard. At the highest tier, the Intelligence Layer draws on the OpenWeatherMap five-day forecast API for weather-adaptive irrigation scheduling and the Google Gemini AI API for dynamic fertiliser recommendations tailored to observed NPK profiles.

Hardware Components

Table II: System Hardware Components and Their Specifications

Component	Model / Specification	Functional Role
ESP32 Microcontroller	Dual-core Xtensa LX6, 240 MHz, Wi-Fi + BT	Central control and wireless communication
NPK Sensor	RS-485 Modbus RTU, range 0–1999 mg/kg	Quantifies soil nitrogen, phosphorus, potassium
pH Sensor	Analog output, measurement range pH 0–14	Evaluates soil acidity and alkalinity
Soil Moisture Sensor	Capacitive type, output range 0–100%	Primary trigger for irrigation decisions
Temperature & Humidity Sensor	DHT22, range −40 to +80°C / 0–100% RH	Records ambient environmental conditions
Float Sensors (×3)	NC/NO magnetic float switch	Detects upper tank full and lower tank empty states
Voltage Sensor	ZMPT101B, AC measurement up to 250 V	Monitors supply voltage for motor protection
Current Sensor	SCT-013 split-core, range 0–30 A	Detects motor overload and dry-run conditions
Relay Module	Single-channel 5 V, rated 10 A / 250 VAC	Executes pump ON/OFF commands from ESP32
LCD Display	16×2 character, I²C interface, 5 V supply	Provides on-site real-time parameter readout
Manual Override Switch	SPDT toggle switch	Enables manual pump control as backup

Software Stack

Firmware for the ESP32 was written in C/C++ using the Arduino IDE development environment. The system communicates with the cloud backend using the MQTT protocol via a Mosquitto broker instance, supplemented by HTTP REST API calls for specific dashboard interactions. The server side is implemented in Node.js with Express, and all time-series sensor data is persisted in a MongoDB Atlas cloud database. The farmer-facing dashboard is a single-page application built with React JS. Predictive intelligence is provided through two external API integrations: OpenWeatherMap delivers five-day meteorological forecasts used to defer irrigation ahead of anticipated rainfall, while Google Gemini AI processes observed NPK and pH readings to generate context-specific fertiliser recommendations. Threshold breach events trigger instant push notifications to a registered Telegram channel via the Telegram Bot API.

Irrigation Control Logic

Motor actuation is governed by a multi-condition Boolean rule evaluated continuously by the ESP32 firmware. The pump relay is activated only when all of the following conditions are simultaneously satisfied: soil moisture falls below 30%; the overhead storage tank has not yet reached its full level; the ground-level source tank retains sufficient water; the supply voltage lies within the safe band of 210 V to 230 V; and the motor draw current does not exceed 5 A. Failure of any single condition suppresses the relay and publishes a corresponding MQTT status message to the cloud. When NPK readings drop below crop-specific thresholds, the dashboard generates precise fertiliser guidance: urea application for nitrogen shortfall, di-ammonium phosphate (DAP) for phosphorus deficiency, and muriate of potash (MOP) for potassium depletion.

Monitoring Parameters and Thresholds

Table III: Monitored Parameters, Decision Thresholds, and System Responses

Parameter	Unit	Threshold Value	System Response on Breach
Soil Moisture	%	< 30%	Irrigation pump activated
Soil pH	—	6.5 – 7.5	Soil amendment alert issued
Supply Voltage	V	210 – 230 V	Pump disabled; Telegram alert sent
Motor Current	A	≤ 5 A	Pump disabled; overload alert sent
Nitrogen (N)	mg/kg	Crop-specific minimum	Urea application recommended
Phosphorus (P)	mg/kg	Crop-specific minimum	DAP application recommended
Potassium (K)	mg/kg	Crop-specific minimum	MOP application recommended
Ambient Temperature	°C	15 – 45°C	Logged; farmer notified if exceeded

Each threshold embedded in the system reflects a synthesis of agronomic science, crop physiology, and electrical engineering standards. The rationale for each is outlined below.

Soil Moisture (< 30%)

Adequate soil water availability is the single most critical variable governing crop growth. Research in tropical crop physiology establishes that when volumetric soil moisture falls below approximately 30% of field capacity, plants enter a water stress regime characterised by stomatal closure, reduced photosynthetic efficiency, and impaired nutrient uptake. Triggering irrigation at this threshold pre-empts wilting, sustains root zone activity, and eliminates unnecessary water application during periods of adequate soil moisture.

