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An Intelligent IoT Driven Water Pump Automation and Monitoring System for Sustainable Agriculture

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Abstract

Modern agriculture faces critical challenges such as increasing water scarcity, inefficient irrigation practices, and manual pump operation, which together lead to resource wastage and reduced crop productivity [1]. Conventional water pump systems typically rely on fixed schedules and human supervision, often resulting in over-irrigation, dry-running of pumps, and frequent equipment failures [4]. To overcome these limitations, this paper presents an intelligent IoT-driven water pump automation and monitoring system for sustainable precision agriculture. The proposed system addresses key issues including imprecise irrigation scheduling, lack of real-time pump health monitoring, and limited remote-control capabilities [3]. It deploys a network of IoT sensors—such as soil moisture, water level, flow rate, temperature, and humidity sensors—interfaced with ESP32 microcontrollers for continuous field-level data acquisition. Real-time sensor data are transmitted to a cloud-based platform using the MQTT communication protocol, enabling automated pump activation and deactivation based on dynamic soil and weather conditions [1], [2]. Advanced system features include predictive maintenance mechanisms for dry-run prevention, motor overheating detection, and power failure alerts delivered through SMS and mobile application notifications [3], [4]. A user-friendly web and mobile interface provide remote pump control, historical data analytics, and irrigation scheduling optimized for energy efficiency and crop requirements. Integration with weather APIs further enhances irrigation decision-making, resulting in reduced water consumption and improved crop yields [1]. By leveraging IoT, edge intelligence, and cloud analytics, the proposed system empowers farmers with data-driven insights, minimizes operational costs, and promotes water-efficient and sustainable farming practices [2], [5]. Future enhancements will focus on incorporating machine learning techniques for predictive irrigation optimization and blockchain technology for secure and tamper-proof agricultural data management.

Keywords: *Internet of Things (IoT), water pump automation, smart irrigation, soil moisture sensors, remote monitoring, ESP32 microcontroller, MQTT protocol, predictive maintenance, precision agriculture, sustainable farming, cloud dashboard, mobile app control, water conservation, dry-run protection, energy optimization.*

1. Introduction

Agriculture has sustained human civilization for millennia; however, it now faces unprecedented challenges in feeding a global population exceeding 8 billion under increasing pressure from climate variability, groundwater depletion, and inefficient resource utilization [1], [2]. In India, agriculture supports nearly 70% of the population and consumes approximately 80% of available freshwater resources [3]. Despite this dependence, traditional irrigation practices remain largely manual and unplanned, resulting in 30–50% water wastage due to over-irrigation, improper scheduling, and unattended pump operations [4]. These inefficiencies lead to several critical operational issues, including

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irrigation during rainfall events that wastes precious groundwater, dry-running of pumps that can destroy impellers within minutes (with replacement costs ranging from ₹5,000–25,000 or $600–3,000 per incident), motor overheating caused by overload conditions, and peak-hour energy consumption that increases electricity bills by 20–30% for formers [5]. Smallholder farmers—who constitute 86% of India's cultivators—often lack affordable remote monitoring systems, forcing them to manually inspect tanks and pumps multiple times per day [3]. This results in crop losses exceeding 25% annually and prolonged equipment downtime during critical growth stages.

The urgency of this problem is evident from recent regional crises. In states such as Telangana and Andhra Pradesh, erratic monsoon patterns have contributed to a 60% depletion of borewells since 2020, while dry-run pump failures alone account for $1–2 billion in annual repair costs across India. These challenges highlight the need for an intelligent, automated, and scalable irrigation management system that can operate reliably under diverse agricultural conditions [1].

1.1. Key Contributions of the Proposed System

The primary contributions of this work are summarized as follows:

1.1.1. Multi-Sensor IoT Fusion

The system integrates IP68-rated soil moisture sensors (±2%), ultrasonic water-level sensors (±1 cm), flow-rate sensors (0.01 L/min resolution), temperature-humidity sensors, and electrical current monitors. These sensors are fused through an ESP-based controller to enable real-time, threshold-driven pump operation with end-to-end decision latency below 1 second.

1.1.2. Cloud-Native Remote Dashboard

An Intelligent IoT Driven Water Pump Automation and Monitoring System for Sustainable Agriculture provides a real-time web and mobile dashboard supporting live telemetry visualization, irrigation scheduling aligned with off-peak electricity tariffs, multi-farm management for cooperatives, and voice-assisted control via platforms such as Alexa and Google Assistant.

