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Internet of things-based smart irrigation system using soil moisture and weather data

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ABSTRACT

Water wastage in agriculture remains a significant challenge due to irrigation practices that often rely on fixed schedules rather than actual field conditions. This study presents an internet of things (IoT)-based smart irrigation system designed to improve water-use efficiency through real-time monitoring and automated irrigation control. The system integrates a capacitive soil moisture sensor with weather information obtained from an online application programming interface (API), while all data processing is performed locally on a Raspberry Pi edge device. A rule-based decision mechanism is used to classify soil conditions into dry, optimal, and wet categories and to determine appropriate irrigation actions based on soil moisture levels and rainfall forecasts. The system was implemented using low-cost and readily available components and tested under controlled conditions with soil moisture levels ranging from approximately 0% to above 85%. Experimental results showed consistent classification of critical dry, optimal, and critical wet conditions, enabling appropriate irrigation responses under different scenarios. In addition, email notifications were generated only during critical conditions, while no alerts were triggered under optimal moisture levels, demonstrating stable and reliable operation. The proposed system provides a practical and cost-effective solution for supporting efficient irrigation management and sustainable agricultural practices.

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1. INTRODUCTION

Efficient water management remains one of the key challenges in modern agriculture, as irrigation accounts for a significant portion of global freshwater consumption. Agriculture is widely recognized as the largest user of freshwater resources, and increasing pressure from climate change, population growth, and rising food demand has intensified concerns about water scarcity and sustainability [1], [2]. In many agricultural settings, irrigation is still carried out based on fixed schedules or manual judgment, without considering real-time soil moisture conditions or short-term weather variations. As a result, such practices often lead to inefficient water use, over-irrigation, and reduced crop productivity [3], [4].

To address these challenges, recent research has increasingly explored the use of internet of things (IoT) technologies for real-time monitoring and control in agricultural systems. Soil moisture sensors, together with environmental and climatic data, allow irrigation systems to respond more dynamically to actual field conditions instead of relying on static schedules [5], [6]. Previous studies have shown that IoT-based irrigation systems can reduce water consumption while maintaining or even improving crop productivity by applying water only when it is needed [7], [8]. These developments align closely with the United Nations Sustainable Development Goal (SDG) 6, which focuses on efficient water use and sustainable water management.

Beyond sensing technologies, data-driven approaches have been introduced to improve decision-making in smart irrigation systems. These approaches combine soil moisture data with weather information to support more adaptive irrigation scheduling. Both data-driven approaches and rule-based decision mechanisms have demonstrated promising results in optimizing irrigation timing and reducing unnecessary water usage [9]–[12]. Such approaches contribute to improved agricultural efficiency and support SDG 2 (Zero Hunger) by promoting sustainable food production.

Despite these advancements, many existing smart irrigation systems rely heavily on cloud-based platforms for data processing and decision-making. While cloud solutions offer high computational capability, they may introduce communication delays, increase system complexity, and raise data privacy concerns, particularly in rural or resource-limited environments with unstable internet connectivity [13], [14]. These limitations can negatively affect system responsiveness, reliability, and real-time irrigation control efficiency [15].

Edge computing has recently emerged as a promising alternative by enabling data processing closer to the source. By performing data analysis and decision-making locally on edge devices such as single-board computers, system latency can be reduced and dependence on continuous internet connectivity minimized [16], [17]. Edge-based approaches have been shown to improve responsiveness, robustness, and energy efficiency in IoT-enabled agricultural applications, making them well suited for precision irrigation systems [18], [19].

However, several limitations still exist in current smart irrigation solutions. Many systems focus mainly on either sensor-based monitoring or cloud-based analytics, without offering a fully integrated and practical solution [20], [21]. Cloud-dependent approaches may suffer from delayed responses and reduced reliability in real-time applications, especially in areas with unstable connectivity. In addition, data-driven systems often require large datasets and higher computational resources, which may not be suitable for low-cost or resource-constrained environments. Furthermore, some systems do not effectively incorporate weather forecast data into irrigation decision-making, limiting their ability to adapt to changing environmental conditions [22], [23].

Recent studies have demonstrated the effectiveness of IoT and automated decision-making in improving irrigation management. For example, data-driven systems in [7], [8], [11] provide data-driven irrigation decisions with high predictive accuracy. However, these approaches often require large datasets, model training, and cloud-based infrastructures, which increase system complexity and limit real-time responsiveness. Similarly, IoT-based systems in [5], [6], [21] enable real-time monitoring but often lack integrated decision-making or effective use of weather forecast data.