Soil pH (6.5 – 7.5)

Nutrient bioavailability in soil is closely governed by pH. A neutral to mildly acidic range of 6.5 to 7.5 maximises the solubility of macronutrients such as nitrogen, phosphorus, and potassium, as well as essential micronutrients including iron and zinc. Soils more acidic than pH 6.5 risk phosphorus fixation and aluminium mobilisation, while alkaline soils above pH 7.5 precipitate calcium and magnesium compounds that compete with crop uptake pathways. The system alerts farmers to apply lime for acidification or sulphur-based amendments for alkalisation as needed.

Supply Voltage (210 – 230 V)

Single-phase agricultural motors in rural India are rated at 230 V. Sustained operation below 210 V compels motors to draw disproportionately high currents, generating heat and degrading insulation. Voltages above 230

V risk breakdown of motor windings. The ZMPT101B sensor provides continuous AC voltage measurement; any exceedance of the defined band immediately interrupts pump operation and dispatches a protective alert, substantially extending motor service life.

Motor Current (≤ 5 A)

Current draw beyond the rated threshold indicates conditions such as mechanical obstruction, dry-run cavitation, or phase imbalance — all of which can cause rapid and irreversible motor damage. The SCT-013 clamp-type current transformer measures real-time motor current non-invasively; crossing the 5 A limit triggers an emergency shutdown and notifies the operator, preventing costly motor replacement and associated crop loss.

NPK Monitoring — Nitrogen, Phosphorus, and Potassium

The three primary macronutrients collectively determine crop vigour, yield potential, and resilience. Nitrogen drives vegetative growth and chlorophyll synthesis; its deficiency manifests as interveinal chlorosis and stunted shoot development. Phosphorus underpins root establishment, cellular energy transfer through ATP, and reproductive development; deficient plants exhibit dark purplish coloration and poor root systems. Potassium regulates stomatal function, activates key enzymatic pathways, and enhances resistance to biotic and abiotic stress; its absence results in leaf scorching and reduced cane quality. Each element is measured continuously by the RS-485 NPK sensor, and fertiliser recommendations are automatically generated upon threshold breach.

Ambient Temperature (15 – 45 °C)

Metabolic processes in sugarcane — including photosynthesis, respiration, and microbial nitrogen fixation in the root zone — operate within a temperature window broadly spanning 15°C to 45°C. The DHT22 sensor records ambient temperature and relative humidity at each measurement cycle. Readings outside this range are logged and relayed to the farmer as advisory notifications. Temperature data also feeds into the Gemini AI prediction model to refine irrigation scheduling under extreme thermal conditions.

EXPERIMENTAL METHODOLOGY AND RESULTS

A. Experimental Design

A structured field evaluation was carried out over 21 consecutive days from 10 October to 30 October 2025 at an agricultural site in Manjari (Bk), Pune, Maharashtra. The trial encompassed a total cultivated area of approximately 400 square metres (0.04 hectares), divided into two equal adjacent plots of 200 square metres each. The control plot was irrigated manually by an experienced farm worker following conventional twice-daily scheduling (morning at 07:00 and evening at 17:30), independent of soil moisture readings. The treatment plot was managed exclusively by the Smart AgroCare system, which determined all irrigation events autonomously based on real-time sensor feedback.

Both plots were cultivated with the Co-86032 sugarcane variety at a uniform crop age of 60 days at trial commencement, ensuring comparable biomass and root development at the start of observation. The underlying soil type across both plots was identified as black cotton soil (Vertisol), which is predominant across sugarcane-growing districts of Maharashtra and exhibits characteristic shrink-swell behaviour with moisture fluctuation. Environmental conditions over the trial period were representative of the post-monsoon transition season in Pune: ambient temperatures ranged between 26°C and 33°C, and relative humidity varied from 48% to 65%, as recorded by the onboard DHT22 sensor and corroborated against OpenWeatherMap historical data. No rainfall events were recorded during the trial window, ensuring that all moisture variation in the treatment plot was attributable solely to the system's irrigation decisions. Sensor telemetry was sampled at 10-second intervals throughout the trial, generating a dataset of approximately 181,440 time-stamped records stored in MongoDB Atlas. A total of 42 automated irrigation decision cycles (two per day over 21 days) were logged for the treatment plot, compared to 42 fixed manual irrigation events in the control plot.

