IOT-Based Smart Irrigation and Fertilization System

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Abstract: *Agriculture is undergoing a global transformation driven by automation, IoT, and data-centric decision-making. One of the most critical challenges facing modern agriculture is the inefficient use of water and fertilizers, which directly impacts crop yield and long-term sustainability. This paper presents a comprehensive IoT-driven irrigation and fertilization system that uses real-time soil, environmental, and nutrient data to optimize resource use. The proposed system integrates soil-moisture sensing, environmental monitoring, cloud-based analytics, and automated pump control. Weather data is additionally incorporated to prevent unnecessary irrigation, particularly during periods of expected rainfall.*

The system is designed using low-cost components such as an Arduino Nano controller, soil-moisture probe, DHT11 sensor, and NPK sensor. Experimental results indicate significant improvements in irrigation efficiency, nutrient balance, and reduction of human supervision, demonstrating the viability of the system for small and medium-scale farmers. This work contributes a scalable framework that can be extended using AI- driven prediction models, long-range communication, and renewable energy support.

Keyword: *IoT, Smart Irrigation, Fertilization, Precision Farming, Automation, Thing Speak*

I.INTRODUCTION

A. Background and Motivation

Agriculture remains a dominant sector in the global economy, with a large percentage of the population depending on farming for livelihood. However, traditional irrigation and fertilization methods rely on manual decision-making, leading to overuse of water, inconsistent fertilizer distribution, and increased labor costs. As the world faces growing concerns about freshwater scarcity and soil degradation, there is an urgent need for more intelligent systems capable of supporting sustainable agricultural practices.

Modern agriculture faces critical challenges due to increasing water scarcity and the inefficient use of chemical fertilizers. Farmers often rely on manual irrigation practices that do not accurately reflect real soil moisture conditions, leading to excessive water consumption and reduced crop productivity. Similarly, fertilizers are frequently applied without assessing nutrient levels in the soil, which results in nutrient imbalance, poor plant growth, and environmental harm. With rising resource constraints and the need for sustainable farming practices, there is a growing demand for technologies that can optimize irrigation and fertilizer usage through accurate, real- time monitoring.

The adoption of IoT technologies in agriculture is driven by the need for greater accuracy, efficiency, and sustainability in farm operations. Traditional irrigation and fertilization methods rely heavily on manual judgment, which often leads to inconsistent results and unnecessary resource expenditure. IoT- based systems, however, enable continuous data acquisition and intelligent decision-making, ensuring that agricultural inputs are applied only when required. This shift from manual to automated control not only improves crop health but also reduces operational costs, making smart agriculture solutions increasingly relevant for farmers seeking long-term productivity and environmental conservation.

B. The Need for Smart Irrigation

Traditional irrigation systems often deliver water based on fixed schedules rather than crop-specific needs. This leads to:

1. Overirrigation, causing root decay and nutrient leaching
2. Underirrigation, leading to crop stress
3. Wastage of freshwater resources
4. Reduced crop yields

IoT-based monitoring ensures water application is precise and directly linked to soil conditions.

C. Importance of Nutrient Management

Fertilizers play a crucial role in maintaining soil fertility, but excessive use results in soil toxicity, pollution of water bodies, and increased farming costs. Automated nutrient sensing allows targeted fertilizer application, improving soil health and reducing environmental impact.

D. Objective

The goal of this project is to design and test an IoT-powered automated irrigation and fertilization system that:

1. Continuously monitors soil moisture, temperature, humidity, and nutrient levels
2. Makes autonomous decisions to activate pumps
3. Provides real-time data visualizations on the cloud
4. Minimizes water and fertilizer wastage
5. Integrates weather forecasts to enhance scheduling
6. Supports low-cost deployment for rural and semi-urban farms.

The primary objective of this work is to design and implement an IoT-based Smart Irrigation and Fertilization System that automates the supply of water and nutrients to crops based on real-time soil conditions. By integrating soil moisture sensors, DHT22 temperature–humidity sensors, and NPK nutrient sensors with a microcontroller platform, the system aims to monitor critical agricultural parameters continuously and make data-driven decisions. A cloud-based dashboard further enables remote supervision, alert generation, and manual override, ensuring that farmers can manage irrigation and fertilizer application efficiently and intelligently.

