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TerraGrow: A Smart Plant and Soil-Aware Monitoring and Irrigation System

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Abstract
Precision agriculture increasingly depends on smart and automated solutions to improve crop health and resource use. This work presents a smart plant monitoring system using the ESP32 microcontroller, along with soil moisture and environmental sensors. It provides real-time insights and automated irrigation for different plant types in various soil conditions. The main goal is to create sustainable growing environments by continuously tracking soil moisture, temperature, and humidity. Machine learning models analyze the collected data. Sensor readings are sent to an interactive web dashboard for easy user access. The system automatically starts irrigation when soil moisture falls below ideal levels, based on threshold values and recommendations from the machine learning model. This method cuts down on manual work, prevents under- or over-watering, and adjusts irrigation based on plant needs and environmental changes. Field tests show the system's ability to enhance plant health, optimize water use, and improve yield consistency with timely data-driven decisions. Machine learning provides tailored recommendations for different crops and soil types, supporting sustainable farming practices. The system's scalable design and user-friendly dashboard make it suitable for both small gardens and larger agricultural projects. The main contribution is an integrated setup that merges IoT-based monitoring with predictive analytics to automate and improve plant care.

Keywords: *Automated irrigation; Data-driven decisions; Machine learning; Plant monitoring; Web dashboard.*

1. Introduction
The rapid growth of the Internet of Things (IoT) and artificial intelligence (AI) has changed modern agriculture by allowing real-time, data-driven decision-making. Recent studies have focused on combining sensor-based systems and cloud computing to automatically track and improve key factors like soil moisture, temperature, and humidity in farming (Kırağ & Tenruh, 2025; Liu et al., 2025). Traditional farming methods, which often rely on manual labor and personal judgment, usually lead to inefficient use of water and fertilizer, lower crop yields, and unsustainable resource management (Rajagopalakrishnan et al., 2025; Vaidya et al., 2025). These issues show a strong need for new systems that support remote supervision, precise control, and predictive analytics for different soil and crop conditions. Recent studies show that using IoT-enabled microcontrollers, like the ESP32, along with machine learning algorithms can improve plant care. Systems that include automated irrigation and sensor feedback can efficiently distribute water and nutrients, reduce waste, and promote plant growth in various agricultural situations (Liu et al., 2025; Rajagopalakrishnan et al., 2025). These platforms offer easy-to-use dashboards and cloud connectivity, allowing users to monitor data and receive recommendations from nearly anywhere. Real-world applications have shown improvements in yield

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consistency, plant health, and overall efficiency, while also supporting sustainability in both small farms and larger operations (Kırağ & Tenruh, 2025; Vaidya et al., 2025). The main goal of this research is to create and assess a cloud-based, ESP32-powered smart plant monitoring system that features automated irrigation, real-time data visualization, and machine learning-based decision support. This study is original because it offers a complete approach, providing a flexible solution that combines IoT hardware, intuitive web interfaces, and predictive analytics to support effective crop management in a changing agricultural environment (Kırağ & Tenruh, 2025; Liu et al., 2025; Vaidya et al., 2025) [1].

1.1. Background and Motivation

Global food security, climate change, and limited resources require new ways to boost crop productivity and sustainability. The use of IoT microcontrollers and sensors makes it possible to gather detailed, real-time data from various agricultural environments. Recent projects have shown that ESP32-based systems, with scalable wireless connectivity, are cost-effective and adaptable for a wide range of plant species and soil types (Rajagopalakrishnan et al., 2025; Vaidya et al., 2025). The creation of machine learning models for farming also improves decision-making by optimizing irrigation schedules, identifying potential plant stress early, and reducing waste. This research aims to address the urgent need for strong, data-driven systems that not only monitor but also manage irrigation and plant health in a constantly changing environment.

1.2. Scope, Objectives, and Contribution

This study involves designing, implementing, and validating a cloud-enabled plant care system focused on the ESP32 microcontroller, soil and environmental sensors, and automatic irrigation systems.

1.2.1. The scope includes

- Real-time monitoring of soil moisture, temperature, and humidity with automated activation.
- Machine learning predictions for proactive and flexible irrigation management.
- A web dashboard for live data access and practical insights.

1.2.2. The main objectives are to

- Show effective, scalable monitoring and management of various plant species across different soil types.
- Measure improvements in water usage efficiency, crop health, and system responsiveness.
- Improve the existing technology by providing a seamless, user-friendly interface for both farmers and researchers.
- The key contribution of this study is a combined IoT and AI framework that links sensing, automation, and predictive analytics, setting a new standard for smart agriculture technology (Kırağ & Tenruh, 2025; Rajagopalakrishnan et al., 2025; Liu et al., 2025; Vaidya et al., 2025) [2].

2. Method

2.1. Hardware and System Design

The developed smart irrigation system was structured around an ESP32 microcontroller, interfacing with capacitive soil moisture sensors, a DHT22 (or DHT11) temperature and humidity sensor, relay modules, solenoid water valves or a water pump, and a digital display for status monitoring. Each sensor and actuator were connected to the ESP32 via dedicated GPIOs, with power drawn from isolated and regulated supplies to minimize noise and ensure operational safety. Sensors were installed at root depth in controlled plots; all outdoor electronics were shielded from environmental exposure using sealed housing in line with best practices Shown in Table 1.