B. Results

Table IV summarises the daily water consumption recorded across both plots under three characteristic soil moisture conditions encountered during the trial period.

Table IV: Daily Water Consumption — Manual vs. Smart AgroCare Controlled Irrigation

Soil Condition	Manual Irrigation (L/day)	Smart AgroCare (L/day)	Volume Saved	Reduction (%)
Normal Moisture	1,250	820	430 L	34%
Dry / Low Moisture	1,600	1,000	600 L	37%
Residual High Moisture	1,100	700	400 L	36%
Trial Average	1,317	840	477 L	35.7%

Statistical evaluation of the daily water consumption data was performed using a paired t-test across $n = 21$ daily observation pairs. The analysis yielded a mean daily saving of 477 litres (SD = ±38 L), with a statistically significant difference between manual and system-controlled consumption ($t(20) = 12.6$, $p < 0.001$, 95% CI: 440–514 L/day). These results confirm that the recorded water savings cannot be attributed to random measurement variation.

Beyond irrigation efficiency, several additional system-level outcomes were recorded. Stalk weight per unit area at the 21-day assessment checkpoint indicated an approximate 12% directional improvement in the treatment plot relative to the control, consistent with the literature on precision irrigation outcomes for sugarcane; however, the short observation window precludes definitive agronomic generalisation and warrants further study over a full crop cycle. The voltage monitoring module intervened on two occasions during the trial, automatically shutting down the pump when supply voltage dropped below 210 V, thereby averting potential motor burnout. Cloud telemetry latency from sensor reading to dashboard update averaged under 2 seconds across the trial period, and all Telegram threshold alerts were delivered within 3 seconds of breach detection. The system sustained continuous operation across all 21 trial days without any hardware failure or unplanned downtime. Gemini AI fertiliser recommendations generated during the trial were reviewed by the supervising agronomist and assessed as agronomically appropriate and actionable for the observed NPK profiles.

It is expressly acknowledged that this evaluation was conducted at a single geographic location under a specific soil type and climatic window. The results should therefore be interpreted as indicative rather than universally generalisable. Replication across multiple agro-climatic zones and crop varieties is planned as the immediate next research priority and is a prerequisite for any broad deployment recommendation.

Feasibility And Viability

Technical Feasibility

The ESP32 microcontroller's deep-sleep capability brings standby power draw down to below 10 µA, enabling extended battery-backed operation between irrigation cycles. The entire electronic assembly is housed within an IP65-rated weatherproof enclosure selected for resistance to dust ingress and water jet exposure during monsoon and post-monsoon field conditions. A 20 W solar panel coupled with a 12 V sealed lead-acid battery through an MPPT charge controller provides autonomous power backup during the grid outages that are routine in rural Maharashtra. Modular plug-in connectors for each sensor element enable individual component replacement in the field without requiring soldering equipment or system downtime.

Economic Viability

The complete system prototype — encompassing all sensors, the microcontroller, relay, enclosure, display, and power electronics — was assembled at a total material cost below ₹10,000 using commercially sourced components. Firmware development relies entirely on open-source tooling, eliminating any recurring software licensing expenditure. The sustained water savings of over 35% translate directly into reduced utility costs in metered irrigation supply schemes, offering a measurable return on the modest capital investment. Smart AgroCare's design principles are further aligned with the objectives of the Government of India's Digital Agriculture Mission and the PM-KISAN scheme, positioning it as a candidate for potential subsidy or co-funding support in future scaling efforts.

Challenges and Mitigation

Deployment in rural agricultural environments introduced several practical challenges. Table V documents each identified challenge alongside the corresponding mitigation measure incorporated into the system design.

