Implementation of Smart Agriculture System for Soil Monitoring and Nutrient Management Applications

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Abstract

The increasing demand for sustainable agriculture and precision farming has accelerated the adoption of intelligent nutrient management systems, with global smart agriculture expected to grow at over 12% annually and improper nutrient management contributing to nearly 20–30% reduction in crop yield worldwide. Additionally, inefficient irrigation and fertilizer usage lead to resource wastage and soil degradation, highlighting the need for real-time monitoring solutions. Traditional farming practices rely on manual soil testing and generalized fertilizer application, which often result in inaccurate nutrient management, over-irrigation, and inconsistent crop quality. Furthermore, conventional methods lack real-time monitoring, remote accessibility, and precise control over soil conditions, reducing overall agricultural efficiency. To address these challenges, the proposed IoT-based nutrient monitoring and management system utilizes the ESP32 microcontroller to develop an intelligent and automated agricultural solution. The system integrates soil moisture sensors for water content analysis, DHT11 sensors for temperature and humidity monitoring, pH sensors for soil acidity assessment, and NPK sensors to measure essential nutrients such as nitrogen, phosphorus, and potassium. The ESP32 processes the collected data and transmits it wirelessly to a cloud platform or mobile application, enabling real-time monitoring and remote decision-making. This allows farmers to optimize irrigation schedules, maintain soil health, and apply fertilizers precisely based on actual nutrient requirements. This smart system enhances crop yield, reduces resource wastage, supports sustainable farming practices, and provides a scalable and cost-effective solution for modern agriculture.

Keywords: Internet of Things, NPK Sensor, Precision Agriculture, Remote Monitoring, Smart Farming, Soil Moisture Sensor, Soil Nutrient Management, Sustainable Agriculture, Wireless Sensor Networks

1. Introduction

The increasing demand for sustainable agriculture and precision farming has significantly accelerated the adoption of intelligent nutrient management systems. Global smart agriculture is projected to grow at over 12% annually, driven by the need to enhance productivity while conserving resources [1]. Studies indicate that improper nutrient management contributes to nearly 20–30% reduction in crop yield worldwide, highlighting the importance of accurate soil monitoring and management [2]. Additionally, inefficient irrigation and excessive fertilizer usage lead to resource wastage, soil degradation, and environmental pollution. In agricultural environments such as crop fields, greenhouses, and smart farms, there is a critical need for systems that provide real-time monitoring of soil conditions, environmental parameters [3], and data-driven decision-making to ensure optimal plant growth and sustainability.

Traditional farming practices rely on manual soil testing and generalized application of water and fertilizers. These methods often lack precision, leading to over-irrigation, nutrient imbalance, and inconsistent crop quality [4]. Farmers typically depend on experience rather than real-time data, which may result in inefficient use of resources and reduced productivity [5]. Additionally, conventional approaches do not support continuous monitoring or remote access, making it difficult to adapt to changing environmental conditions. The absence of automated control systems further limits the ability to maintain optimal soil health and maximize yield.

In real-time scenarios, these limitations create several critical challenges affecting agricultural efficiency and sustainability. Improper nutrient levels can result in poor plant growth, reduced crop yield, and soil fertility degradation [6]. Over-irrigation leads to water wastage and nutrient leaching, while under-irrigation affects plant health and productivity. The lack of continuous monitoring prevents timely intervention, increasing the risk of crop damage [7]. Furthermore, absence of remote accessibility and automated decision-making limits the ability to manage large-scale farms effectively. These challenges highlight the need for an intelligent [8], IoT-based nutrient monitoring system capable of real-time soil analysis, precise irrigation control, and optimized fertilizer management, ensuring improved crop yield, reduced resource wastage, and sustainable agricultural practices.

2. Literature Survey

Alreshidi [9] proposed a smart sustainable agriculture system integrating Internet of Things (IoT) and Artificial Intelligence (AI) for real-time monitoring and intelligent decision-making in farming operations. Diaconu et al. [10] proposed an experimental study on the quality characteristics of sweet potato cultivars grown in sandy soils, focusing on agricultural productivity and crop performance. Anghel [11] proposed the optimal design and modeling of tactile resistive and capacitive sensor interfaces for mechatronic systems.

Coccia et al. [12] proposed an analysis of the evolution of sensor research, highlighting technological trends and future directions in sensing systems.

Popescu et al. [13] proposed an investigation on the impact of ultraviolet post-processing on three-dimensional printed components using masked stereolithography. The study improved material properties and durability of printed parts. The work lacked application in agricultural systems.

