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Hydroponic Farming System Using for Sustainable Indoor Agriculture Solutions

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Abstract

In indoor farms, urban agriculture setups, research laboratories, and commercial hydroponic facilities, there is a critical requirement for systems that can maintain optimal growing conditions and ensure efficient resource utilization. These environments demand automated, real-time monitoring solutions capable of regulating water, nutrients, and environmental parameters to maximize crop yield. Traditional farming methods rely heavily on soil-based cultivation and manual monitoring, which often result in inefficient water usage, inconsistent nutrient supply, and reduced productivity. Furthermore, conventional systems lack automation, remote accessibility, and precise environmental control, limiting their effectiveness in modern agricultural practices. To address these challenges, the proposed IoT Enabled Smart Hydroponic System for Indoor Farming utilizes the ESP32 microcontroller integrated with solar power and IoT technology to develop an intelligent and sustainable farming solution. The system incorporates sensors for temperature, humidity, water level, and nutrient concentration to continuously monitor plant growth conditions. An AC water pump is automatically controlled to regulate irrigation and nutrient delivery, while a 16x2 LCD provides real-time system updates and a buzzer generates alerts during abnormal conditions. The system operates in both manual and automatic modes, allowing users to control operations remotely via IoT platforms or enable autonomous regulation based on sensor data. Solar power integration ensures energy efficiency and eco-friendly operation. This smart system enhances crop productivity, optimizes resource utilization, reduces manual effort, and supports the development of sustainable indoor farming solutions.

Keywords: Cloud Computing, Hydroponics, Indoor Farming, Internet of Things, Plant Growth Chamber, Renewable Energy, Smart Agriculture, Solar Power, Water Nutrient Management

1. Introduction

The increasing demand for sustainable and resource-efficient agriculture has significantly accelerated the adoption of advanced farming technologies such as hydroponics and controlled environment agriculture [1]. Hydroponic systems can reduce water usage by up to 90% compared to traditional soil-based farming, making them highly suitable for regions facing water scarcity. Additionally, indoor farming technologies are growing at over 12% annually [2], driven by climate variability, urbanization, and the decreasing availability of arable land. These advancements highlight the need for intelligent systems that can maintain optimal growing conditions [3]. In environments such as indoor farms, urban agriculture setups, research laboratories, and commercial hydroponic facilities, there is a critical requirement for solutions that provide real-time monitoring [4], automated control, and efficient resource management to maximize crop yield and sustainability.

Traditional farming methods rely heavily on soil-based cultivation and manual monitoring practices. These approaches often lead to inefficient water usage [5], inconsistent nutrient distribution, and dependency on environmental conditions such as rainfall and temperature. Manual monitoring makes it difficult to maintain precise control over essential parameters like humidity [6], temperature, and nutrient concentration. Additionally, conventional systems lack automation and remote accessibility, limiting their ability to adapt to changing conditions in real time [7]. This results in reduced productivity and inefficient use of resources, especially in controlled indoor farming environments.

In real-time scenarios, these limitations create several critical challenges affecting agricultural efficiency and sustainability. Inconsistent nutrient supply can lead to poor plant growth and reduced crop quality, while improper water management results in wastage or inadequate irrigation. The absence of continuous monitoring prevents timely adjustments, increasing the risk of crop damage. Furthermore, lack of automation increases labor dependency and operational costs. Without remote monitoring capabilities, managing large-scale or distributed hydroponic systems becomes difficult. These challenges highlight the need for an intelligent, IoT-based hydroponic system capable of continuous environmental monitoring, automated nutrient and water control, and energy-efficient operation, ensuring improved crop yield, optimized resource utilization, and sustainable indoor farming practices.

2. Literature Survey

Hossain et al. [8] proposed an analysis of the impacts of chemical fertilizers and pesticides on soil degradation, groundwater contamination, and human health. Kumari et al. [9] proposed a study on heavy metal contamination in soil, analyzing sources, accumulation, and its effects on agricultural productivity and human health. Ali et al. [10] proposed an analysis of nutrient roles in crop production, focusing on their contribution to plant growth and yield improvement.