In contrast to existing approaches, the proposed system addresses these limitations by integrating soil moisture sensing, weather-aware decision-making, and edge-based processing within a unified framework. Unlike cloud-dependent or data-driven systems, the proposed approach performs all data processing locally on a Raspberry Pi, enabling faster response times and reducing reliance on continuous internet connectivity. In addition, a lightweight rule-based decision mechanism is adopted to ensure system simplicity, computational efficiency, and practical deployment in real-world agricultural environments.

The main contributions of this study are summarized as follows: (i) development of a low-cost IoT-based smart irrigation system that integrates soil moisture sensing with real-time weather data; (ii) implementation of an edge computing approach using a Raspberry Pi to enable fast and reliable local decision-making; (iii) design of a lightweight rule-based decision mechanism for adaptive irrigation control without relying on complex data-driven models; and (iv) experimental validation of the system under soil moisture levels ranging from approximately 0% to above 85%, representing critical dry, optimal, and critical wet conditions. Motivated by these contributions, this study presents an IoT-based smart irrigation system that integrates sensing, local processing, and rule-based decision-making to improve irrigation efficiency and reduce unnecessary water usage [24], [25].

2. METHOD

This section describes the methodology used to design and implement the proposed IoT-based smart irrigation system. The focus is on developing a low-cost and practical solution that integrates soil moisture sensing, weather information, and rule-based decision-making using an edge computing approach. Unlike complex decision-making models, the proposed system employs a lightweight rule-based decision mechanism, making it suitable for real-time operation in resource-constrained environments.

2.1. System architecture

The proposed smart irrigation system consists of four main functional components: sensing, data acquisition, decision-making, and actuation. Soil conditions are continuously monitored using a capacitive soil moisture sensor installed in the field, which provides real-time measurements of soil moisture levels. At the same time, relevant weather information, such as rainfall probability and ambient temperature, is retrieved from an online weather application programming interface (API).

All collected data are transmitted to a Raspberry Pi, which serves as the edge computing unit. The Raspberry Pi processes both sensor and weather data locally, enabling real-time decision-making while reducing dependence on continuous internet connectivity. Based on the processed inputs, the system determines whether irrigation is required and automatically controls water flow through a solenoid valve connected to the irrigation system.

In addition, system status and irrigation actions are communicated to the user through notification services, enabling remote monitoring and improved awareness of field conditions. The overall data flow of the system can be summarized as follows: (i) soil moisture and weather data are collected; (ii) data are processed locally on the Raspberry Pi; (iii) the decision mechanism evaluates irrigation conditions; and (iv) appropriate actions are executed through the actuator and notification system. The modular design of the system allows each component to operate independently while remaining fully integrated within the overall architecture. This design simplifies deployment, maintenance, and future system expansion. Figure 1 illustrates the overall system architecture, showing the integration of soil moisture sensing, weather data acquisition edge-based processing using Raspberry Pi, rule-based decision-making, automated irrigation control through a solenoid valve, and user notification services for monitoring and supervision.

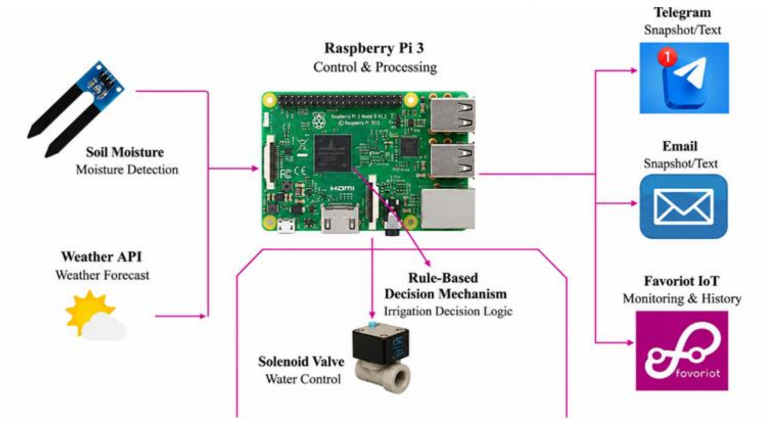


Figure 1. Overall system architecture

2.2. Hardware and software implementation

The system is implemented using low-cost and readily available hardware components. A Raspberry Pi 3 Model B+ is used as the main controller due to its compact size and sufficient processing capability for edge-based applications. A capacitive soil moisture sensor is employed to measure soil moisture levels reliably. Since Raspberry Pi does not support direct analog input, an MCP3008 analog-to-digital converter (ADC) is used to convert the sensor output into digital signals. Irrigation is controlled using a relay-connected solenoid valve, which enables automatic regulation of water flow based on system decisions. The software is developed in Python and is responsible for sensor data acquisition, weather data retrieval from the API, execution of the decision logic, and control of the actuator. Notification services are also integrated to inform the user about soil conditions and irrigation status.

