AI-Based Smart Irrigation System Using IoT and Machine Learning for Precision Agriculture

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ABSTRACT

Efficient water management is a cornerstone of sustainable precision agriculture, yet traditional irrigation often suffers from over-irrigation due to static scheduling. This paper presents a robust IoT-enabled smart irrigation framework that leverages the ESP32 microcontroller and a suite of environmental sensors (soil moisture, DHT22, rain, and water flow) integrated with machine learning for dynamic decision-making. Unlike threshold-based systems, our approach utilizes a Random Forest classifier to predict irrigation needs based on multivariate environmental inputs, achieving a prediction accuracy of 94.2%. Real-time data is synchronized with the Thing Speak cloud platform, enabling remote monitoring and data-driven insights. Experimental results demonstrate a 35% reduction in water consumption compared to conventional methods while maintaining optimal soil moisture levels for crop growth.

Keywords: Artificial Intelligence, Internet of Things, Smart Irrigation, ESP32, Machine Learning, Precision Agriculture, Thing Speak

INTRODUCTION

Global freshwater scarcity poses a significant threat to agricultural productivity, which currently accounts for approximately 70% of worldwide water withdrawals [1]. Traditional irrigation techniques, often relying on manual labor or timer-based systems, fail to account for the dynamic nature of soil moisture and micro-climatic variations, leading to significant water wastage and nutrient leaching [2]. The advent of the Internet of Things (IoT) and Machine Learning (ML) offers a transformative approach to precision agriculture by enabling real-time monitoring and intelligent actuation [3].

Previous studies have explored threshold-based automation; however, these systems often lack the robustness to handle environmental noise and complex weather patterns. Advancements in Artificial Intelligence (AI), cloud computing, and embedded systems have enabled intelligent agricultural monitoring. This research proposes an integrated IoT-ML architecture using the ESP32 platform to bridge this gap, focusing on predictive irrigation control that adapts to real-time environmental flux. The key contributions of this work include: (i) a multi-sensor IoT framework for field data acquisition; (ii) a Random Forest-based decision engine achieving 94.2% accuracy; and (iii) cloud-enabled remote monitoring via the ThingSpeak platform with demonstrated 35% water savings compared to conventional methods.

System Architecture and Implementation

The proposed system integrates Internet of Things (IoT) technology with Machine Learning (ML) to enable intelligent irrigation management. The system continuously monitors environmental and soil parameters using multiple sensors and automatically controls irrigation based on real-time data analysis [4]. The architecture is organized into three functional layers: the sensing layer, the communication and processing layer, and the decision-making layer.

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Hardware Components

The system is built around the ESP32 Dev Kit V1, a low-cost, dual-core microcontroller with integrated Wi-Fi. The hardware setup includes a Capacitive Soil Moisture Sensor (measuring volumetric water content — preferred over resistive sensors due to corrosion resistance), a DHT22 temperature and humidity sensor, a Rain Sensor (FC-37) for rainfall detection, a Water Flow Sensor (YF-S201) to measure water volume delivered, a Relay Module, and a 12V DC Water Pump. Table 1 summarizes the components and their functions.

Table 1. Hardware Components and Their Functions

Component	Function
ESP32 Controller	Central processing unit responsible for sensor interfacing, cloud communication, and pump control
Capacitive Soil Moisture Sensor	Measures soil moisture content to determine irrigation requirements
DHT22 Sensor	Measures ambient temperature and relative humidity
Rain Sensor (FC-37)	Detects rainfall to prevent unnecessary irrigation
Water Flow Sensor (YF-S201)	Measures the quantity of water supplied during irrigation
Relay Module	Acts as an electronic switch for controlling the water pump
12V DC Water Pump	Delivers water from the storage tank to the agricultural field

Cloud Communication

The ESP32 collects digital and analog signals from the sensors and transmits the data to the ThingSpeak cloud platform via Wi-Fi every 15–30 seconds. ThingSpeak provides real-time visualization, historical data storage, and remote monitoring of agricultural parameters. Farmers can access the dashboard using a smartphone or personal computer to observe field conditions and irrigation status from any location with internet connectivity.

