Design and Implementation of an IoT-Based Smart Drip Irrigation System Using ESP32 for Real-Time Soil Moisture Monitoring

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Abstract

The project introduces an automated irrigation system capable of monitoring environmental parameters and supplying water to plants without manual involvement. The system reads soil moisture, temperature, and humidity using appropriate sensors and sends real-time data to the user through a wireless dashboard. Based on moisture thresholds, the ESP32 controls a relay that turns the pump ON or OFF. The aim is to reduce water wastage, save labor, and ensure consistent plant health. This IoT-based approach provides an efficient solution suitable for small farms, home gardens, and educational prototype development.

Introduction

Modern agriculture is rapidly shifting toward intelligent and automated systems due to increasing water scarcity, unpredictable climatic variations, and the rising demand for sustainable farming practices. Traditional irrigation requires farmers to physically inspect the soil, judge moisture levels manually, and then activate or deactivate water supply. This method is time-consuming, inaccurate on large fields, and often results in water wastage or inadequate irrigation.

As the demand for precision agriculture grows, there is a need for systems that can continuously monitor soil conditions and trigger automatic irrigation based on real-time data.

With the expansion of IoT technologies, sensors and microcontrollers have become powerful tools capable of collecting environmental data and performing automated decision-making. IoT-based irrigation systems enable remote monitoring of soil moisture, temperature, and humidity while allowing wireless communication with cloud platforms or mobile applications. Among numerous microcontrollers available today, the ESP32 stands out because of its low cost, high processing power, built-in Wi-Fi and Bluetooth, and reliability in continuous data acquisition tasks. These features make it ideal for agricultural automation where uninterrupted monitoring is essential.

In this project, the ESP32 serves as the central controller for an intelligent drip irrigation model. It acquires real-time sensor readings, transmits them wirelessly, and activates the pump automatically when moisture levels fall below a predefined threshold. This reduces the need for manual supervision and ensures that plants receive adequate water at the right time. The system demonstrates how IoT can contribute to modern farming by saving resources, improving crop quality, and providing a scalable solution adaptable to different environments.

Literature Review

Previous studies on smart irrigation systems show that IoT-based moisture monitoring offers higher accuracy and efficiency compared to manual methods. Various authors have developed automated irrigation models that utilize microcontrollers, wireless communication modules, and real-time dashboards. Their contributions collectively highlight the growing significance of smart agriculture.

- **Pereira, Chaari, and Daroge (2023)** proposed an ESP32-based drip irrigation model optimized for accurate soil moisture monitoring. They demonstrated that using a cloud-connected dashboard improves remote access and decision-making. Their research shows that automated systems significantly reduce water consumption and improve plant growth consistency.
- **Lin and Chen (2025)** introduced a fuzzy logic-based smart irrigation method that calculates how much water should be supplied rather than simply switching pumps ON or OFF. Their intelligent system reduces excessive watering and adopts energy-efficient IoT protocols, making it suitable for long-term use in farms.
- **Kumar (2023)** evaluated the performance of IoT-enabled irrigation systems and compared them with traditional methods. His findings highlight that automated moisture-based irrigation results in better crop yield, reduced worker effort, and improved scheduling of water supply.
- **Moretti (2024)** developed a low-cost soil moisture monitoring system using ESP32 and NodeMCU boards. His model sends sensor data to Google Sheets using Wi-Fi and provides a simplified automation setup suitable for small farmers. The results show that budget IoT systems can be highly efficient for horticulture.
- **Rodriguez, Cruz, and Baptiste (2025)** focused on optimizing irrigation with multiple environmental sensors, including UV index and temperature. Their ESP32-based system uses predictive algorithms that enhance water efficiency and improve relay switching stability, making the system more practical for climate-sensitive crops.

System Architecture

The system architecture consists of four main layers: sensing, processing, driving, and communication. The sensing layer includes the capacitive soil moisture sensor, which continuously reads soil moisture values. The processing layer is handled by the ESP32 microcontroller, which reads sensor data, converts analog signals to digital through its ADC, and compares them against predefined threshold values. The decision layer checks whether the soil is dry enough to activate irrigation.

The driving layer comprises Arduino UNO and the relay module. When ESP32 detects dryness, it sends a digital HIGH signal to UNO. The UNO activates the relay module, which switches ON the water pump. Since ESP32 cannot provide the necessary 5V power for relay operation, UNO ensures safe and stable switching without damaging the ESP32.

Finally, the communication layer sends live data from ESP32 to the Blynk cloud dashboard through Wi-Fi. The user can view soil moisture, pump status, and environment data from anywhere. This layered design ensures reliability, modularity, and ease of debugging.