Chiriță et al. [14] proposed mechanized soil sampling techniques for agricultural land mapping, focusing on automation and efficiency in data collection. Costache et al. [15] proposed a method for oxygenation of stationary water bodies to improve water quality using engineered solutions. Stanciu et al. [16] proposed the design of an active thermal element for solar thermal energy measurement using finite element method-based heat transfer simulation.

Padmavathi et al. [17] proposed the use of advanced sensing technologies in agriculture integrating soil, crop, climate, and farmland monitoring using IoT frameworks. Coccia et al. [18] proposed an analysis of scientific developments and technological trajectories in sensor research, focusing on innovation patterns.

Hartono et al. [19] proposed a portable IoT-based soil nutrient monitoring system for precision agriculture that enabled real-time nutrient analysis. Brendan et al. [20] proposed a farm-scale soil moisture sensing and mapping system, providing design and operational recommendations for effective deployment. Coccia [21] proposed an analysis of sources of technological innovation, focusing on radical and incremental innovation strategies for competitive advantage.

3. Proposed System

Figure 1 illustrates the architecture of an IoT-based smart soil nutrient monitoring and irrigation system built around the ESP32. The system integrates multiple sensors including soil moisture, DHT11 (temperature and humidity), pH sensor, and NPK sensor to continuously monitor soil and environmental conditions. A regulated power supply ensures stable operation of all components. The ESP32 processes real-time sensor data and controls output devices such as an LCD display, AC Pump 1 (irrigation), AC Pump 2 (fertilizer/nutrient supply), and IoT connectivity for remote monitoring. This system enables precision agriculture by automating irrigation and optimizing nutrient management

Regulated Power Supply: The regulated power supply provides stable DC voltage (3.3V/5V) required for the ESP32, sensors, and output devices. It ensures reliable system performance by eliminating voltage fluctuations.

ESP32 Microcontroller + Software: The ESP32 acts as the central controller of the system. It collects data from all sensors, processes it using embedded software, and performs decision-making based on predefined thresholds. It also handles Wi-Fi communication for IoT data transmission.

Input Sensors

- **Soil Moisture Sensor:** Measures the water content in the soil. When moisture drops below a threshold, it triggers irrigation.
- **DHT11 Sensor:** Monitors ambient temperature and humidity, which influence crop growth and irrigation needs.
- **pH Sensor:** Determines soil acidity or alkalinity, helping maintain optimal conditions for nutrient absorption.
- **NPK Sensor:** Measures Nitrogen (N), Phosphorus (P), and Potassium (K) levels, enabling precise fertilizer application.

Output Devices

- **LCD Display:** Displays real-time sensor readings and system status for local monitoring.
- **AC Pump 1 (Irrigation Control):** Activated when soil moisture is low to provide water to crops.
- **AC Pump 2 (Fertilizer Control):** Used for nutrient delivery based on pH and NPK readings.
- **IoT Module (Wi-Fi via ESP32):** Sends real-time data to cloud platforms or mobile applications for remote monitoring and control.

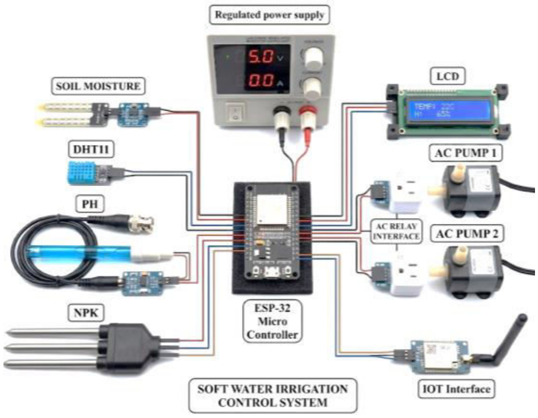

Figure 1. IoT-Based Smart Soil Nutrient Monitoring and Irrigation System.

3.1 Working Procedure

The proposed system as shown in Figure 2 continuously collects data from all sensors and processes it using the ESP32. If soil moisture falls below a predefined level, the irrigation pump is activated automatically. Similarly, nutrient levels (NPK) and pH values are monitored to control fertilizer application through a second pump. Environmental parameters such as temperature and humidity are also considered for intelligent decision-making. All collected data is displayed on the LCD and transmitted to a cloud platform via IoT, allowing farmers to monitor field conditions remotely and take timely actions.

Figure 3 illustrates the circuit diagram of an IoT-based smart soil nutrient monitoring and irrigation system designed for precision agriculture. The system is powered by a regulated power supply unit comprising a step-down transformer, bridge rectifier, filter capacitors, and a 7805-voltage regulator to provide a stable +5V output.