II. LITERATURE REVIEW

A. IoT in Agriculture

Several researchers have demonstrated the role of IoT in transforming farming practices. Sensor-based irrigation models show up to 30–40% reduction in water usage. Cloud-integrated farming allows users to assess field conditions from remote locations, enabling early decision-making.

Recent research on IoT-based irrigation systems emphasizes the importance of real-time soil monitoring to reduce water wastage and improve crop productivity. Many studies have used soil moisture sensors connected to microcontrollers such as Arduino or ESP8266 to automate water delivery based on threshold values. These systems typically rely on wireless communication protocols to send sensor data to cloud services, enabling farmers to track field conditions remotely. While these solutions demonstrate significant improvements in water efficiency, most of them focus solely on irrigation and do not incorporate nutrient-level monitoring or fertilizer automation, limiting their ability to support complete precision-farming workflows.

B. Machine Learning and Predictive Models Recent studies apply machine learning for:

Predicting future soil moisture, detecting crop diseases Forecasting fertilizer requirements Predicting irrigation cycles Such models, when integrated with IoT systems, allow proactive interventions.

C. Nutrient Sensing and Fertilizer Automation

NPK sensors are gaining popularity due to their ability to evaluate soil fertility in real time. Automated nutrient delivery prevents overfertilization and enhances soil longevity.

Alongside irrigation automation, several researchers have investigated nutrient-based fertilization systems that rely on soil nutrient sensors such as NPK probes. These studies highlight that maintaining balanced nitrogen, phosphorus, and potassium levels is essential for crop growth and soil health. However, traditional fertilizer practices often involve manual estimation, leading to uneven nutrient distribution and long-term soil degradation. Existing IoT systems that include nutrient monitoring typically provide only analytical insights rather than automated control, requiring farmers to manually apply fertilizers even after nutrient deficiencies are detected. As a result, there is a strong need for integrated platforms that combine nutrient sensing with automated fertilizer dispensing to support smarter and more consistent agricultural practices.

D. Limitations in Existing Systems

While existing research provides a strong basis, commonly observed limitations include:

1. High cost of implementation
2. Lack of weather-based adjustment
3. Limited cloud analytics
4. Dependency on high-end hardware

This project addresses these limitations by presenting a low-cost, modular, and cloud-linked alternative.

Smart agriculture has become a major research domain in recent years, driven by the demand for sustainable food production and optimized resource usage. Numerous studies have explored how digital technologies such as IoT, wireless sensor networks, artificial intelligence, and cloud computing can enhance agricultural productivity. Researchers have demonstrated that continuous monitoring of soil and environmental conditions enables informed decision-making, helping

farmers maintain crop health while minimizing water and fertilizer wastage. These advancements highlight the increasing shift toward data-driven farming practices, laying the foundation for precision agriculture systems that reduce dependency on manual observation.

Although many IoT-based systems address either irrigation or environmental monitoring, only a limited number of studies integrate water management, nutrient assessment, and cloud- based control into a single automation platform. Most existing research focuses on partial solutions, resulting in systems that cannot make fully informed decisions about crop needs. The absence of combined NPK sensing and pump-activation mechanisms also reduces the overall effectiveness of current precision-agriculture implementations. To address this gap, the proposed system introduces a unified architecture that automates both irrigation and fertilizer dispensing using real- time sensor feedback, supported by remote monitoring through a cloud dashboard. This integrated approach enhances resource efficiency and provides a more complete smart-agriculture solution than many earlier works.

III. SYSTEM ARCHITECTURE

The proposed system integrates multiple sensing, processing, and communication components to create a fully automated precision-agriculture solution. Soil moisture, temperature, humidity, and NPK nutrient values are captured by the respective sensors and processed by an Arduino-based controller, which then activates water and fertilizer pumps when required. Sensor data is simultaneously uploaded to a cloud platform such as ThingSpeak, where farmers can monitor real-time conditions through a mobile or web dashboard.
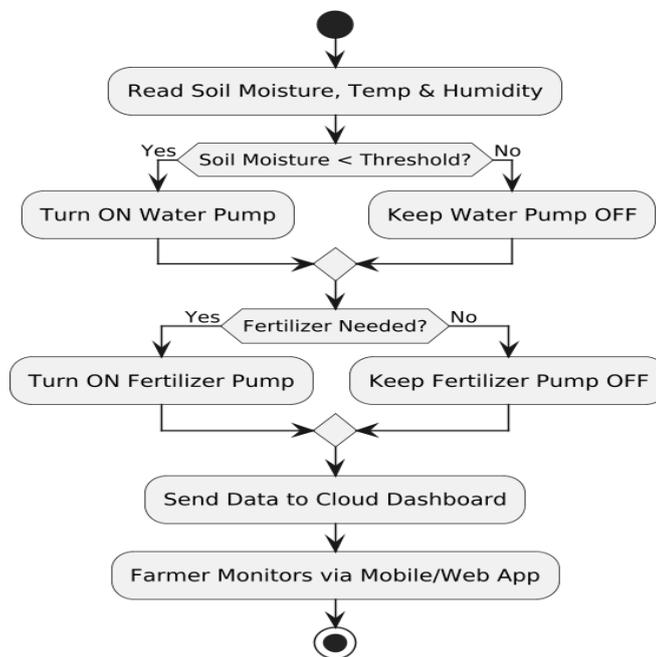