Brown et al. [11] proposed a revised definition of plant nutrients to advance scientific understanding and innovation in plant nutrition. Tariq et al. [12] proposed an analysis of metabolite regulation by nutrients in plants, focusing on biochemical processes and nutrient interactions.

Hawkesford et al. [13] proposed an analysis of macronutrient functions in plants, focusing on their role in physiological and biochemical processes. Ravichandran [14] proposed an overview of the significance of plant nutrients in agriculture, highlighting their role in crop productivity and soil health. Ma et al. [15] proposed an analysis of nitrogen, phosphorus, and potassium functions in plant energy status and their influence on rice growth and development.

Zewide et al. [16] proposed a review of micronutrients and their effects on crop production, focusing on their role in plant growth and deficiency management. Aye et al. [17] proposed an analysis of plant nutrient roles, deficiencies, and management strategies for improving agricultural productivity. Lopez et al. [18] proposed a study on the effects of nutrient deficiency on root architecture and root-to-shoot ratio in crops. Yahaya et al. [19] proposed a review of the chemistry of nitrogen, phosphorus, and potassium fertilizers in soil, focusing on their behavior and impact on crop production. Noulas et al. [20] proposed advanced fertilizer management strategies for optimizing crop nutrient requirements and improving agricultural efficiency.

3. Proposed System

Figure 1 illustrates the architecture of an IoT-based smart hydroponic irrigation and indoor farming system built around the ESP32. The system integrates environmental sensors such as temperature, humidity, and soil moisture sensors to continuously monitor plant growth conditions. A regulated power supply (RPS), supported by solar energy and battery storage, ensures uninterrupted operation. The ESP32 processes real-time sensor data and controls output devices including an LCD monitor, AC pump for irrigation, buzzer for alerts, and IoT connectivity for remote monitoring. An Auto/Manual (A/M) switch allows users to choose between automatic and manual operation modes. This system enables efficient water management and optimized plant growth in controlled environments.

RPS with Solar Integration: The system is powered using solar panels and battery storage, ensuring sustainable and uninterrupted energy supply. The RPS converts and regulates voltage to power the ESP32 and all connected components.

ESP32 Microcontroller: The ESP32 acts as the central controller, collecting data from sensors, processing it using embedded software, and controlling output devices. It also manages IoT communication for remote monitoring and control.

Input Sensors

- **Temperature Sensor:** Monitors ambient temperature to maintain optimal plant growth conditions.
- **Humidity Sensor:** Measures air humidity levels, which influence plant transpiration and growth.
- **Soil Moisture Sensor:** Detects water content in the growing medium and determines irrigation requirements.

Auto/Manual (A/M) Control Switch: This switch allows users to select between automatic mode (sensor-based operation) and manual mode (user-controlled irrigation).

Output Devices

- **LCD Monitor:** Displays real-time sensor data and system status for local monitoring.
- **AC Pump (Irrigation System):** Automatically activated when soil moisture falls below a predefined threshold, ensuring efficient water delivery.
- **Buzzer** Provides alerts when abnormal conditions occur, such as low moisture or system faults.
- **IoT Module (via ESP32 Wi-Fi):** Sends real-time data to cloud platforms, enabling remote monitoring and control through mobile or web applications.

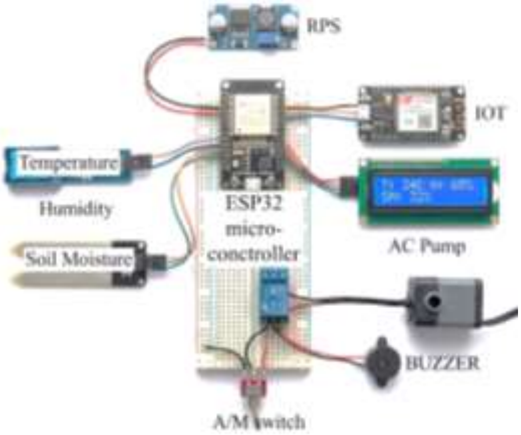

Figure 1. IoT-Based Smart Hydroponic Irrigation and Plant Growth System.

