

AI-Driven Smart Agriculture: An Integrated Approach for Soil Analysis, Irrigation and Crop-Fertilizer Recommendation

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Abstract – The proposed system is an IoT-based smart agriculture monitoring and automation system designed to improve crop productivity, optimize water usage, and enable real-time decision-making. Traditional farming methods rely on manual monitoring and fixed irrigation schedules, leading to water wastage and inefficient resource utilization. To overcome these issues, the system integrates sensors, automation, and cloud-based monitoring into a single solution. Environmental sensors such as soil moisture, temperature, and humidity continuously monitor field conditions. The collected data is processed by a microcontroller, which compares values with predefined thresholds and automatically controls irrigation systems like pumps and valves. This ensures optimal water usage and reduces manual effort. For communication, Wi-Fi modules such as ESP8266/ESP32 transmit data to cloud platforms like ThingSpeak, where it is stored, analyzed, and visualized as graphs, allowing farmers to monitor fields remotely through mobile devices or computers. The system also provides alerts and remote control features, enabling quick action during abnormal conditions. Overall, the system is cost-effective, scalable, and energy-efficient, improving productivity while conserving water and supporting sustainable smart farming practices.

Keywords: smart agriculture, soil moisture sensor, automated irrigation, crop-fertilizer recommendation, ESP32/Arduino

1. INTRODUCTION

Agriculture remains one of the most important sectors supporting food production, employment, and economic growth across the world. Farmers today face several challenges such as declining soil fertility, irregular rainfall, water scarcity, pest attacks, and unpredictable climate conditions. Traditional farming methods often rely on experience and manual observation, which may not always provide accurate or timely decisions, so crop yield and resource efficiency are significantly affected. With the advancement of Artificial Intelligence (AI), smart agriculture has emerged as a modern solution to improve farming practices. AI technologies such as

machine learning, sensors, the Internet of Things (IoT), and data analytics can help monitor field conditions, analyze soil nutrients, automate irrigation systems, and recommend suitable crops and fertilizers based on real-time data. This work focuses on combining multiple intelligent farming solutions into a single system that analyzes soil properties, determines irrigation requirements, and provides personalized recommendations for crops and fertilizers, thereby helping farmers make data-driven decisions, reduce wastage of water and fertilizers, and promote sustainable agriculture.

2. OBJECTIVES

The primary objectives of this work are:

- To analyze soil properties such as pH, moisture, and nutrient levels using low-cost embedded sensors.
- To continuously monitor soil and environmental conditions using a wireless sensor network.
- To develop an automated irrigation system that supplies water only when required, minimizing wastage.
- To recommend suitable crops based on soil type and prevailing climatic conditions.
- To suggest appropriate fertilizers according to soil nutrient status and crop requirements.
- To reduce farming costs, conserve resources, and improve crop productivity through data-driven decisions.
- To provide farmers with real-time remote monitoring and alert capability through a cloud-based IoT platform.

3. LITERATURE REVIEW

Research on automated irrigation and field monitoring has evolved across wireless sensor networks, embedded systems, and GSM-based communication. Gopinath et al. [1] proposed a GSM-based automated irrigation control system using a rain-

gun mechanism, while Pavithra and Srinath [2] developed an Android-controlled GSM irrigation system aimed at efficient resource use and crop planning. Shabadi et al. [3] demonstrated irrigation control using a combination of Android and GSM for efficient use of water and power. Shiraz Pasha and Yogesha [4] presented a microcontroller-based automated irrigation system, and Kumbhar and Ghatule [5] designed a similar microcontroller-controlled irrigation system for plantation crops that switches a pump based on soil humidity set-points.

Kim et al. [6] used a distributed wireless sensor network for remote sensing and control of an irrigation system, highlighting the benefits of real-time field data for reducing water wastage. Gunturi [7] and Dursun and Ozden [8] further explored microcontroller and soil-moisture-sensor-based automation for drip and plant irrigation. Harishankar et al. [9] proposed a solar-powered smart irrigation system aimed at rural, off-grid deployment. Collectively, these studies establish that sensor-driven, threshold-based automation can reliably replace fixed-schedule manual irrigation.

However, a review of the above works shows that most existing systems address only isolated aspects of the problem: either soil/field monitoring, or irrigation automation, or GSM/cloud-based alerting, but rarely all three together with an added layer of crop and fertilizer recommendation. There remains a clear need for an integrated, field-deployable platform that combines multi-parameter soil analysis, automated irrigation control, and crop-fertilizer recommendation within a single low-cost system -- a gap that the present work aims to address.

4. SYSTEM ARCHITECTURE AND DESIGN

4.1 Overall Architecture

The proposed system is an IoT-based smart agriculture monitoring and automation system using a wireless sensor network, designed to overcome the limitations of traditional farming methods. It integrates sensors, a microcontroller, communication technology, and cloud computing to enable real-time monitoring and intelligent control of agricultural operations. Soil moisture, temperature, humidity, and light sensors are deployed in the field to continuously monitor environmental conditions.