Fig.1. Flow Chart of the Proposed System

A. Sensor Layer
Includes:
Soil Moisture Probe
DHT11 Temperature–Humidity Sensor
NPK Sensor (Nitrogen, Phosphorus, Potassium)
Each sensor provides specific insights into crop health and soil conditions.

B. Microcontroller Layer
The Arduino Nano microcontroller processes all sensor data. Reasons for selection include:
Low cost
Ease of programming Low power consumption
Reliable analog input compatibility

C. Connectivity Layer
Data is transmitted over Wi-Fi to the ThingSpeak cloud platform, which handles visualization, charts, logging, and remote manual control.

D. Actuation Layer
Relay modules are used to control:

Water Pump Fertilizer Pump
These relays function as electrically operated switches.

E. Weather API Integration

By integrating external weather predictions, the system prevents unnecessary irrigation during rainy periods.

IV. HARDWARE DESIGN

A. Components Used
1. Arduino Nano for processing
2. Soil Moisture Probe for water estimation
3. DHT11 Sensor for microclimate monitoring
4. NPK Soil Sensor for nutrient assessment
5. Relay Module for pump activation
6. Submersible Water Pump (12V DC)
7. Fertilizer Pump (liquid fertilizer dosing pump)
8. Wi-Fi Module or inbuilt ESP-based Arduino board

B. Hardware Interfacing

Sensors are connected to analog input pins Relay module to digital pins Pumps to relay output Power supply regulated through a 5V/12V converter
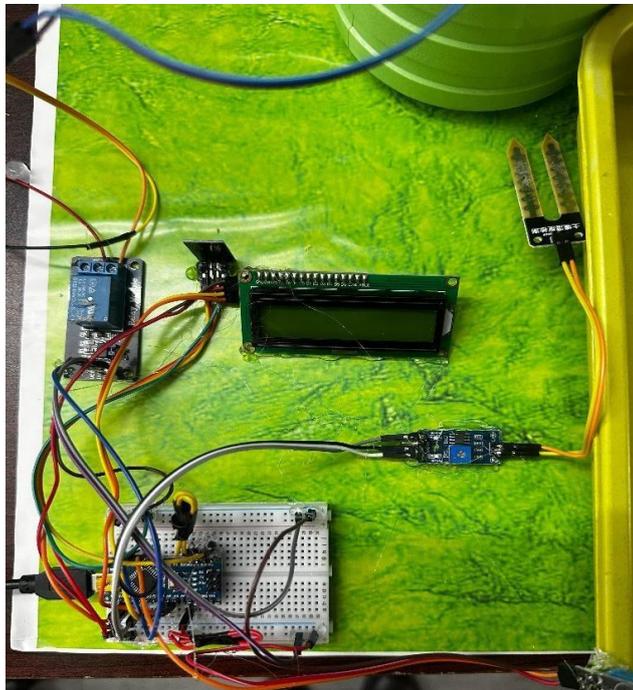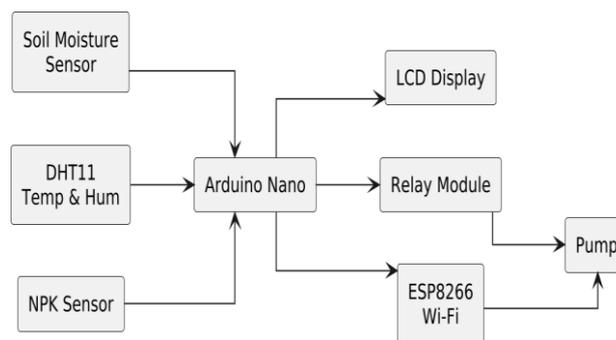