3.1 Working Procedure

The flowchart as shown in Figure 2 illustrates an IoT-based smart irrigation system powered by an ESP-32 microcontroller. A solar panel charges a battery, which supplies power to the system. The ESP-32 receives input from multiple sensors, including temperature, humidity, and soil moisture sensors, to monitor environmental conditions.

An automatic/manual (A/M) switch allows users to toggle between automated and manual control of the irrigation process. Based on the sensor data and selected mode, the ESP-32 controls various output devices such as an AC pump for irrigation, an LCD monitor for displaying real-time data, a buzzer for alerts, and an IoT module for remote monitoring and control. This setup ensures efficient water management by automating irrigation based on soil moisture levels and environmental conditions.

Figure 3 illustrates the circuit diagram of an IoT-based solar-powered hydroponic indoor farming system designed for efficient and automated plant cultivation. The system is powered by a regulated power supply unit consisting of a step-down transformer, bridge rectifier, filter capacitors, and a 7805-voltage regulator to provide a stable +5V output, which can be supported by solar energy sources.

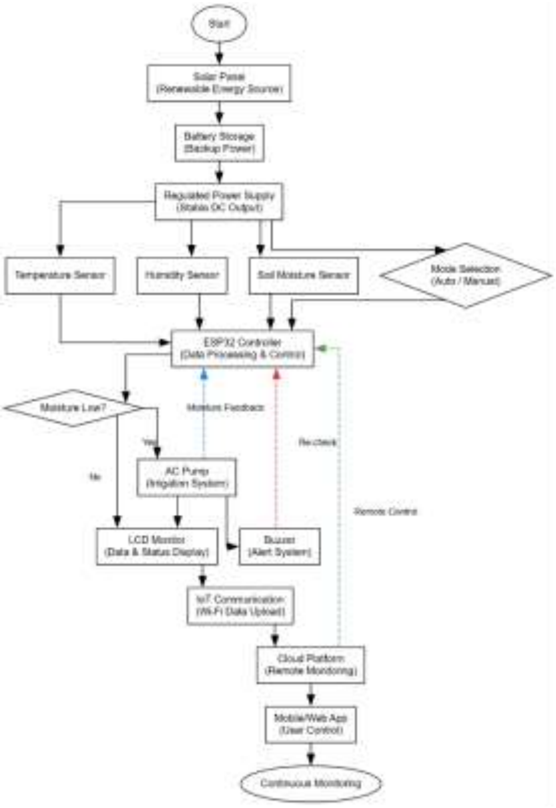

Figure 2. Proposed Flowchart.

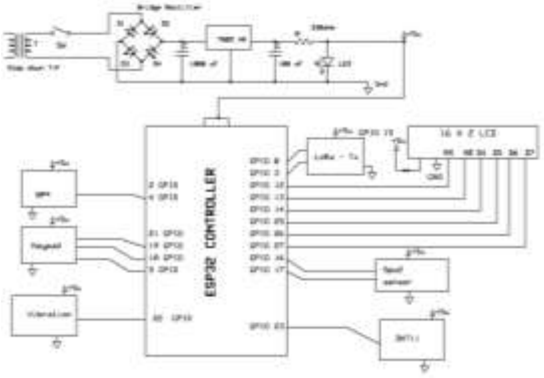

Figure 3. Circuit Diagram.