2.3. System operating algorithm

The system operating algorithm governs the irrigation decision-making process. The algorithm continuously monitors soil moisture data and classifies soil conditions into three categories: dry, optimal, and wet. These classifications are based on predefined moisture thresholds determined through empirical calibration during controlled testing. Specifically, soil moisture values below approximately 15% are classified as dry, values between 30% and 45% are considered optimal, and values above 85% are classified as wet. These threshold ranges were selected based on experimental observations to reflect practical irrigation requirements under controlled conditions.

When the soil is classified as dry, the system evaluates weather information obtained from the weather API, particularly rainfall prediction. If rainfall is expected, irrigation is delayed to avoid unnecessary water usage. Otherwise, irrigation is activated through the solenoid valve. When the soil moisture level falls within the optimal range, irrigation is not triggered, as the soil already contains sufficient moisture for crop growth. Similarly, when the soil is classified as wet, irrigation is stopped immediately to prevent over-irrigation and potential waterlogging. The algorithm operates in a continuous loop, allowing the system to adapt dynamically to changing environmental conditions. By integrating real-time sensing with weather-aware decision-making, the system ensures efficient and responsive irrigation control. It is important to note that the proposed system does not rely on decision-making or model training. Instead, it utilizes a rule-based decision mechanism, which provides a lightweight, transparent, and computationally efficient solution suitable for edge-based deployment. Figure 2 presents the flowchart of the system operating algorithm, illustrating the sequence of monitoring, decision-making, and actuation processes.