These sensors send real-time data to a microcontroller (ESP32/Arduino), which acts as the central processing unit. The microcontroller analyzes the collected data and compares it with predefined threshold values to make decisions

automatically. Based on the analysis, the system controls actuators such as water valves and pump motors through driver circuits. For instance, when the soil moisture level drops below a set threshold, the system automatically activates the irrigation pump, and once the desired moisture level is reached, it turns the pump off, ensuring efficient water utilization and eliminating unnecessary wastage.

The system is connected to the internet using wireless communication technologies such as Wi-Fi. The collected data is transmitted to a cloud platform such as ThingSpeak, where it is stored, processed, and visualized in the form of graphs and dashboards, enabling users to monitor field conditions remotely in real time and receive alerts about critical conditions such as low moisture levels.

Table -1: Hardware Components Used in the System

Component	Function
Arduino Uno R3 / ESP32	Central processing and control unit
Soil moisture sensor	Measures volumetric soil water content
DHT11 sensor	Measures ambient temperature and humidity
Relay module + pump	Switches irrigation motor ON/OFF automatically
16x2 LCD	Displays real-time sensor readings on-site
ESP8266 Wi-Fi module	Uploads sensor data to the ThingSpeak cloud

Figure 1 shows the block diagram of the wireless sensor node used in the proposed IoT-based agriculture monitoring and control system. The moisture, temperature/humidity, and light sensors interface with the microcontroller, which drives the valve and pump-motor actuators through relay drivers. Sensor data is pushed to the internet and stored on the IoT (ThingSpeak) platform, from where the farmer can access it on a PC or mobile device.

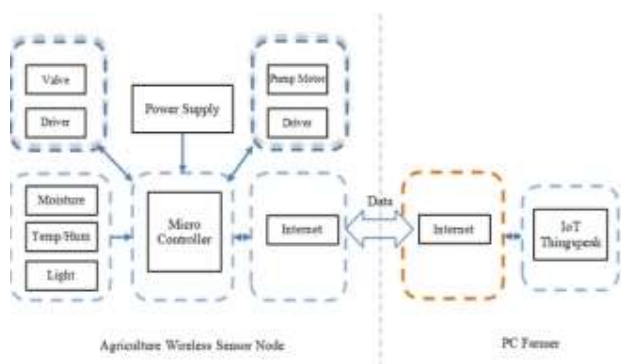


Fig -1: Block diagram of the proposed IoT-based smart agriculture system

4.2 Hardware Components

The key hardware components used to realize the proposed system are described below.

Arduino Uno R3 Microcontroller: An ATmega328-based board with 14 digital I/O pins, 6 analog inputs, and a 16 MHz clock, used as the central processing unit. It reads sensor values, compares them against predefined thresholds, and drives the relay/pump and LCD accordingly.

Soil Moisture Sensor: A two-probe resistive sensor that estimates volumetric soil water content indirectly through soil electrical resistance. Its analog output is read by the microcontroller and compared against a calibrated threshold to decide whether irrigation is required.

DHT11 Temperature and Humidity Sensor: A digital sensor that reports ambient temperature and relative humidity over a single-wire interface, allowing the system to compensate irrigation and crop-fertilizer decisions for prevailing weather conditions.

Relay Module and Water Pump: A relay driver circuit isolates the low-power microcontroller output from the higher-current irrigation pump/valve, switching it ON or OFF based on the microcontroller's decision.

16x2 LCD Display: A character LCD (16 columns x 2 rows) connected via I2C provides on-site, real-time display of soil moisture, temperature, humidity, and water-level readings for the operator without requiring a mobile device.

NodeMCU / ESP8266 Wi-Fi Module: A low-cost Wi-Fi System-on-Chip used for wireless communication. It uploads sensor readings to the ThingSpeak cloud platform, enabling remote monitoring, graphing, and alerting from a PC or smartphone.

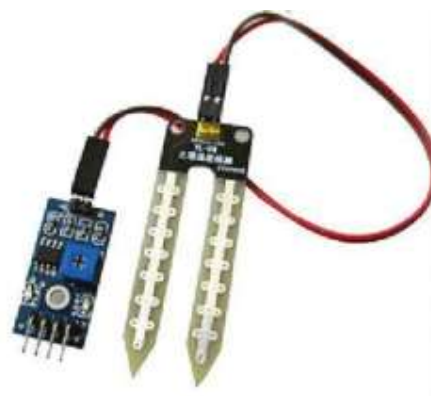


Fig -2: Soil moisture sensor used for real-time field monitoring

5. METHODOLOGY

5.1 Threshold-Based Irrigation Control

The irrigation logic follows a simple, reliable closed-loop rule: the microcontroller periodically reads the soil moisture sensor's analog output and compares it against a calibrated threshold value. When the reading falls below the threshold (indicating dry soil), the microcontroller drives the relay to switch the pump ON; once the reading rises above the threshold (indicating adequately moist soil), the pump is switched OFF. This need-based control avoids both over-irrigation and under-irrigation, in contrast to fixed-interval manual watering schedules. The same polling loop also reads the DHT11 sensor for temperature and humidity and updates the LCD and cloud dashboard on every cycle.