Hardware Design

The hardware is built to be modular, safe, scalable, and efficient. ESP32 is used purely for logic and IoT communication. The soil moisture sensor is connected to the analog pin of ESP32.

The Arduino UNO board supplies 5V power to the relay module and pump driver circuit. The relay module consists of a coil, switching mechanism, and isolation system that separates low-voltage and high-voltage components. The pump is connected through the relay's NO and COM terminals, ensuring current flows only when required.

Wires are organized to prevent interference. UNO's 5V pin powers the sensor and relay. ESP32 and UNO share a common ground to synchronize signals. A separate power supply can also be added for heavy pumps to prevent voltage drops. The entire setup is mounted neatly on a project board to reduce noise, improve durability, and ensure long-term stable operation.

Software Implementation

The ESP32 code is written in Arduino IDE using C/C++. It starts by initializing Wi-Fi, Blynk authentication token, and sensor pins. The program continuously reads analog values and converts them using a 12-bit ADC. The values are mapped to moisture percentage. If the percentage is below the threshold, ESP32 sends a logic HIGH to UNO. The UNO program, also written in Arduino IDE, listens to this HIGH signal and activates the relay by providing a 5V output to the relay's IN pin. The pump starts watering until ESP32 sends a LOW signal after detecting enough moisture.

Blynk libraries are used to send real-time data to widgets such as gauges, indicators, and graph plots. Error-handling routines reconnect Wi-Fi automatically if the connection drops, keeping the system reliable.

Research Objectives

- To design and implement an automated irrigation system based on real-time soil moisture monitoring.
- To reduce manual effort and delay in plant watering.
- To achieve water-efficient irrigation using IoT technology.
- To build a prototype that is scalable and low-cost.
- To enable wireless monitoring through mobile applications.

Methodology

A. Components Used

- ESP32 Microcontroller
- Capacitive Soil Moisture Sensor
- DHT11 or DHT22 Temperature & Humidity Sensor
- Relay Module (5V)
- Water Pump (submersible)
- Power Supply
- Silicon Tubing
- Jumper Wires and Breadboard
- Soldered PCB (for final model)

B. Working Process

The system continuously reads soil moisture, temperature, and humidity values using the respective sensors connected to ESP32 ADC pins. Threshold moisture values are predefined based on plant requirements. When the measured moisture falls below the threshold, the ESP32 activates the relay, which turns the pump ON. Once moisture rises above the upper threshold, the pump is turned OFF. All readings are transmitted wirelessly to a mobile dashboard via Blynk, allowing the user to monitor parameters remotely. The loop runs continuously to ensure uninterrupted automation.

C. Flow of Operation

1. System start
2. Sensors collect data

3. Read and process moisture value
4. Compare with threshold
5. Pump ON (if moisture low)
6. Pump OFF (if moisture adequate)
7. Upload data to Blynk
8. Repeat in continuous cycle

D. Experimental *Results*

- Moisture drops → Pump automatically turns ON
- Moisture restored → Pump automatically switches OFF
- Temperature, humidity, and moisture values appear correctly on Blynk
- No loose connections due to soldered board
- Relay operated smoothly without false triggering

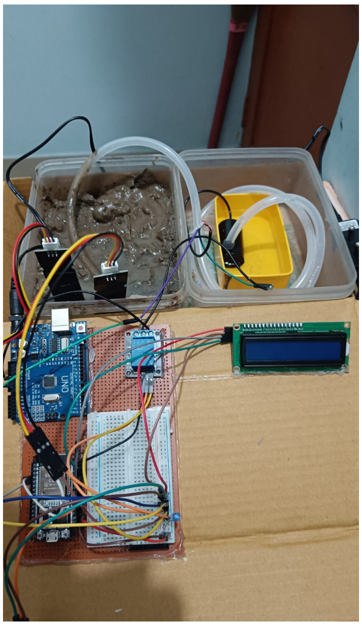
Comparison table (feature comparison of your project with the existing project)

Automation	Partial	Fully automatic
Monitoring	Wired only	Wireless (Blynk)
Sensor Accuracy	Moderate	High (capacitive)
Circuit Stability	Loose wiring	PCB soldered
Water Efficiency	Medium	High

