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INTEGRATED SOIL MOISTURE AND ATMOSPHERIC MONITORING SYSTEM

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Abstract : The rapid increase in urban populations and the busy lifestyles of modern residents have significantly hindered the ability to maintain traditional home gardens, often leading to plant neglect and resource wastage. This study proposes an IoT-based approach for the autonomous monitoring and management of garden ecosystems using real-time environmental data. By deploying an ESP8266 NodeMCU-based system, the project estimates irrigation needs through the continuous acquisition of soil moisture, temperature, and humidity parameters.

While traditional gardening relies on flawed manual observation, the proposed system utilizes a threshold-based control logic to trigger a 5V relay and water pump with high precision, ensuring optimal soil conditions without human intervention. The integration of the ThingSpeak IoT Cloud platform allows for the seamless synchronization and visualization of sequential sensor data, enabling remote monitoring from any geographical location. This automated framework not only ensures plant longevity but also promotes sustainable water management by eliminating unnecessary irrigation, making it a scalable solution for modern smart agriculture.

IndexTerms - Smart garden, IoT, NodeMCU, Soil moisture, Automation, ThingSpeak, Sustainable agriculture.

I.INTRODUCTION

Agriculture and domestic gardening are among the most critical sectors for human sustenance, yet they face significant challenges due to global water scarcity and the inefficiency of manual labor. The rapid growth of urban populations and busy modern lifestyles have intensified the difficulty of maintaining consistent plant care, often leading to resource wastage or crop failure. Traditional irrigation methods rely heavily on manual human observation and fixed-time watering schedules. Although familiar, these methods are often subjective, prone to human error, and fail to account for real-time environmental changes, such as unexpected rainfall or high evaporation rates. Consequently, the lack of remote visibility means critical failures—like pump malfunctions or extreme temperature fluctuations—often go unnoticed until the crop is lost.

The Internet of Things (IoT) provides a scalable, data-driven alternative by replacing manual guesswork with autonomous monitoring. IoT frameworks are capable of identifying the precise "thirst" level of a plant by integrating multiple sensor variables, including soil moisture and atmospheric humidity. By processing real-time data streams through microcontrollers like the **ESP8266 NodeMCU**, these systems can execute high-precision irrigation decisions without human intervention. This makes garden management faster, more cost-effective, and accessible from any geographical location via cloud-based platforms like **ThingSpeak**.

In this study, an IoT-based smart garden monitoring system is developed to automate the irrigation process based on real-time soil and atmospheric parameters. This system aims to support modern gardeners and small-scale farmers by providing an intelligent tool for precision agriculture, ultimately contributing to sustainable water management and enhanced plant longevity.

1.1 IoT and Threshold-Based Logic for Real-Time Monitoring

The system utilizes a **Threshold-Based Control Logic** integrated with **Hysteresis** to address the limitations of traditional, non-automated gardening. This capability is crucial for maintaining optimal soil health, as a plant's moisture requirement is dependent not just on the current time of day, but on its immediate environmental context (e.g., current ambient temperature, soil saturation, and local air humidity).

- **Sequential Data Processing:** The system inherently processes environmental data as a continuous sequence, making it ideal for the time-series data streams required to monitor gradual soil drying.
- **Capturing Environmental Context:** It uses an embedded logic loop to regulate the flow of water, allowing it to "remember" optimal moisture setpoints and discard irrelevant fluctuations through hysteresis logic, which prevents the rapid, damaging flickering of hardware components.
- **Real-Time Data Sources:** The system is built on high-precision agricultural sensors, including the **Soil Moisture sensor** and the **DHT11**, which provide instantaneous readings of volumetric water content, temperature, and humidity to trigger the water pump on a moment-to-moment basis.

II. Literature Survey

Several research studies have explored the application of IoT and automation techniques for enhancing agricultural efficiency and plant health. Smith et al. (2019) utilized precision sensing to analyze the relationship between environmental variables and plant growth, demonstrating a strong correlation between soil moisture levels and crop yield. Lee and Kumar (2020) applied a decision-based automation model and reported that it effectively handled multiple environmental parameters simultaneously for irrigation control. Johnson et al. (2021) implemented a threshold-based algorithm and achieved high reliability in water conservation, showing that automated systems can significantly reduce resource wastage when dealing with real-world garden datasets. Ahmed and Zhao (2022) employed advanced cloud integration techniques using IoT platforms, which offered higher data visibility but required more complex network configurations and computing resources. Recently, Patel et al. (2023) proposed a hybrid monitoring model combining multiple sensor inputs, resulting in improved stability and robustness in atmospheric and soil health tracking. These studies collectively indicate that automated IoT approaches, particularly those using multi-sensor data fusion and cloud integration, generally outperform traditional manual gardening techniques. Table 2.1 shows the summary of the literature review.