Machine Learning Decision Engine

Data stored on the ThingSpeak platform is processed by a machine learning module. A Decision Tree algorithm was initially implemented due to its simplicity and interpretability. The model is trained on a dataset comprising soil moisture, temperature, humidity, and rain status, outputting a binary decision: 'Pump ON' or 'Pump OFF.' In advanced stages, a Random Forest algorithm was evaluated for higher accuracy and better handling of sensor noise.

The decision-making logic utilizes a Random Forest algorithm trained on a comprehensive dataset of environmental parameters to mitigate sensor noise and provide stable irrigation predictions. The system workflow is: (1) Initialize sensors and establish Wi-Fi connectivity. (2) Read sensor data and upload to ThingSpeak cloud. (3) The ML model evaluates irrigation requirements. (4) The ESP32 receives the prediction; if 'ON,' it triggers the relay to start the pump. (5) The system monitors soil moisture in real-time and stops the pump once the target moisture level is reached.

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EXPERIMENTAL RESULTS AND ANALYSIS

The system was evaluated over a 30-day trial period across varying weather conditions. The Random Forest model demonstrated superior performance compared to simple Decision Trees, achieving a classification accuracy of 94.2% and an F1-score of 0.93. Comparative analysis with a conventional timer-based system revealed a 35% reduction in total water volume consumed, primarily due to the rain-sensor override and moisture-aware termination logic. ThingSpeak visualizations confirmed stable data latency (<2 s) and high availability, validating the system's suitability for real-time agricultural monitoring.

The system was tested under the following representative environmental scenarios: (1) Low Moisture Condition (moisture <30%): The system correctly identified the low moisture level and activated the pump. (2) High Moisture Condition (moisture >70%): The pump remained OFF, preventing over-irrigation. (3) Rainfall Detected: Even with low soil moisture, the system stayed OFF when the rain sensor was active, conserving water. (4) Low Tank Level: An alert was generated when the water tank level was insufficient to start the pump. The integration of the water flow sensor allowed quantification of water savings, estimated at 25–40% compared to traditional methods.

Algorithm Performance Comparison

A comparison between Decision Tree and Random Forest algorithms showed that Random Forest provided more stable predictions and better resistance to overfitting. Table 2 summarizes the performance metrics for both algorithms.

Table 2. Comparison of Decision Tree and Random Forest Algorithms

Parameter	Decision Tree	Random Forest
Accuracy	Moderate (~82%)	High (94.2%)
F1-Score	~0.80	0.93
Overfitting	More Likely	Less Likely
Noise Handling	Moderate	Excellent
Stability	Moderate	High

CONCLUSION AND ETHICAL CONSIDERATIONS

This research successfully implemented a robust IoT-driven smart irrigation framework utilizing Machine Learning for optimized water management. By integrating the ESP32 microcontroller with Random Forest prediction logic, the system achieved a classification accuracy of 94.2% and significant water conservation gains of 25–40% compared to conventional timer-based methods. Real-time cloud monitoring via ThingSpeak with sub-2-second data latency confirmed the system's operational reliability.

From an ethical perspective, this system promotes sustainable water use, reduces agricultural runoff, and contributes to environmental protection — aligning with the United Nations Sustainable Development Goal 6 (Clean Water and Sanitation) and SDG 2 (Zero Hunger). The system does not collect personal user data, and all sensor readings are anonymized in cloud storage.

Future work will focus on: (i) integrating weather forecast APIs to anticipate rain events more effectively; (ii) deploying edge computing nodes to minimize cloud dependency and reduce latency; (iii) exploring solar-powered energy harvesting for autonomous operation; and (iv) developing a dedicated mobile application to

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improve accessibility for smallholder farmers. This research provides a solid foundation for the deployment of advanced AI techniques in modern precision agriculture.

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