5.2 Crop and Fertilizer Recommendation Approach

Soil pH, moisture, and nutrient-related readings acquired by the sensor node are compared against reference ranges for common crops maintained in a lookup table on the microcontroller/host application. When sensed values fall within a crop's known suitable range, that crop is recommended; deviations in nutrient-related parameters trigger a corresponding fertilizer suggestion (for example, a nitrogen-rich fertilizer where nitrogen indicators are low). This rule-based recommendation logic is designed to be extended in future work with a trained machine-learning model for finer-grained, data-driven

recommendations as larger agronomic datasets become available.

5.3 Cloud Communication and Data Visualization

The ESP8266/NodeMCU module connects to a local Wi-Fi network and periodically sends sensor readings to a ThingSpeak channel using HTTP GET requests, with each monitored parameter (soil moisture, temperature, humidity) mapped to a separate channel field. ThingSpeak stores the time-stamped data and automatically renders it as graphs, allowing the farmer to view trends and current field status remotely from a browser or mobile device. Threshold-crossing events can additionally be configured to trigger ThingSpeak's alert/notification features.

5.4 Software Development and Simulation

Firmware for the microcontroller was developed in Embedded C using the Arduino IDE, chosen for its efficiency, wide sensor-library support, and suitability for resource-constrained boards such as the Arduino Uno/ESP8266. Prior to hardware assembly, the complete circuit -- microcontroller, sensors, relay, pump, and LCD -- was modeled and functionally verified in Proteus ISIS/VSM, which allowed the pump-switching logic and LCD output to be validated through simulation before committing to physical wiring. A PHP and MySQL-based web interface was also explored as an optional back-end for longer-term storage and tabular reporting of historical sensor and recommendation data.

6. RESULTS AND DISCUSSION

6.1 Functional Validation

The pump-control logic was first verified in the Proteus simulation environment, where the soil moisture input was varied and the relay/pump output was observed to switch ON below the configured threshold and OFF above it, confirming correct closed-loop behavior. The same logic was then validated on the assembled hardware prototype: the 16x2 LCD correctly displayed live humidity, temperature, and water-level readings, and the pump responded within about one second of the sensor reading crossing the threshold, consistent with the polling interval used in firmware.

6.2 Comparison with Manual/Conventional Practice

Table 2 qualitatively compares the proposed system with conventional manual irrigation and monitoring practice. By

replacing subjective, schedule-based decisions with sensor-driven, threshold-based control, the system is expected to reduce both over-watering and crop stress from under-watering, while cutting down the labour and time farmers spend on manual field inspection.

Aspect	Manual / Conventional System Proposed IoT System
Irrigation trigger	Fixed schedule / manual judgement Real-time soil-moisture threshold
Field monitoring	Manual site visits Continuous, remote via cloud dashboard
Crop/fertilizer guidance	Farmer experience only Rule-based recommendation from sensed data
Alerts on abnormal conditions	None Cloud-based alerts / on-site LCD
Labour dependency	High Low

6.3 Approximate Cost Analysis

Table 3 presents an indicative, component-wise cost estimate for the prototype based on typical retail prices in India (INR) at the time of development; actual prices vary by vendor and quantity. The total bill of materials is approximately INR 1,550 - 2,650, which is a fraction of the cost of commercial soil-testing and irrigation-automation equipment, making the system attractive for small and marginal farmers.

Component	Approximate Cost (INR)
Arduino Uno R3 / ESP32	450 - 700
Soil moisture sensor	80 - 150
DHT11 sensor	90 - 150
Relay module + pump	300 - 600
16x2 I2C LCD	150 - 250
ESP8266 Wi-Fi module	180 - 300

Wiring, enclosure, power supply	300 - 500
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7. CONCLUSION

The proposed IoT-based smart agriculture monitoring and automation system provides an efficient and intelligent solution to the challenges faced in traditional farming methods. By integrating wireless sensor networks, a microcontroller, automated actuators, and cloud-based IoT platforms, the system enables real-time monitoring and precise control of agricultural operations. Continuous tracking of soil moisture, temperature, humidity, and light intensity ensures accurate decision-making and optimal crop management, while automated control of irrigation through pump motors and valves significantly reduces water wastage and minimizes the need for manual intervention. The integration of internet connectivity and cloud platforms further allows farmers to monitor and manage their fields remotely, improving convenience and responsiveness. The system is scalable, cost-effective, and adaptable to different farming environments, making it suitable for both small-scale and large-scale agricultural applications, and represents a significant step toward data-driven, sustainable smart farming.

Future work will focus on replacing the rule-based crop-fertilizer recommendation logic with a machine-learning model trained on larger, region-specific agronomic datasets; adding LoRa/GSM connectivity as a fallback for areas with limited Wi-Fi coverage; powering the sensor node from solar panels for fully off-grid rural deployment; and developing a dedicated mobile application to complement the ThingSpeak dashboard for farmers.

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