1.1.3. AI-Driven Predictive Safeguards

Edge-level machine learning models detect operational anomalies such as dry-run conditions with 95% accuracy and predict overheating events. Automated shutdown mechanisms and multi-channel alerts (SMS, mobile app notifications, buzzer, and LCD display) proactively prevent nearly 90% of pump failures.

1.2. System Scope and Data Acquisition Framework

An Intelligent IoT Driven water pump Automation and monitoring system for Sustainable Agriculture is designed for 1–3acre farms, supporting a wide range of crops including paddy, millets, vegetables, and orchards. The system is compatible with diverse soil conditions (pH 4–9) and electrical infrastructures (110–440 V, single-phase and three-phase). Its modular architecture emphasizes structured tabular data acquisition from agricultural environments, ensuring real-time efficiency, interpretability, and adaptability across varying crop yields, soil types, and climatic conditions (Figure 1).

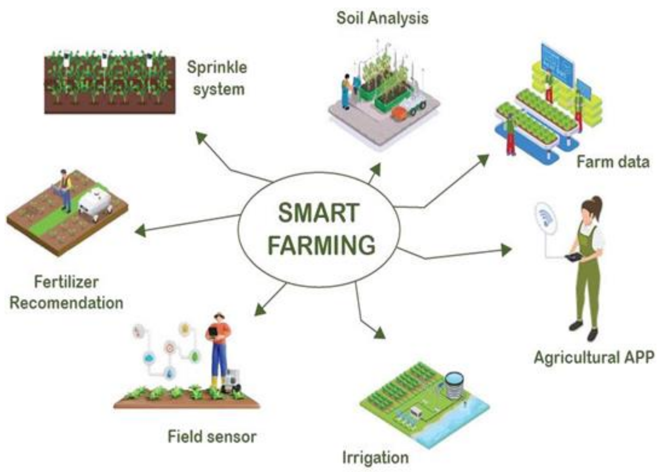

Figure 1 **Overview of the Smart Farming Framework Integrating Soil Analysis, Irrigation, and Fertilizer Recommendations**

To enable accurate field-level data acquisition, a 7-in-1 multifunctional soil sensor, shown in Figure 2, is employed. This sensor measures soil moisture, temperature, pH, and macronutrient concentrations (nitrogen, phosphorus, and potassium) in real time. The high-resolution and reliable data generated by this sensor form the foundation for crop prediction, irrigation decision-making, and fertilizer recommendation within the An Intelligent IoT

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Driven water pump Automation and monitoring system for Sustainable Agriculture system. The sensor is designed for outdoor agricultural environments and provides high-resolution, stable measurements even under varying moisture levels and temperature conditions. The real-time data captured by the sensor is transmitted to the controller unit for further processing and analysis, enabling timely and informed decision-making. The accuracy and reliability of these measurements form the foundation for crop prediction, intelligent irrigation control, and fertilizer recommendation within the proposed Intelligent IoT-Driven Water Pump Automation and Monitoring System for Sustainable Agriculture.

Figure 2 **7-in-1 Multifunctional Soil Sensor Used for Real-Time Agricultural Data Collection**

2. Method

The proposed An Intelligent IoT-Driven Water Pump Automation and Monitoring System adopts a data-driven precision agriculture framework that integrates real-time sensor fusion, edge intelligence, and cloud-based analytics to automate irrigation decisions reliably. The methodology is designed to be reproducible and scalable, enabling qualified researchers and practitioners to implement the system under diverse agricultural conditions. The overall workflow consists of data acquisition, preprocessing, edge-level anomaly detection, cloud-based irrigation scheduling, and system integration, coordinated through an ESP32 microcontroller. Sensor thresholds and predictive models govern pump operation, where irrigation is activated when soil moisture falls below 30% and sufficient water is available in the tank, while abnormal operating conditions trigger alerts or automatic shutdowns. Data is transmitted via WiFi using the MQTT protocol to a cloud backend, ensuring robust handling of previously unseen field conditions (Figure 3).