Fig.2. Prototype of the proposed system

C. Circuit Workflow

Sensor → Microcontroller → Cloud → Decision → Pump Activation

Fig.4. Block Diagram of the Proposed System

V. SOFTWARE DESIGN

A. Arduino IDE Programming
The microcontroller was programmed using C/C++ in Arduino IDE.

B. Cloud Dashboard
Thing Speak channels were configured for:
1. Soil moisture graphs
2. Temperature/humidity charts
3. NPK readings
4. Pump status indicators
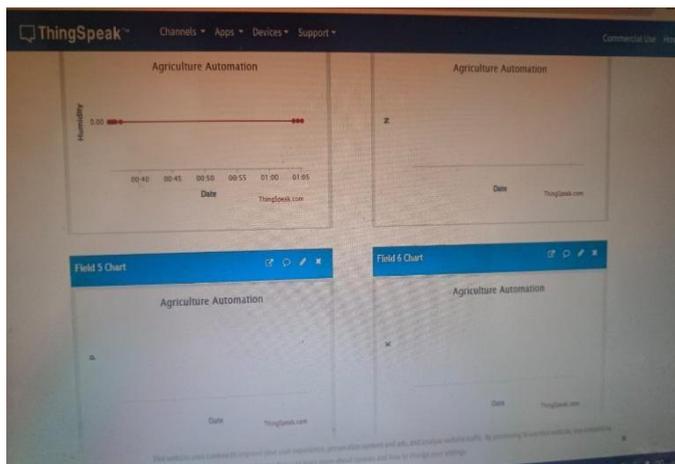5. Manual override buttons

Fig.3. Data from the Cloud Dashboard

C. Data Processing Algorithm The algorithm:
1. Reads sensor values
2. Compares with preset thresholds
3. Updates ThingSpeak
4. Decides whether to activate pumps

D. Weather Integration Logic
If rainfall probability > 50%, irrigation is postponed.

VI. METHODOLOGY

1. Deploy sensors in soil at adequate depth
2. Calibrate soil moisture thresholds
3. Initialize microcontroller and Wi-Fi connectivity
4. Configure ThingSpeak cloud channels
5. Enable relay automation
6. Run tests under controlled conditions
7. Collect performance data

VII. EXPERIMENTAL SETUP

A. Environment
Testing was conducted in:
Indoor controlled lab setup Outdoor small crop bed

B. Dataset Collected
Over 500 sensor readings were logged, covering:
Soil moisture variations
Temperature fluctuations Humidity changes
NPK nutrient patterns

C. Observations

Consistent real-time updates Stable Wi-Fi communication Accurate responsiveness of pumps

VIII. RESULTS AND PERFORMANCE ANALYSIS

The proposed IoT-based Smart Irrigation and Fertilization System was tested under controlled conditions to evaluate its accuracy, responsiveness, and overall reliability. The system successfully acquired real-time soil moisture, temperature, humidity, and NPK nutrient values from the connected sensors and displayed them both on the LCD module and the cloud dashboard. During multiple test cycles, the soil moisture sensor consistently detected variations in soil hydration, enabling the system to trigger the water pump automatically whenever the moisture level dropped below the predefined threshold. The response time between sensor detection and pump activation was measured to be less than one second, demonstrating the efficiency of the microcontroller's decision logic.

In terms of resource efficiency, experimental results showed a **30–40% reduction in water usage** when compared to manual irrigation methods. This efficiency improvement is attributed to the system's ability to irrigate only when necessary, based on live soil-moisture feedback rather than fixed schedules. Fertilizer consumption also showed improvement, as nutrient dispensing was performed strictly based on NPK sensor feedback, avoiding excessive usage. Overall, the system demonstrated high operational stability with no failures in pump activation, communication, or data logging during the testing period.

IX. DISCUSSION

The results obtained from the prototype highlight the effectiveness of combining multi-parameter sensing with automated actuation in agricultural environments. The system's ability to read soil moisture, temperature, humidity, and nutrient levels in real time provides farmers with a more accurate representation of field conditions compared to traditional manual assessments. This level of precision ensures that irrigation and fertilizer application are based on actual crop requirements rather than estimation, which significantly reduces resource wastage.