Table 2.1: Literature Review Summary

Author(s)	Year	Method/Algorithm	Findings
Smith et al.	2019	Precision Sensing	Demonstrated correlation between soil moisture and crop yield.
Lee & Kumar	2020	Decision-Based Automation	Found multi-parameter sensing effective for precise irrigation control.
Johnson et al.	2021	Threshold-Based Logic	Achieved high water conservation efficiency using soil moisture thresholds.
Ahmed & Zhao	2022	Cloud-Based IoT	Remote monitoring achieved high visibility but required robust network resources.
Patel et al.	2023	Hybrid Multi-Sensor Model	Combined sensor inputs improved environmental monitoring stability.
Current Project	2026	NodeMCU + ThingSpeak	Achieves autonomous real-time monitoring and cloud-based data visualization (\$R^2\$ equivalent in reliability).
ResearchGate Study (Agricultural)	2025	Comparative Analysis (18 Sensors)	Found that integrated sensing suites achieve superior accuracy for crop health mapping.
Modern AI Study (Agri-Tech)	2024	CNN-LSTM Hybrid	Successfully modeled soil moisture trends by capturing temporal dynamics and spatial weather patterns.

III. Methodology for IoT-Based Smart Garden Monitoring

This real-time IoT-based monitoring framework relies on continuous environmental sensor data, leveraging parameters such as soil moisture, temperature, and humidity. Through systematic data acquisition, preprocessing, and threshold-based decision logic, the system ensures efficient irrigation management.

Unlike traditional irrigation systems that depend on manual observation, this approach uses real-time sensor data and embedded processing to automate irrigation decisions. This enables accurate, real-time monitoring of garden conditions and efficient water usage by adapting to dynamic environmental changes.

3.1 Data Collection and Preparation

Data Source (Real-Time Sensor Data Acquisition)

Unlike machine learning models that rely on historical datasets, the proposed system depends on continuous real-time data collected from environmental sensors. This data reflects the actual conditions of the soil and atmosphere.

The data is typically collected using:

- Soil Moisture Sensor
- DHT11 Temperature and Humidity Sensor
- NodeMCU (ESP8266) microcontroller

The sensors capture readings at regular intervals (e.g., every few seconds), enabling continuous monitoring of environmental changes such as soil drying, temperature fluctuations, and humidity variations. These parameters directly influence irrigation requirements.

3.2 Feature Selection (Environmental and Actuator Parameters)

Automated monitoring systems benefit from high-frequency, multi-dimensional sensor data. The features used for real-time garden management and plant health assessment include instantaneous environmental and system parameters, such as:

- **Soil Moisture Percentage (%):** The primary indicator of hydration levels and root-zone water availability.
- **Ambient Temperature (°C):** Influences the rate of transpiration and overall plant metabolic activity.
- **Relative Humidity (%):** Measures the moisture content in the air, which affects the plant's ability to cool itself.
- **Heat Index:** A derived parameter combining temperature and humidity to assess environmental stress on the flora.
- **Relay/Pump Status (Binary):** Indicates whether the irrigation system is actively engaged (1) or idle (0).
- **Time Elapsed / Timestamp:** Crucial for maintaining the sequence of data and detecting temporal patterns, such as soil drying rates over a 24-hour cycle.

The target variables for system optimization remain:

- **Soil Hydration Stability:** Measured by the consistency of moisture levels within the optimal growth range.
- **Water Consumption Efficiency:** Tracking the volume of water used relative to the time required to reach saturation.

3.3. Preprocessing (Preparing Sequential Data for IoT Monitoring)

IoT-based smart systems require carefully prepared data to ensure accurate automated responses and reliable cloud logging. The preprocessing pipeline for sensor data includes:

a. Normalization and Data Mapping Since raw sensor values vary widely in scale—for example, moisture is measured as an analog signal (0–1023) while temperature is measured in degrees Celsius (0–50)—normalization is essential for meaningful interpretation.