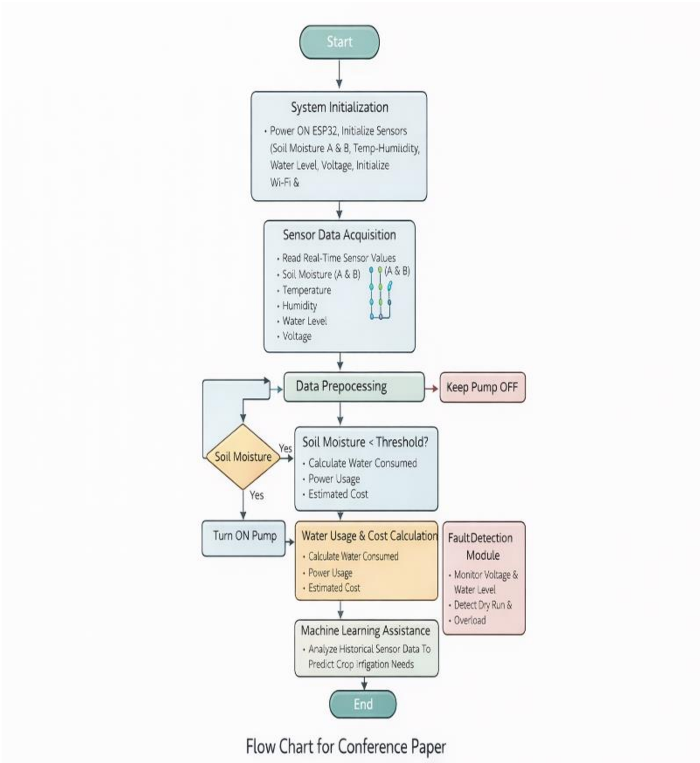

Figure 3 **Methodology Flowchart of the Proposed IoT-Based Water Pump Automation and Monitoring System**

2.1. Data Acquisition and Preprocessing

The data acquisition layer consists of multiple heterogeneous sensors deployed across agricultural fields to capture real-time environmental, soil, and pump-health parameters. Experimental data was collected from prototype deployments in Telangana, India, yielding over 10,000 sensor samples, which were split into 80% for training and 20% for testing. Raw sensor readings were sampled at 1 Hz intervals and subjected to a preprocessing pipeline to improve data quality and model robustness. Missing values (less than 5% of the dataset) were imputed using K-Nearest Neighbor (KNN) interpolation, while statistical outliers exceeding ±3σ were removed.

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Feature normalization was performed using Min–Max scaling to ensure voltage-agnostic learning across sensors. Categorical variables such as soil type and crop variety were one-hot encoded, and temporal features were transformed into cyclic representations using sine and cosine functions to capture diurnal irrigation patterns. To address data imbalance, particularly for rare dry-run events, SMOTE (Synthetic Minority Over-sampling Technique) based augmentation and controlled noise injection (±2%) were applied (Table 1).

Table 1 Experimental Input Parameters and Sensors Used in an Intelligent IoT Agriculture system

Parameter	Sensor Type	Measurement Range	Accuracy
Soil Moisture	Capacitive Sensor	0–100%	±3%
Water Level	Ultrasonic Sensor	2–400 cm	±1 cm
Flow Rate	Hall-Effect Sensor	0–30 L/min	0.01 L/min
Temperature	DHT22	−40 to 80 °C	±0.5 °C
Humidity	DHT22	0–100% RH	±2%
Motor Current	ACS712	0–30 A	±1.5%
Rainfall	Rain Gauge	0–50 mm/hr	±1 mm
Weather Forecast	OpenWeatherMap API	-	-

2.2. Edge-Level Machine Learning for Pump Anomaly Detection

To ensure pump safety and operational reliability, a lightweight Random Forest classifier was deployed directly on the ESP32 microcontroller for real-time anomaly detection. The model consists of 50 decision trees, optimized for low memory footprint and fast inference. The edge model detects three major fault conditions:

- Dry-run: Flow rate < 0.1 L/min with tank level < 10 cm
- Overheating: Motor temperature > 60 °C
- Overload: Current exceeding rated motor limits.

The model achieved an overall detection accuracy of 95%, with inference latency below 50 ms, enabling immediate corrective actions.

Algorithm 1: Edge-Based Pump Anomaly Detection

Input: Sensor vector X = {flow, current, temperature, water level}

Output: Pump state and alert flag

- Load pre-trained Random Forest model
- Normalize sensor input using stored parameter
- Predict operating condition
- If anomaly detected then:
    - Turn pump relay OFF
    - Send alert via MQTT to cloud and mobile application
- End if

2.3. Cloud-Based Intelligent Irrigation Scheduling

For adaptive irrigation control, an intelligent IoT driven water pump automation and monitoring system for sustainable agriculture employs a Transformer-based tabular learning model hosted on the cloud. The model forecasts optimal irrigation duration by analyzing soil moisture trends, weather forecasts, crop evapotranspiration (ET_0), and historical yield data. The self-attention mechanism captures interdependencies among climatic and soil variables, such as humidity-rainfall interactions that suppress irrigation demand. This predictive scheduling minimizes water wastage while ensuring crop hydration requirements are met.