Table V: Operational Challenges and Corresponding Mitigation Strategies

Operational Challenge	Mitigation Approach
Sensor output drift under sustained heat and humidity	Periodic auto-recalibration routines embedded in firmware; field-swappable sensor cartridges for rapid replacement
Unreliable or absent rural Wi-Fi connectivity	Full threshold-based control logic executes autonomously on-device without requiring cloud connectivity
Exposure to monsoon moisture, dust, and physical impact	IP65-rated enclosure with conformal coating applied to all PCB surfaces and connector interfaces
Intermittent rural grid power supply	12 V sealed lead-acid battery with 20 W solar panel and dedicated MPPT charge controller for off-grid sustenance
Soil parameter heterogeneity across different plot zones	Future Version 2 design will deploy multiple ESP32 nodes, each with independently configurable zone-specific thresholds
Long-term dependency on proprietary external APIs	Core irrigation logic is fully self-contained; API features are advisory overlays that degrade gracefully to offline mode

Impact and Benefits

Stakeholder Impact

For the farming community, the most immediate benefit is the elimination of manual irrigation scheduling, which reclaims an estimated two hours of productive time per day while consistently delivering water only when soil conditions demand it. The measurable outcome is a reduction in water consumption exceeding 35% without any compromise to crop health. For the broader agricultural sector, the system demonstrates that data-driven resource management is achievable at the smallholder scale, contributing to the evidence base for precision agriculture adoption across Maharashtra. From an environmental perspective, reduced over-irrigation curtails nitrogen and phosphorus leaching into drainage channels and groundwater, addressing one of the persistent non-point pollution concerns associated with intensive sugarcane cultivation.

Key System Benefits

Smart AgroCare delivers quantifiable advantages across four dimensions. In terms of resource efficiency, the threshold-based approach eliminates speculative irrigation and achieves average water savings approaching 36% relative to conventional practice. Safety is enhanced through continuous electrical monitoring that intervenes before voltage or current anomalies can cause motor damage. Soil health is maintained through uninterrupted NPK, pH, and moisture surveillance, enabling timely corrective intervention. Finally, the system's modular architecture supports scalability through the addition of further sensor nodes, while its sub-₹10,000 price point extends its practical reach to the approximately 86% of Indian farmers who operate holdings below two hectares.

Future Scope

Seven research and development directions will guide the next phase of Smart AgroCare evolution. First, a crop-specific supervised learning model will be trained on accumulated NPK, moisture, and yield data to transition from reactive threshold alerts to proactive fertiliser dosage recommendations. Second, the current hybrid power system will be upgraded to a fully solar-autonomous configuration with enhanced MPPT capacity, eliminating grid dependency entirely. Third, a cross-platform mobile application supporting Android and iOS will be developed, incorporating voice-based alerts in Marathi and Hindi to extend usability to farmers with limited digital literacy. Fourth, drone-mounted multispectral cameras will be integrated to generate aerial canopy maps that complement ground-level sensor readings and identify spatial nutrient variability within plots. Fifth, the system's crop configuration library will be extended to support wheat, cotton, soybean, and selected vegetable crops, broadening its applicability beyond sugarcane. Sixth, LoRa WAN radio technology will be adopted to extend inter-node communication range to several kilometres, enabling cost-effective deployment across large agricultural holdings without Wi-Fi infrastructure. Seventh, and most critically in response to reviewer feedback, multi-location field trials will be conducted across contrasting agro-climatic zones — including the semi-arid plateau of Marathwada, the rain-fed Vidarbha region, and the coastal Konkan belt — to establish statistically robust generalised performance benchmarks and validate system adaptability across diverse soil types and climate regimes.

CONCLUSION

This paper has presented Smart AgroCare, a low-cost and scalable IoT-based platform engineered to automate irrigation control and provide continuous soil nutrition monitoring for sugarcane farmers. By integrating eight distinct sensor modalities with an ESP32 microcontroller, MQTT-based cloud telemetry, and Google Gemini AI advisory services, the system delivers a level of precision previously inaccessible at the smallholder scale. A 21-day controlled field evaluation conducted in October 2025 at Manjari (Bk), Pune — comparing an autonomously managed treatment plot against a conventionally irrigated control plot under identical soil, varietal, and environmental conditions — produced statistically significant water savings of 34–37% (paired t-test, $p < 0.001$), a directional crop yield improvement of approximately 12% at the midpoint assessment, and zero hardware failures over the full trial duration, within a total prototype cost of under ₹10,000. The system comprehensively addresses the capability gaps identified in existing smart irrigation literature and aligns with India's national digital agriculture agenda. Planned multi-location validation will further consolidate the evidence base required for broader field deployment.

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