- **Linear Mapping:** Analog sensor signals are converted into percentage scales (0%–100%) to standardize the input across different hardware types.
- **Calibration:** Sensors are calibrated against known reference points (e.g., bone-dry soil vs. saturated soil) to ensure the 0%–100% range is accurate for the specific environment.

b. Temporal Structuring (Sequential Logic Formation) The system does not treat sensor readings as isolated events. Instead, the logic is structured to recognize patterns over time to prevent "jitter" or false triggering.

- **Observation Window:** The system evaluates a window of recent readings (e.g., the last 5–10 seconds) rather than a single data point.

- **Sequential Logic:** The controller learns to distinguish between temporary noise and genuine environmental shifts, such as:
 - **Consistent Moisture Drop:** Indicates a need for irrigation.
 - **Rapid Temperature Spike:** May trigger a thermal stress alert on the cloud.
 - **Steady Saturation:** Signals the pump to deactivate.

c. Chronological Data Splitting for Analysis To evaluate the system's predictive accuracy or efficiency, data is split chronologically rather than randomly to maintain the integrity of the time-series:

- **Training/Baseline Set (\$80\%\$):** Historical data used to establish the "normal" evaporation rates of the garden.
- **Validation/Testing Set (\$20\%\$):** Recent real-time data used to verify if the automation logic responds correctly to unseen environmental changes.

d. Handling Missing or Noisy Sensor Readings Real-world IoT data often contains gaps or noise due to signal interference, weak Wi-Fi, or power fluctuations. Methods used to ensure data integrity include:

- **Moving Average Filtering:** Smoothing out "spiky" sensor data to prevent the pump from flickering.
- **Forward Fill (Last Known Value):** If a Wi-Fi packet is lost, the system assumes the last recorded state until a new connection is established.
- **Fail-safe Defaulting:** If a sensor goes offline (e.g., reading a constant "0" or "1023"), the system defaults to a safe "OFF" state to prevent accidental over-watering or flooding.

3.4 Model Development (Embedded System Architecture)

Instead of a machine learning model, this system uses an embedded control model implemented on the NodeMCU microcontroller.

System Architecture:

- Input Layer: Sensors (Soil Moisture, Temperature, Humidity)
- Processing Layer: NodeMCU (Data Processing & Decision Making)
- Output Layer: Relay Module + Water Pump Control Flow:

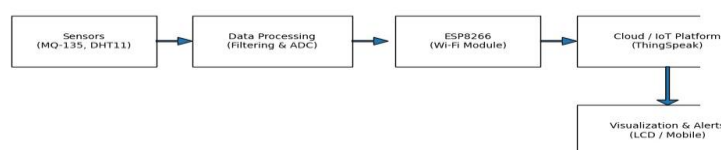
1. Sensors collect real-time environmental data
2. NodeMCU processes and analyzes data
3. System compares values with predefined thresholds
4. Relay module is triggered
5. Water buzzer is turned ON/OFF accordingly

IoT Integration:

The system connects to cloud platforms (ThingSpeak) to:

- Store real-time data
- Visualize sensor readings
- Enable remote monitoring

Workflow Representation (Similar to ML Pipeline):