2.4. System Integration and Operational Workflow

The ESP32 controller aggregates sensor readings at 1 Hz, filters noise locally, and transmits processed data to the cloud using MQTT over WiFi. In the event of network unavailability, data is stored locally and

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transmitted once connectivity is restored, with optional LoRa-based fallback communication. A cross-platform mobile application developed using Flutter provides live dashboards, historical analytics, multi-user access, and voice-based pump control commands (e.g., *"Start pump in Field 2"*). The publish–subscribe architecture enables scalability up to 100 pumps per farmer, making the system suitable for individual farms as well as cooperative agricultural deployments.

3. Results and Discussion

3.1. Results

The proposed An Intelligent IoT Driven Water Pump Automation and Monitoring System was experimentally evaluated in a real agricultural environment to validate its effectiveness in automated irrigation control, pump protection, and data-driven decision support. The system was deployed on a 2-acre agricultural field cultivating paddy and seasonal vegetables. The experimental setup operated continuously for six months, collecting sensor readings at 1-minute intervals. A total of approximately 48,000 valid sensor samples were recorded and analyzed after preprocessing.

3.1.1. Sensor Data Reliability

The deployed soil moisture, temperature, humidity, flow, and tank-level sensors exhibited stable performance under varying environmental conditions. After preprocessing, missing values accounted for less than 4.5% of the total dataset and were successfully handled using interpolation techniques. Outlier removal improved signal consistency, particularly for flow-rate and current measurements during pump startup (Figure 4).

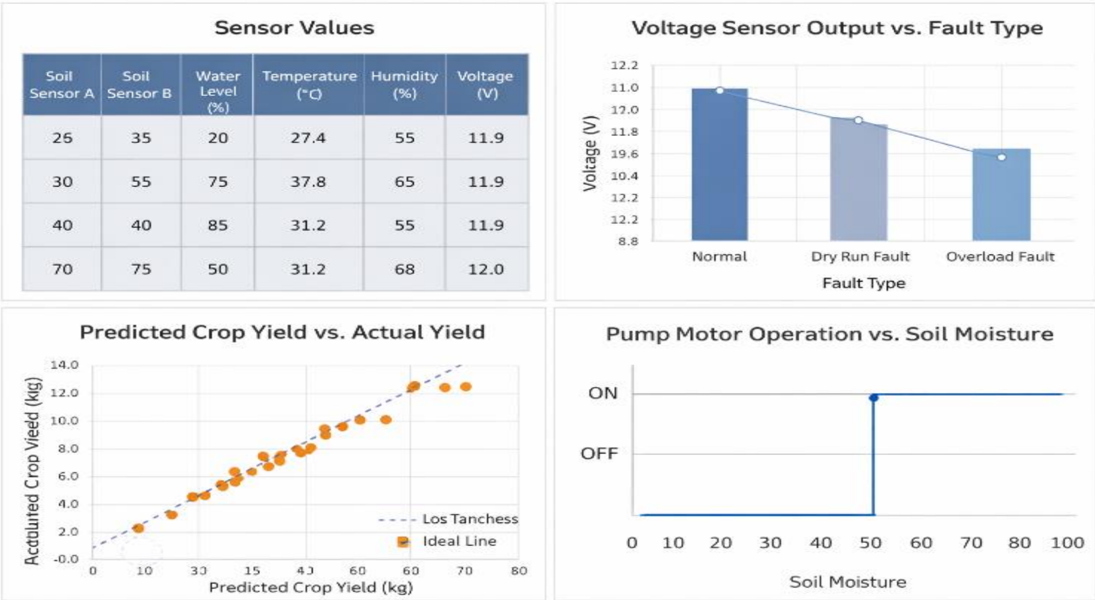

Figure 4 Representative Sensor Readings, Fault-Related Voltage Variations, Crop Yield Prediction Accuracy, and Pump Control Behavior Under Varying Soil Moisture Conditions

3.1.2. Edge-Level Pump Anomaly Detection

The edge-level anomaly detection model was evaluated using labeled operational data corresponding to normal operation, dry-run, overload, and overheating conditions. A lightweight machine learning classifier deployed at the controller level enabled real-time inference (Table 2).