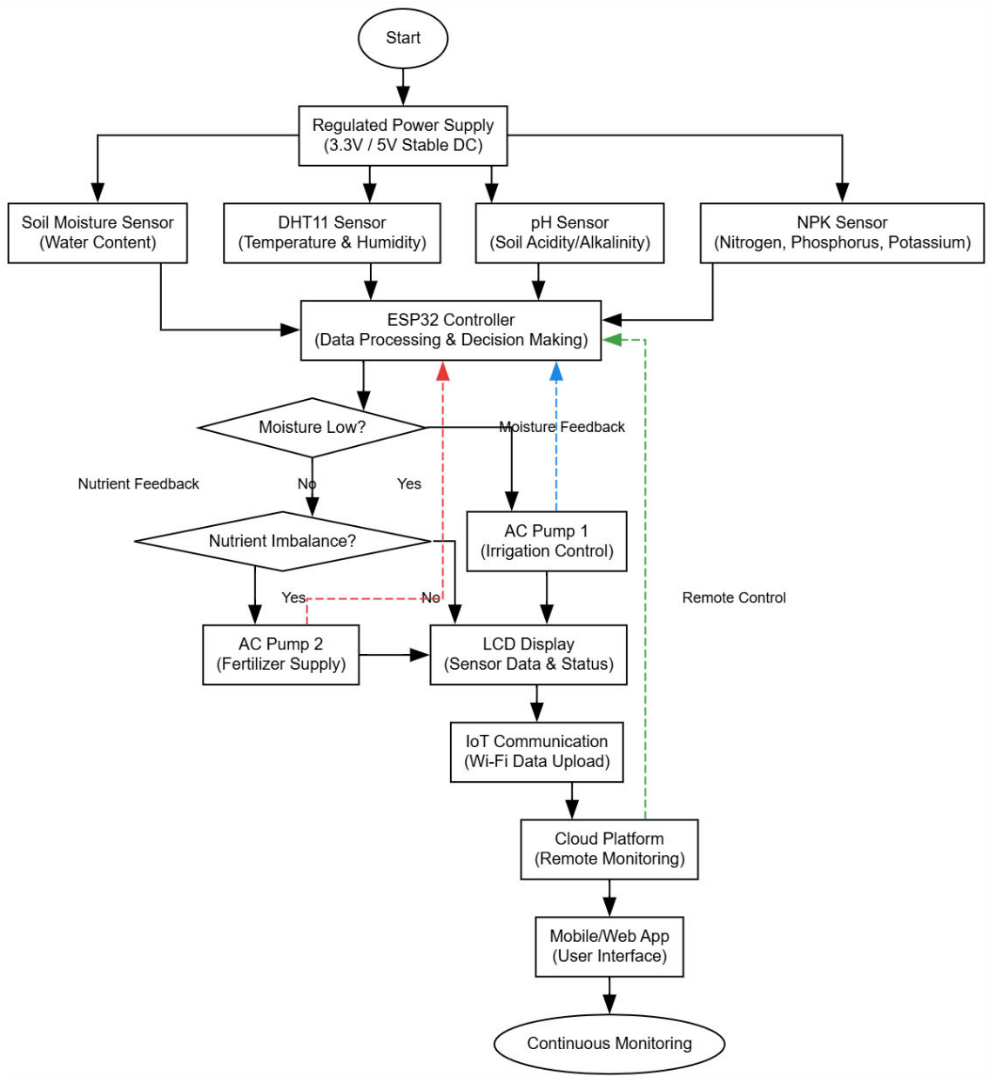

Figure 2. Proposed Flowchart.

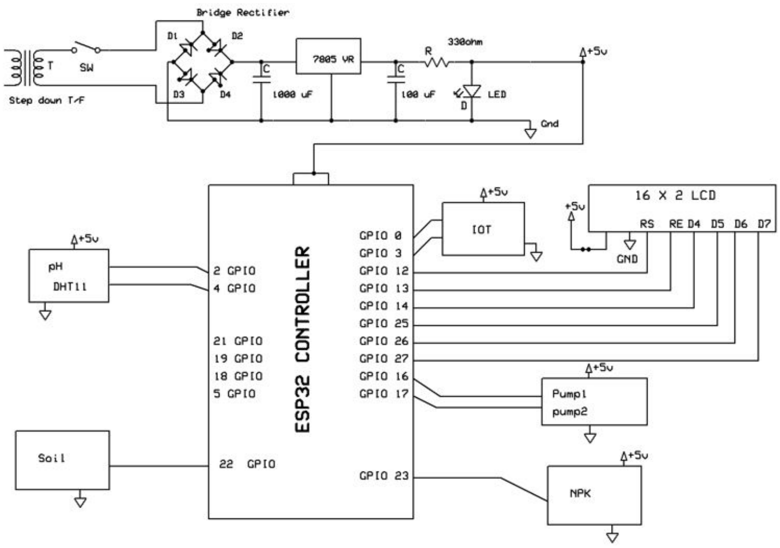

Figure 3. Circuit Diagram of IoT-Based Smart Soil Nutrient Monitoring and Irrigation System