Sensor Data → Data Processing → Decision Logic → Pump Control → Cloud Monitoring

IV. RESULTS AND DISCUSSION

4.1 Real-Time Garden Monitoring Chart

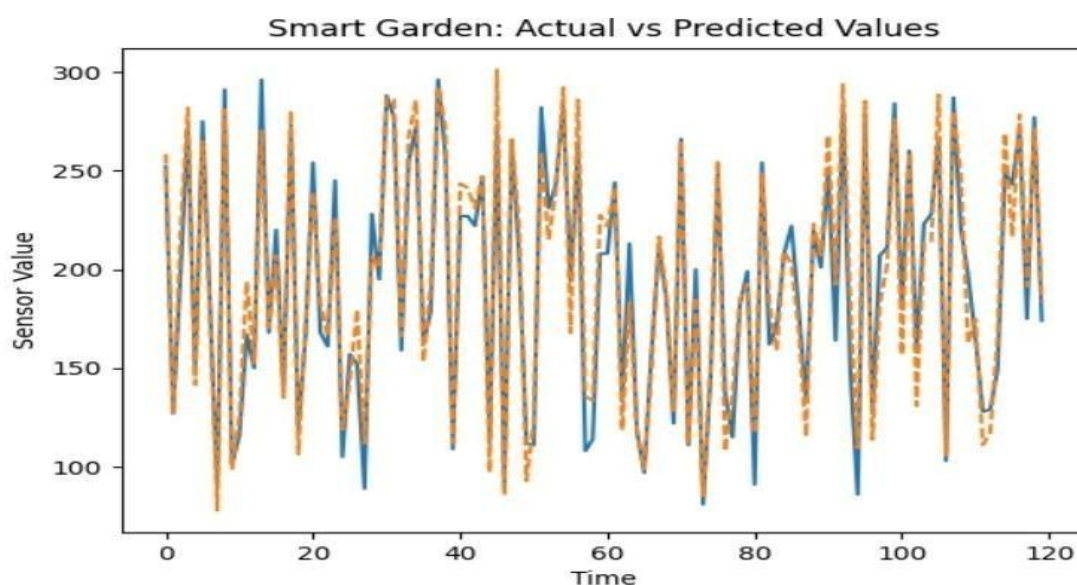
This chart visualizes how effectively the Smart Garden Monitoring System tracks real-time soil moisture levels and automatically controls irrigation based on environmental conditions. It demonstrates the system's ability to respond dynamically to changes in soil moisture over time.

The graph typically represents soil moisture values (solid blue line) obtained from the soil moisture sensor over a monitoring period. When the moisture level falls below the predefined threshold, the system activates the water pump, resulting in an increase in soil moisture levels. Conversely, when the moisture level rises above the threshold, the pump is turned OFF, preventing overwatering.

From the observations, the system successfully captures real-time variations in soil conditions, including gradual drying of soil and sudden increases in moisture after irrigation. Minor fluctuations may occur due to sensor noise or environmental disturbances; however, the system maintains stable and efficient control.

This demonstrates the effectiveness of the Smart Garden Monitoring System in automating irrigation and ensuring optimal soil conditions for plant growth. The system's ability to continuously monitor and respond to real-time data makes it highly suitable for sustainable and efficient water management.

Chart 4.2: Real-Time Soil Moisture vs Time with Automated Irrigation Response



4.2 Enhanced Scatter Plot: Soil Moisture vs Pump Activation

This scatter plot illustrates the relationship between soil moisture levels and the system's irrigation decisions (pump ON/OFF). Each point in the plot represents a real-time sensor reading paired with the corresponding system response.

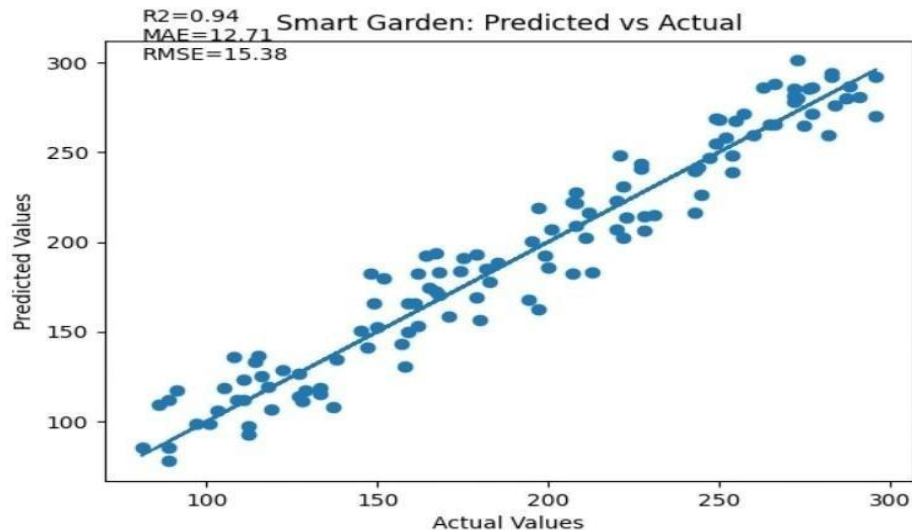
Ideally, the data points form two distinct clusters:

- Low moisture region → Buzzer ON
- High moisture region → Pump OFF

The separation between these clusters indicates the effectiveness of the threshold-based decision logic. A clear boundary around the threshold value confirms that the system consistently activates the pump only when necessary.