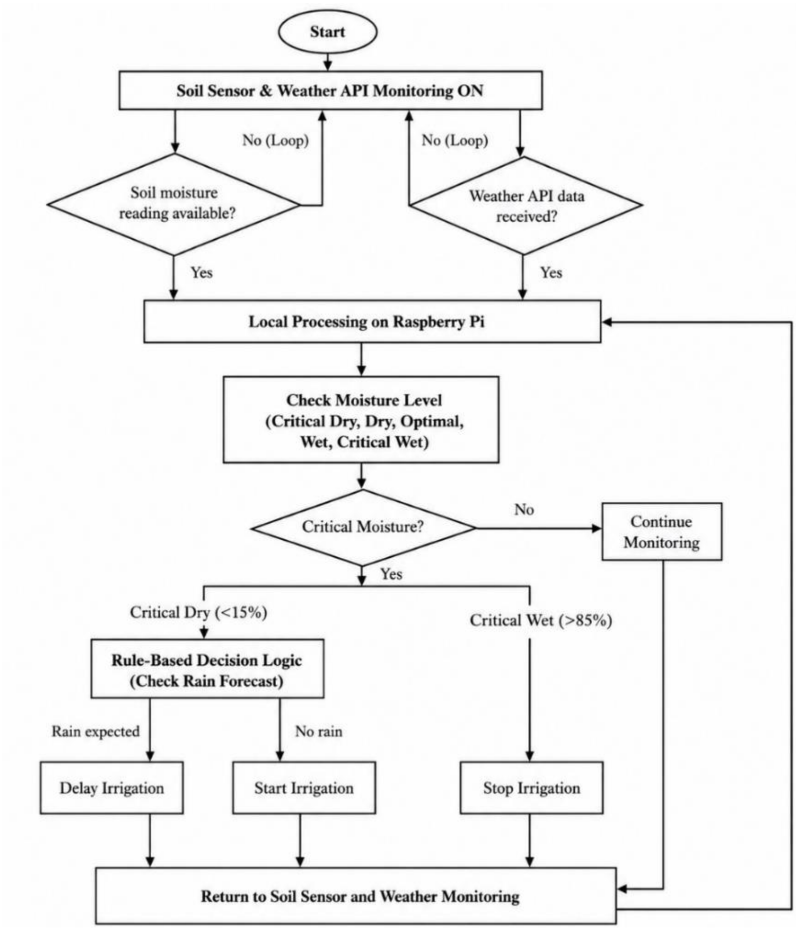


Figure 2. Flowchart of the system operating algorithm

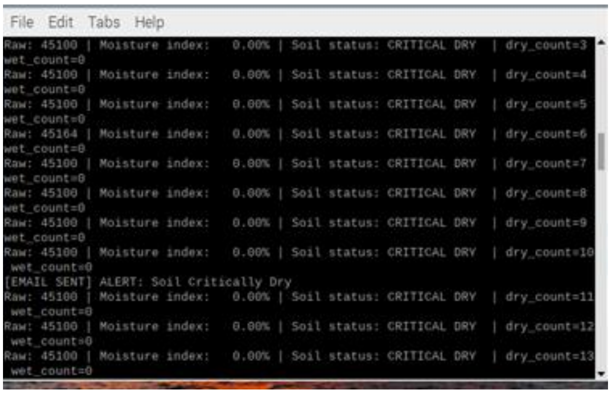
3. RESULTS AND DISCUSSION

This section presents the preliminary evaluation of the proposed IoT-based smart irrigation system. The assessment focuses on validating the system’s ability to accurately classify soil moisture conditions and to provide reliable notification support. The results are intended to verify the core functionality of the system prior to full-scale deployment and automated irrigation control under real field conditions.

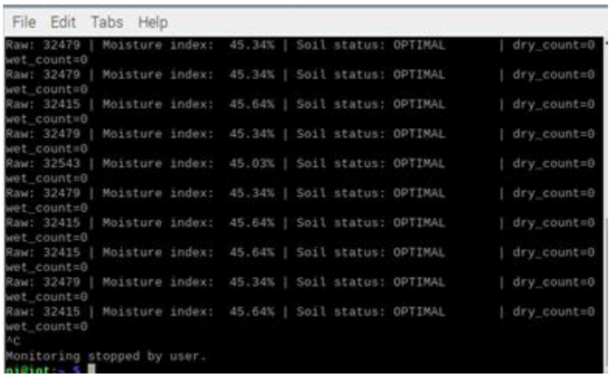
3.1. Soil moisture classification results

The system was tested under three predefined soil moisture conditions: critical dry, optimal, and critical wet. Soil moisture readings were continuously acquired using a capacitive sensor and processed locally on the Raspberry Pi. Based on these readings, the system classified soil conditions into the predefined categories using the proposed rule-based decision mechanism.

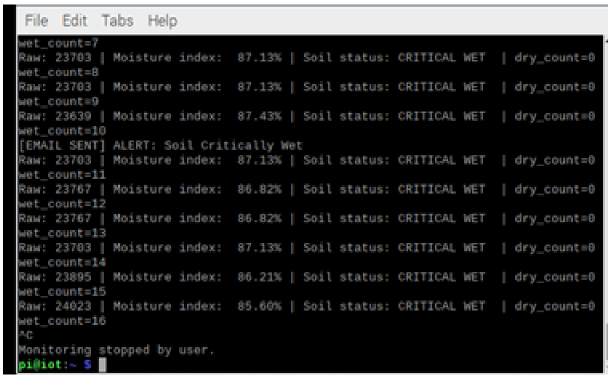
The results demonstrate that the proposed system performed reliably under all tested conditions, with appropriate irrigation responses and notification behavior across critical dry, optimal, and critical wet scenarios. Figure 3 presents the console output under different soil moisture conditions: Figure 3(a) critical dry, Figure 3(b) optimal, and Figure 3(c) critical wet. The displayed outputs include moisture index values, classification labels, and internal counter values used to ensure decision stability. These results confirm that the system is capable of continuous monitoring and stable classification without fluctuation or inconsistent behavior.



(a)



(b)



(c)

Figure 3. Console output for soil moisture conditions: (a) dry, (b) optimal, and (c) wet

From an operational perspective, classification stability is essential for reliable irrigation control. Accurate identification of dry conditions ensures timely irrigation, while correct detection of optimal and wet conditions prevents unnecessary or excessive watering. This directly contributes to improved water-use efficiency and reduces the risk of over-irrigation, which can negatively affect crop health.

3.2. Notification system performance

The notification functionality of the system was evaluated by analyzing the email alerts generated under different soil moisture conditions. The system demonstrated condition-based notification behavior, where alerts were generated only when necessary. When the soil condition was classified as critically dry, the system successfully generated an email alert indicating insufficient moisture and recommending immediate irrigation. Similarly, when the soil was classified as critical wet, the system issued a notification advising the user to stop irrigation due to excessive moisture levels. No notifications were generated during optimal soil conditions, confirming that the system avoids unnecessary alerts.

Figure 4 shows examples of the email notifications generated during testing. Each notification includes relevant information such as moisture percentage, sensor readings, and recommended actions, providing clear and actionable insights to the user. This selective alert mechanism improves system usability and supports efficient decision-making by ensuring that users are notified only under critical conditions. It also enhances remote monitoring capabilities, reducing the need for continuous manual supervision.