The ESP32 microcontroller serves as the central control unit, interfacing with sensors such as a pH sensor and DHT11 sensor for monitoring soil acidity, temperature, and humidity, along with a soil moisture sensor for assessing water content in the soil. An NPK sensor is integrated to measure essential soil nutrients (Nitrogen, Phosphorus, and Potassium), enabling advanced soil health analysis. Based on sensor data, the ESP32 controls irrigation through pump modules to supply water efficiently. An IoT module allows real-time remote monitoring and data transmission to cloud platforms, while a 16×2 LCD displays current soil conditions and system status. This intelligent system optimizes water usage, improves crop yield, and supports sustainable farming practices through automated decision-making.

4. Results and Discussion

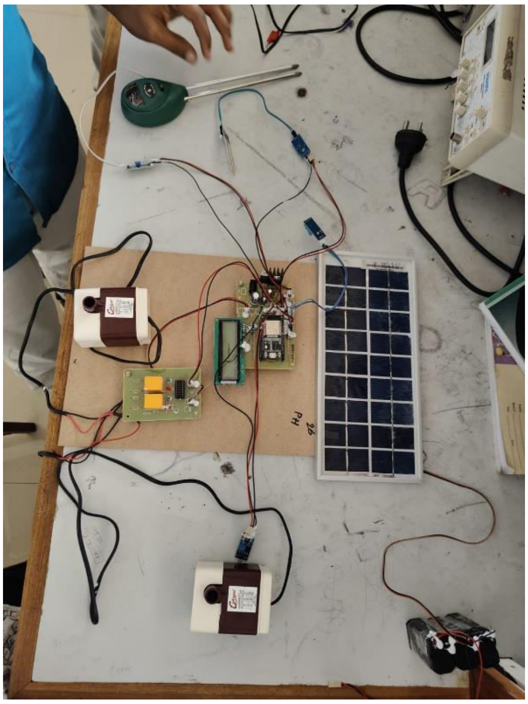

Figure 4. Hardware Setup of Solar Power IoT Crop Farming System.

Figure 4 shows the complete hardware implementation of the Solar Power IoT Crop Farming system. The setup includes an ESP32 microcontroller, solar panel, sensors for soil and environmental monitoring, relay module, water pumps, and LCD display used to monitor and control irrigation using solar energy.

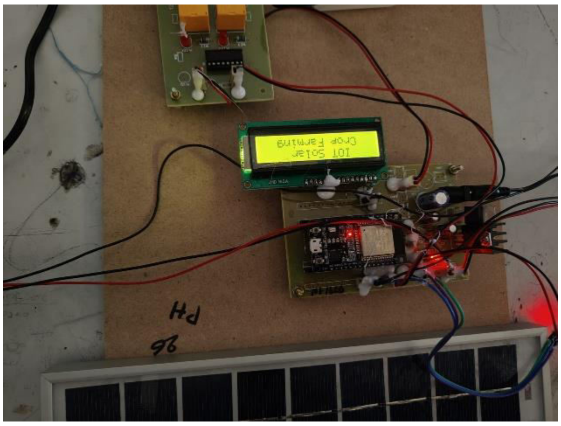

Figure 5. LCD Output Display of IoT Crop Farming System

Figure 5 shows the LCD display output of the IoT crop farming system. The display provides real-time information such as system status, crop farming conditions, and sensor readings processed by the ESP32 controller.

5. Conclusion

The proposed IoT-based nutrient monitoring and management system provides an efficient and intelligent solution for modern precision agriculture by integrating real-time sensing, automation, and IoT connectivity. By utilizing the ESP32 microcontroller along with soil moisture, temperature, humidity, pH, and NPK sensors, the system enables accurate assessment of soil conditions and nutrient levels. This data-driven approach allows farmers to make informed decisions regarding irrigation and fertilizer application, ensuring optimal resource utilization and improved crop productivity. The IoT-based remote monitoring and control further enhance flexibility and accessibility, enabling timely interventions under changing environmental conditions. This system effectively overcomes the limitations of traditional farming practices by providing continuous monitoring, precise nutrient management, and reduced resource wastage. Finally, it promotes sustainable agriculture, improves yield quality, and supports the development of smart, scalable, and efficient farming solutions.

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