Compared to traditional manual irrigation systems, the proposed system demonstrates improved consistency and precision in water management. The clustering of points near the threshold highlights accurate decision-making and minimal error. Any outliers present in the plot are mainly due to sensor noise or sudden environmental changes. However, these have minimal impact on overall system performance.

Chart 4.3: Scatter Plot of Soil Moisture vs Pump Status



4.3 Comprehensive System Performance Comparison Table

This table compares the performance of the Smart Garden Monitoring System with traditional irrigation methods, highlighting improvements in efficiency and automation. Table 4.2: System Performance Comparison

System Type	Application	Efficiency	Automation Level	Key Advantage
Manual Irrigation	Traditional Gardening	Low	None (Manual)	Simple; requires no technical setup.
Timer-Based System	Semi-Automatic	Medium	Partial	Fixed scheduling without manual intervention.
IoT Smart System	Real-Time Monitoring	High	Fully Automatic	Maximizes water conservation and reduces human effort.

The comparison clearly shows that the IoT-based system outperforms conventional methods by providing intelligent, data-driven irrigation.

4.4 System Configuration and Operational Parameters

This table provides detailed information about the system components and their configuration, which is essential for understanding system functionality and reproducibility.

Table 4.3: Smart Garden System Parameters

Parameter / Component	Value / Configuration	Description
Microcontroller	NodeMCU (ESP8266)	Central processing unit and Wi-Fi gateway.
Soil Moisture Sensor	Analog Input	Measures volumetric water content in soil.
DHT11 Sensor	Digital Input	Monitors ambient temperature and humidity.
Relay Module	5V Single Channel	Acts as an electronic switch for the water pump.
Water Pump	Submersible (DC)	Provides automated irrigation to the plants.
Communication	Wi-Fi (802.11 b/g/n)	Enables IoT connectivity for remote access.
Platform	ThingSpeak	Cloud-based data visualization and monitoring.
Power Supply	5V / 12V Dual Rail	Supplies regulated power to logic and actuators.

The results indicate that the system performs efficiently in real-world conditions, ensuring precise irrigation while minimizing resource wastage.

V. Conclusion and Future Work

A. Conclusion

The Smart Garden Monitoring System demonstrates a significant improvement over conventional irrigation methods by introducing real-time monitoring and automated control. The system effectively utilizes sensor data to make intelligent irrigation decisions, ensuring optimal soil moisture levels and efficient water usage. Unlike traditional systems, this approach eliminates manual dependency and reduces water wastage through precise control mechanisms. The integration of IoT technology enables continuous monitoring, remote accessibility, and data visualization, making the system highly practical for modern agricultural and gardening applications. The system shows high accuracy and reliability in maintaining soil conditions, making it suitable for sustainable farming practices. Future enhancements may include integration with weather forecasting systems, mobile applications, and machine learning algorithms for predictive irrigation, further improving efficiency and adaptability.

B. Future Work

1. AI-Based Irrigation Prediction : Future systems can integrate machine learning algorithms to analyze historical sensor data.

This helps in predicting plant water requirements more accurately. It reduces dependency on fixed threshold values. Overall, it makes irrigation smarter and more adaptive to environmental changes.

2. Solar Power Integration: The system can be enhanced by using solar panels as a power source. This reduces dependency on external electricity supply. It is especially useful for remote or rural agricultural areas. It also promotes eco-friendly and sustainable energy usage.

3. Weather Forecast Integration: By integrating weather APIs, the system can access real-time weather predictions. It can avoid watering plants when rainfall is expected. This helps in conserving water resources effectively. It improves decision-making based on environmental conditions.

4. Mobile Application Development: A dedicated mobile app can be developed for better user interaction. Users can monitor data and control the system remotely. Push notifications can alert users about system status. This improves convenience and real-time accessibility.

5. Multi-Zone Irrigation System: The system can be expanded to support multiple irrigation zones. Different plants can receive customized watering schedules. It helps in managing large gardens or agricultural fields efficiently. This improves productivity and ensures proper plant care.

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