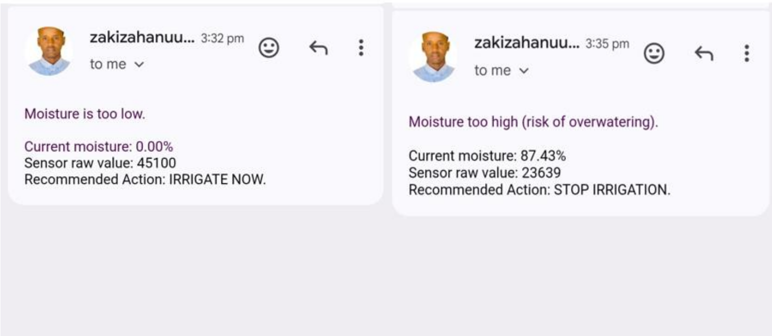


Figure 4. Email notification of soil moisture status

3.3. Performance summary and comparative discussion

Table 1 summarizes the overall system performance under different soil moisture conditions, including classification accuracy, irrigation actions, and notification behavior. The performance of the proposed system is consistent with previous IoT-based irrigation studies reported in [5], [21], [25], which demonstrated the effectiveness of IoT-enabled soil moisture monitoring for irrigation management. Unlike many existing approaches that rely on cloud processing or complex data-driven models, the proposed system performs decision-making locally on a Raspberry Pi using a lightweight rule-based mechanism. This reduces computational complexity while maintaining reliable operation under different soil moisture conditions.

Table 1. System performance under different soil moisture conditions

Condition	Moisture Level (%	Accuracy	Irrigation action	Notification
Critical dry	~0%	100%	Irrigation triggered	Yes
Optimal	~45%	100%	No irrigation	No
Critical wet	~85%	100%	Irrigation stopped	Yes

The results demonstrate that the proposed system performs reliably under all tested conditions, achieving 100% classification accuracy across critical dry, optimal, and critical wet scenarios, with appropriate response actions in each case. The integration of soil moisture sensing with weather-aware decision-making enables the system to make informed irrigation decisions, reducing unnecessary water usage. Compared to conventional irrigation methods, which typically rely on fixed schedules or manual control, the proposed system offers a more adaptive and responsive approach. By considering real-time soil conditions and environmental factors, the system ensures that irrigation is applied only when needed. This not only improves water-use efficiency but also contributes to sustainable agricultural practices

In addition, the use of edge-based processing allows for rapid decision-making without reliance on continuous cloud connectivity. This makes the system particularly suitable for deployment in rural or resource-constrained environments where network availability may be limited. Although the current evaluation is limited to controlled experimental conditions, the results provide strong evidence of the system's effectiveness and reliability. Future work will focus on extended field deployment, quantitative analysis of water savings, and comparative evaluation against traditional irrigation systems under real-world conditions.

4. CONCLUSION

This paper presented an IoT-based smart irrigation system that integrates soil moisture sensing, weather-aware decision-making, and edge computing to support efficient irrigation management. The proposed system was designed using a lightweight rule-based decision mechanism and implemented on a Raspberry Pi platform. Experimental results demonstrated reliable performance under controlled conditions. The system successfully classified soil moisture levels into critical dry, optimal, and critical wet categories and achieved 100% classification accuracy during testing. The notification mechanism also operated effectively by generating alerts only during critical conditions while avoiding unnecessary notifications during optimal states.

The main contribution of this work is the development of a low-cost and practical smart irrigation solution that combines real-time sensing, weather forecast integration, and local processing within a single framework. By performing decision-making at the edge, the system reduces dependence on continuous cloud connectivity while maintaining fast response and operational reliability. Overall, the proposed system has the potential to improve water-use efficiency and support sustainable agricultural practices through condition-based irrigation management. Future work will focus on large-scale field deployment, integration of additional environmental parameters, and long-term evaluation under real agricultural conditions.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Zakarie Abdi Mohamud	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Rozeha Binti A. Rashid		✓				✓		✓		✓	✓	✓	✓	
Yazid Abubakar Sufyan	✓		✓	✓			✓		✓	✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors confirm that there are no financial, professional, or personal relationships that could have influenced the conduct or reporting of this study.

DATA AVAILABILITY

The data used to support the findings of this study were generated during system development and preliminary testing. This data is not publicly available at this stage but can be obtained from the corresponding author upon reasonable request.

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