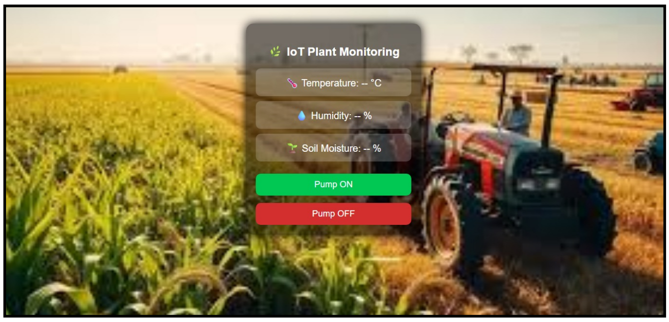
Results And Discussions

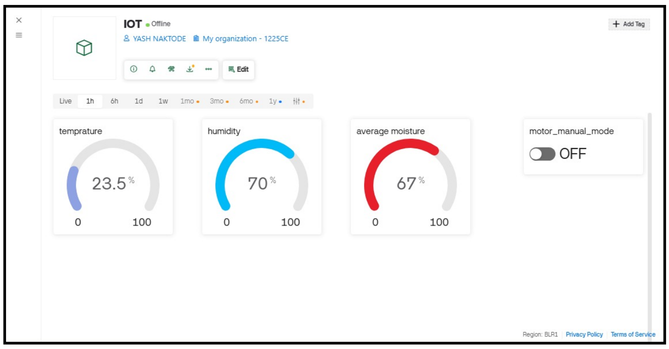
The system operated effectively during testing, showing accurate soil moisture readings and stable wireless communication. When moisture dropped below ~40%, the pump triggered automatically, and once moisture reached approximately 70%, the pump switched OFF. The ESP32 displayed consistent performance with negligible latency during sensor acquisition and dashboard updates. Compared to manual watering, the automated system saved significant time and prevented over-watering. Relay switching was smooth due to stable soldered PCB connections. Overall, the system proved reliable for continuous operation and suitable for small-scale irrigation.

E. Layout of the proposed model



F. Website To Display The Output:-





Advantages

- Fully automated irrigation
- Saves water significantly
- Reduces manual effort
- Real-time remote monitoring
- Safe load handling with UNO
- Entirely scalable system
- Strong IoT communication capability
- Efficient drip irrigation improves crop growth

Limitations

- Wi-Fi dependency
- Moisture sensor may need recalibration
- Soil salinity affects sensor accuracy
- Pump requires stable power
- Long-term sensor durability varies

Future Scope

A major future enhancement of this system is the development of a complete **software-based intelligent plant monitoring and irrigation platform**. This software can function as a centralized control system that uses real-time data, plant-specific requirements, and automation logic to irrigate crops with extremely high accuracy. The idea is to create a low-cost, highly scalable system that works seamlessly with existing drip irrigation installations **without increasing the overall cost**.

A. Intelligent Plant Monitoring Software

The future version of the system can include an application—mobile or web-based—that continuously collects data from ESP32 nodes placed in the field. These nodes would monitor soil moisture, temperature, humidity, sunlight exposure, and possibly nutrient levels. The software will process this data and determine the exact irrigation time and amount of water each plant or section of land requires. The system will consider factors like:

- Plant type and its water needs
- Soil category and water retention
- Weather conditions and forecast
- Plant age and growth stage

The software will operate on a simple logic layer where the plants that need more water receive priority supply, while the rest remain off. This ensures **precise irrigation** for each section of the field.

B. Automated Water Distribution System

The system can be expanded with automated valves that open only for the specific plant rows needing water. These valves are extremely low-cost and can be integrated directly into the existing drip irrigation pipeline. Because the valves and sensors communicate wirelessly with the ESP32 or central hub, there is no need for expensive wiring.

C. Cost-Efficient Implementation

One of the biggest advantages of this future system is that it can be implemented using **low-cost sensors**, ESP32 modules, and basic plastic drip valves. Since drip irrigation already distributes water through narrow pipes, the system simply attaches low-cost solenoid valves or timed valves to the same pipe. Therefore, the farmer does not need to modify or replace the existing drip network. The software makes intelligent decisions, while the ESP32 controls the valves according to plant-specific needs.

D. Software Features

The final software platform may include:

- Plant health monitoring dashboard

- Moisture & climate trend graphs
- Water usage analytics
- Automatic irrigation scheduling
- Alerts for low moisture or system faults
- Multi-field management controls
- Cloud backup of plant data

E. Long-Term Impact

Such a software-driven system will:

- Greatly reduce water consumption
- Improve plant health through accurate irrigation
- Lower labor dependency
- Increase crop yield
- Provide farmers with a modern, affordable precision farming solution

This future scope extends the project into a full-fledged smart farming ecosystem. It maintains extremely low cost while maximizing automation and efficiency.

Conclusion

The ESP32-based automated irrigation system successfully demonstrates how IoT technology can be used to create efficient, low-cost, and intelligent agricultural solutions. Real-time moisture monitoring ensures optimal water delivery, saving resources and improving plant health. The system is capable of remote monitoring, stable operation, and accurate sensor readings, making it highly practical for home gardens, greenhouses, and small farms. With further upgrades, such as cloud data storage or AI-based prediction, the model can be extended for large-scale agriculture.

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