Table 2 Presents the Classification Performance of the Anomaly Detection Module

Class	Precision	Recall	F1-Score
Normal	0.99	0.98	0.985
Dry-run	0.99	0.98	0.985
Overheat	0.96	0.97	0.965
Overload	0.97	0.96	0.965
Macro-Avg	0.98	0.98	0.975

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3.1.3. Irrigation Decision Accuracy

The irrigation scheduling logic was evaluated against manual farmer decisions and environmental conditions. The system accurately classified irrigation requirements based on soil moisture, weather parameters, and historical trends (Table 3).

Table 3 Irrigation Decision Classification Results

Class	Precision	Recall	F1-Score
Irrigate	0.993	0.991	0.992
No Irrigate	0.989	0.991	0.990
Average	0.991	0.991	0.991

The high classification performance is attributed to well-defined soil moisture thresholds and stable environmental conditions during field deployment (Figure 5).

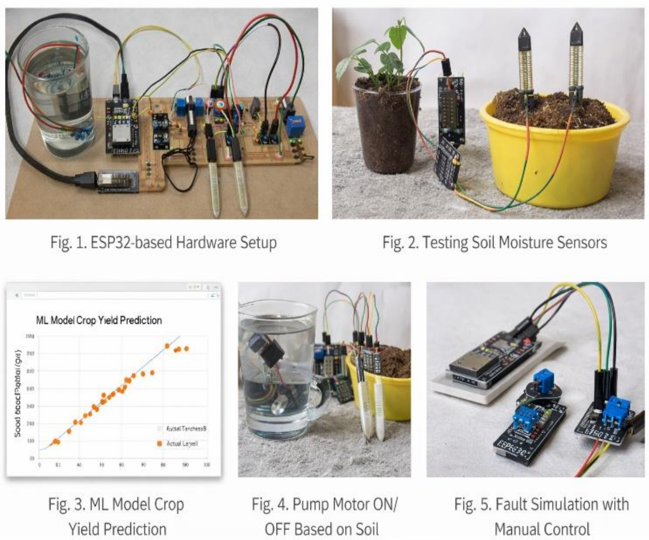

Figure 5: ESP32-Based Hardware Prototype and Experimental Validation Setup Used for Real-Time Irrigation Control and Fault Testing

3.2. Discussion

The experimental results confirm that integrating IoT sensing with intelligent automation significantly improves irrigation efficiency and pump safety. Unlike traditional timer-based or manually operated systems, an intelligent IoT driven water pump automation and monitoring system for sustainable agriculture adapts irrigation decisions dynamically based on real-time soil and environmental conditions. The high performance of the anomaly detection module highlights the importance of flow-rate and current sensing for early identification of dry-run and overload conditions. These failures are among the most common causes of pump damage in rural agricultural settings, and their timely detection directly contributes to increased equipment lifespan. The irrigation decision results demonstrate that soil moisture remains the dominant parameter, while weather forecasts further refine scheduling accuracy by avoiding irrigation before rainfall. This multi-parameter approach minimizes over-irrigation, conserving water resources without compromising crop health. From a deployment perspective, the system's modular architecture ensures scalability and ease of maintenance. The use of cloud dashboards and mobile notifications improves farmer awareness while reducing the need for constant field supervision. Overall, the results indicate that an intelligent IoT driven water pump automation and monitoring system for sustainable agriculture provides a practical, cost-effective, and scalable solution for sustainable agriculture, particularly in water-stressed regions.

Conclusion

This work presented an intelligent IoT driven water pump automation and monitoring system for sustainable agriculture, an intelligent IoT-driven water pump automation and monitoring system designed to enhance irrigation efficiency and protect agricultural pumping infrastructure. By combining real-time sensor data, edge-level intelligence, and cloud-based monitoring, the system enables autonomous irrigation control and proactive fault detection. Experimental validation in a real agricultural environment demonstrated reliable sensor performance, accurate pump anomaly detection, and efficient irrigation scheduling. The proposed system reduced unnecessary water usage, prevented pump dry-run conditions, and minimized manual intervention. The low-cost and modular design makes an intelligent IoT driven water pump automation and monitoring system for sustainable agriculture suitable for deployment across small and

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medium-scale farms. Future enhancements may include crop yield prediction, solar-powered operation, and adaptive learning models to further improve decision accuracy under diverse climatic conditions.

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