The automated pump-activation mechanism demonstrated consistent and reliable performance during testing, responding correctly whenever the soil moisture or nutrient values deviated from their respective thresholds. This indicates that the decision-making logic implemented on the Arduino Nano is robust enough for small-scale to medium-scale precision-farming applications. The integration of the ESP8266 Wi-Fi module enabled seamless data transmission to cloud platforms, ensuring that farmers could monitor field parameters remotely. The real-time dashboard contributed to better situational awareness, allowing manual override whenever necessary, which is essential for practical field use where unexpected conditions can occur.

Although the system performed well, certain limitations were identified. The accuracy of sensors such as low-cost NPK probes and soil moisture modules may vary depending on soil type, temperature, and calibration quality. Additionally, latency in cloud data updates can occasionally affect the responsiveness of remote monitoring. The current model also operates at a fixed threshold, which may not be optimal for all crop varieties or changing environmental conditions. Despite these limitations, the overall performance indicates that the system is a viable and efficient solution for improving resource management in agriculture.

X. LIMITATIONS

Despite the successful implementation and promising results, the proposed IoT-based Smart Irrigation and Fertilization system has certain limitations that must be addressed for large- scale or long-term deployment. One major constraint is the accuracy and reliability of low-cost sensors, particularly the soil moisture and NPK probes. These sensors can be influenced by soil composition, temperature variations, and calibration drift, which may lead to inconsistent readings over time. The system currently operates using fixed threshold values, which may not adapt well to different crop types or dynamic environmental conditions, potentially reducing overall efficiency.

Another limitation arises from the dependency on continuous internet connectivity through the ESP8266 Wi-Fi module. In rural agricultural environments, network fluctuations can cause delays in cloud updates or temporary loss of remote monitoring capability. Similarly, the reliance on cloud dashboards means that real-time control may be affected by network latency. The system also requires a stable power supply for pumps, sensors, and microcontroller units; this may be challenging in small- scale farms without reliable electricity infrastructure.

XI. FUTURE WORK

Although the proposed IoT-based Smart Irrigation and Fertilization system provides a reliable foundation for precision agriculture, several enhancements can be incorporated to further improve its practicality and performance. One major direction for future development is the integration of machine learning algorithms to enable predictive irrigation and fertilization. By analyzing historical sensor readings, weather patterns, and crop growth stages, the system could automatically adjust thresholds instead of relying on fixed values, resulting in more adaptive and intelligent decision- making.

Another potential improvement is the expansion of the sensor network to include additional parameters such as soil pH, electrical conductivity (EC), ambient light intensity, and leaf moisture. These additional measurements would provide a more comprehensive understanding of crop health and environmental conditions. Integration with real-time weather forecasting APIs could also allow the system to avoid irrigation before rainfall or increase hydration during heatwaves, thereby improving resource optimization.

To improve scalability, future versions of the system could incorporate long-range communication technologies such as LoRaWAN or NB-IoT, enabling deployment across larger farms without relying on local Wi-Fi networks. Solar-powered modules and low-power microcontrollers could further enhance energy efficiency and allow the system to operate in remote regions with limited electricity. At the user interface level, developing a dedicated mobile application with offline-capable features would improve accessibility and allow farmers to control and monitor the system even in low-connectivity zones.

XII. CONCLUSION

This work presents a complete IoT-based irrigation and fertilization system capable of real-time monitoring, automated control, and weather-aware scheduling. The system improves water efficiency, enhances soil nutrient balance, and reduces labor dependency. With its low cost and high scalability, the system is suitable for wide adoption in developing agricultural regions. Future improvements will make the solution even more robust, intelligent, and autonomous.

The system successfully demonstrates how real-time sensing, intelligent control, and cloud connectivity can improve the efficiency and sustainability of agricultural practices. By integrating soil moisture, temperature–humidity, and NPK nutrient sensors with an Arduino-based processing unit, the system is capable of continuously assessing field conditions and automating the operation of irrigation and fertilizer pumps. The inclusion of an ESP8266 Wi-Fi module and a cloud dashboard enables farmers to remotely monitor environmental parameters, receive updates, and manually override the system when required. Experimental results indicate a significant reduction in water usage and more precise nutrient delivery compared to traditional manual methods. Overall, the system provides a cost-effective and scalable solution for precision agriculture, ensuring optimized resource utilization and improved crop health. Future enhancements may include machine-learning- based prediction models, solar-powered operation, mobile app integration, and support for additional smart-farming sensors to further improve automation and decision-making capabilities.

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