The ESP32 microcontroller serves as the central control unit, interfacing with sensors such as fire and gas sensors for safety monitoring and an ultrasonic sensor for water level detection in the nutrient reservoir. A robotic or actuator module is included for automated system operations such as nutrient flow control, while a mode selection switch allows switching between different operational modes. An IoT module enables real-time monitoring and control through cloud platforms, and a 16×2 LCD displays system parameters and status. A buzzer provides alert notifications during abnormal conditions. This integrated system enhances indoor farming efficiency by automating monitoring, ensuring optimal growth conditions, and enabling remote management.

4. Results and Discussion

Figure 4 shows the LCD display indicating the startup message of the IoT Enabled Smart Hydroponic System. The ESP32 controller initializes the system and prepares the sensors and IoT modules for monitoring plant growth parameters.

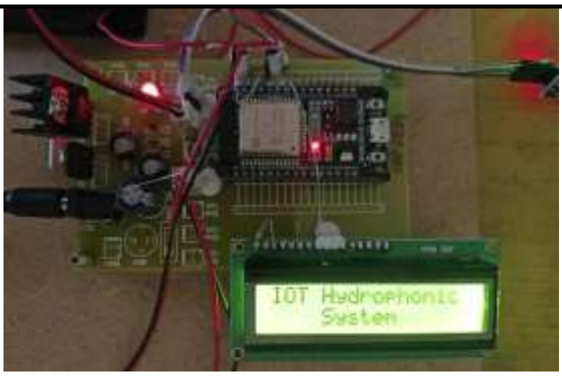

Figure 4. LCD Display Showing IoT Hydroponic System Initialization.

Figure 5 shows the complete hardware implementation of the hydroponic farming system. The setup includes the ESP32 microcontroller, water pump, cooling fan, sensors, relay module, and LCD display used to monitor and control environmental conditions for indoor plant cultivation.

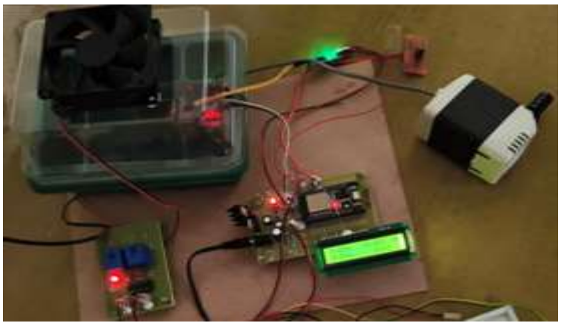

Figure 5. Hardware Setup of IoT Enabled Smart Hydroponic Indoor Farming System.

Figure 6 shows the IoT dashboard used for remote monitoring and control of the hydroponic system. The interface displays parameters such as temperature, humidity, soil moisture status, and allows users to control the pump and fan in both manual and automatic modes.

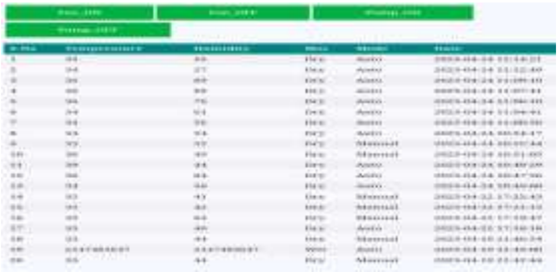

Figure 6. IoT Web Server Monitoring Interface

5. Conclusion

The proposed IoT Enabled Smart Hydroponic System for Indoor Farming offers an efficient and sustainable solution for modern agriculture by integrating real-time monitoring, automation, and renewable energy. By utilizing the ESP32 microcontroller along with sensors for temperature, humidity, water level, and nutrient concentration, the system ensures precise control over plant growth conditions, leading to improved crop yield and consistency. The automated control of the water pump enables efficient irrigation and nutrient delivery, while the LCD display and buzzer provide real-time feedback and alerts for abnormal conditions. The flexibility of manual and automatic operation modes, combined with IoT-based remote monitoring and control, enhances user convenience and system adaptability. Additionally, solar power integration promotes energy efficiency and environmentally friendly operation.

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