2.2. Data Acquisition and Calibration

Sensor data for soil moisture and environmental variables were polled by the ESP32 at 30-second intervals, processed locally, and transmitted to a real-time dashboard (either Blynk or a custom web app) for monitoring and manual override. The soil moisture sensor was calibrated using a two-point reference (air-dry and water-saturated), aligned with the approach by Hassebo et al. (2025) and validated against manual readings. The DHT22 was cross-checked using a precision lab

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thermometer/hygrometer [3].

2.3. Automated and AI-Guided Irrigation

The control logic operated in two modes

- **Automatic Mode:** The ESP32 continuously compared soil moisture readings to crop-specific thresholds. When values dropped below these limits, the relay module actuated the water valve/pump, maintaining optimal root moisture. Water flow ceased once desired soil conditions were restored, ensuring efficient water usage.
- **AI Mode:** All environmental and actuation data were logged in the cloud (e.g., Google Sheets or Mongo DB). An LSTM-based machine learning model—trained using historical multisensory data—predicted irrigation timing and quantities for each plant-soil-climate scenario. Data was split 70% for training, 15% for validation, and 15% for testing as per the protocol in Parvez et al. (2025) Shown in Table 2 and 3.

Table 1 Soil Moisture Thresholds and Irrigation

Plant	Moisture Threshold	Irrigation Duration(s)
Tomato	38	120
Basil	32	90
Lettuce	40	100
Carrot	39	115
Pepper	33	105

Table 2 Temperature Ranges and Irrigation

Plant	Target Temp(°C)	Irrigation Duration(s)
Tomato	24-28	120
Basil	21-26	90
Lettuce	18-23	100
Carrot	19-24	115
Pepper	23-27	105

Table 3 Humidity Ranges and Irrigation

Plant	Target Humidity (%)	Irrigation Duration(S)
Tomato	55-65	120
Basil	60-70	90
Lettuce	60-80	100
Carrot	55-75	115
Pepper	50-70	105

3. Results and Discussion

3.1. Results

The ESP32-based smart irrigation system was evaluated across five crop varieties in a controlled experimental environment. The hardware was installed according to the method detailed previously, with sensors monitoring soil moisture, temperature, and humidity, and a relay module managing automated pump operation.

During four weeks of deployment

- Automated irrigation cycles were reliably triggered when soil moisture fell below the preset thresholds, restoring optimal root-zone moisture for each plant type.
- **System logs confirmed real-time sensor readings:** Over 95% of irrigation events occurred within target temperature (18–28°C) and relative humidity (50–80%) ranges.
- The integration of threshold-based and AI-predicted irrigation resulted in water usage savings of 30–40% compared to manual schedules, as measured by daily consumption logs [4].
- **Crop health indicators were positive:** For all five monitored species, plants maintained higher average leaf turgidity, exhibited consistent growth, and showed fewer signs of drought stress.
- Data was continuously sent to a cloud dashboard for remote monitoring and analysis. Users successfully adjusted moisture thresholds via a mobile app

interface, allowing personalized control and flexibility [5].

Performance analysis of the machine learning mode (LSTM model) indicated accurate prediction of irrigation needs, with validation accuracy rates above 90% and timely activation of watering cycles in response to predicted dry conditions. Sensor readings and pump activations were stable, reflecting robust interfacing and practical hardware design.

3.2. Discussion

The results demonstrate that the ESP32-based smart irrigation system achieved significant gains in agricultural efficiency and sustainability. By leveraging automated sensing and data-driven control, the system delivered targeted irrigation only when soil moisture reached crop-specific thresholds, resulting in substantial water savings. Compared to traditional manual watering, this technology enables more consistent maintenance of optimal soil and climate conditions, which is a critical factor in promoting robust plant health and uniform growth. A key insight from the findings is that integrating IoT devices and predictive AI models—such as per-plant LSTM networks—offers benefits that extend beyond simple automation. The capacity for remote threshold adjustment and real-time feedback via a user-facing dashboard empowered users to respond quickly to changing environmental factors, thereby minimizing both under- and over-watering risks. The positive plant health outcomes observed across all five test crops highlight the effectiveness of intelligent irrigation management in supporting higher yields and resilience against drought stress. Another important dimension is scalability and practical deployment. The use of low-cost, widely available sensors and microcontrollers makes this solution accessible for small-scale farmers and home gardeners, not just large commercial operations. Experimentation indicated reliable platform operation over extended periods, suggesting that this approach could be adapted to larger farm contexts with minimal modification. Additionally, the modular structure and multi-mode operation (AI, auto, manual) provided system resilience against sensor failure, network outages, and user error, enhancing confidence in long-term robust operation.

Conclusion

The results of this research confirm that an ESP32-based smart irrigation system directly addresses the challenges of inefficient water use and inconsistent manual crop management in modern agriculture. Through data-driven control, automated sensor readings, and IoT connectivity, the system maintained optimal soil moisture and environmental conditions for a variety of crops, resulting in improved plant health, reduced drought stress, and 30–40% water savings compared to manual irrigation methods. The flexible platform also allows for responsive, remote management and easy adjustment of irrigation parameters, further minimizing risk of over- or under-watering. These findings validate that the integration of real-time monitoring, predictive scheduling, and automated irrigation forms a practical and sustainable solution for both small and large growing operations. The system’s low cost, adaptability to different crops and soil types, and reliable performance make it a viable tool for widespread adoption, supporting the long-term sustainability of agricultural water management. Future developments should focus on refining calibration processes and scaling deployment to a broader range of fields and crops, but the core problem of resource inefficiency is effectively solved by this IoT-based approach.

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