DESIGN OF AN IOT-BASED SMART IRRIGATION SYSTEM USING SOIL MOISTURE SENSORS FOR WATER EFFICIENCY

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ABSTRACT

Water scarcity and inefficient irrigation practices remain key challenges in agriculture. This study aims to design and evaluate an IoT-based smart drip irrigation system controlled by an ESP32 microcontroller for optimizing water use. The system integrates a calibrated YL-69 soil moisture sensor and DHT21 temperature-humidity sensor for real-time environmental monitoring, with control and data visualization provided via the Blynk platform. Experimental results demonstrated that the system effectively maintained soil moisture within the optimal range of 30 – 50%. The developed system achieved irrigation efficiency between 90 – 95% and reduced total water consumption by approximately 40% compared to conventional methods. The results showed that integrating soil moisture sensors within an IoT-based control framework can significantly enhance water efficiency.

Keywords: *Smart Irrigation; Water Efficiency; Internet of Things; ESP32 Microcontroller; Soil Moisture*

INTRODUCTION

Water is a vital resource that sustains the agricultural sector, where its use is crucial for achieving sustainable food production (Ali et al., 2022). Globally, agriculture accounts for approximately 70% of freshwater consumption, making water management essential not only to reduce waste but also to enhance crop yields and resilience to climate change (Ingrao et al., 2023). Therefore, a deep understanding of water's importance in agriculture drives efforts to optimize its utilization, particularly in developing countries like Indonesia, which rely heavily on the agrarian sector for national economic stability (Hashemi et al., 2024; Lina Sudarwati & Nasution, 2024).

Despite water's crucial role in agriculture, conventional irrigation often relies on manual scheduling, which can lead to over-irrigation and water waste. (Di Gennaro et al., 2024). These systems lack automation or feedback mechanisms, resulting in uneven water distribution and low efficiency across large fields (Yerli et al., 2023). Studies show that conventional methods consume nearly 70 – 80% of total freshwater used in agriculture, intensifying scarcity in arid regions (Imbernón-Mulero et al., 2025). Furthermore, their limited adaptability to environmental changes and high evaporation losses make them environmentally unsustainable in the long term (Morchid et al., 2025).

Compared to conventional agriculture, an automated irrigation system offers advantages such as up to 50% water savings, improved crop yields through timely watering, and reduced manual labor, ultimately making farming more sustainable and economical. Satra et al., (2023) states that the inefficient management of manual irrigation leads to high water consumption and labor demand. They designed an automatic irrigation system utilizing a microcontroller, humidity sensors, and a single-pole, double-throw (SPDT) relay to control the water pumps. The results showed a significant reduction in water usage, promoting sustainable and low-cost practices in agricultural and gardening applications. However, their system lacks integration with mobile applications, IoT platforms, or modules for real-time remote access.

To address these limitations, recent advances in agricultural technology have enhanced irrigation efficiency through the use of IoT, smart sensors, and data-driven management, enabling real-time monitoring of soil and environmental conditions for precise and resource-efficient irrigation (García et al., 2020). Modern systems have evolved beyond conventional timer-based irrigation to intelligent solutions, including drip irrigation, automated controllers, and agricultural drones, which can significantly reduce water consumption by up to 50% while simultaneously increasing crop yields by as much as 30% (Askaraliev et al., 2024). Collectively, these advancements represent a transformative shift in irrigation, empowering agriculture with technologies that support adaptability and efficiency.

Building upon these technological advancements, the implementation of smart irrigation systems represents a progressive approach to sustainable water management in agriculture. Smart irrigation systems integrate IoT-based technologies, such as ESP32 microcontrollers combined with soil moisture, temperature, and humidity sensors, to deliver precise and efficient water management in agricultural fields (Morchid et al., 2025). These systems automatically control pumps and valves based on real-time soil moisture thresholds, ensuring optimal irrigation while minimizing human intervention and error. As a result, they can improve water-use efficiency by up to 50% compared to the conventional method (Di Gennaro et al., 2024).

To achieve this level of precision, the system is integrated with a YL-69 soil moisture sensor, which continuously monitors soil moisture in real-time. This sensor features a potentiometer that allows sensitivity adjustment for accurate detection of varying soil conditions (Cahyatama et al., 2024). When the soil moisture exceeds the threshold, the relay automatically disconnects the current to the water pump, preventing unnecessary irrigation. The pump, which automatically supplies water to the plants, is controlled by the ESP32 microcontroller acting as the central control unit in the developed automatic irrigation prototype (Fahrezi et al., 2024).

This study presents an ESP32-based IoT smart drip irrigation system utilizing the YL-69 soil moisture sensor to monitor soil conditions in real-time. Data is processed and transmitted to the Blynk application for remote monitoring and control, ensuring optimal soil moisture levels are maintained. The system enhances water efficiency, reduces costs, and supports sustainability by integrating solar power. Its modular, low-cost design makes it suitable for small-scale farmers and allows for integration with additional sensors, promoting broader precision farming applications that enhance productivity and environmental sustainability.

METHODOLOGY

Research Tools and Materials

In this study, the tools and materials included an ESP32 microcontroller as the central controller, responsible for reading sensor data, processing information, and controlling actuators. The YL-69 soil moisture sensor measured the moisture content of the growing medium, while the DHT21 sensor measured ambient temperature and humidity. An LCD I2C display was used to show real-time sensor readings, and data were also transmitted to the Blynk application via Wi-Fi for remote monitoring. A relay module functioned as an electronic switch to control the solenoid valve, which automatically regulated water flow based on soil moisture levels. LED indicators provided visual feedback on system status. Additionally, a nozzle system was integrated as a temperature control mechanism to lower the heat when the ambient temperature exceeded the threshold.

Research Procedure

1. Research Flow

The research begins with a literature and field review to identify irrigation problems, determine system requirements, and select suitable technologies such as sensors and microcontrollers, shown in Figure 1.

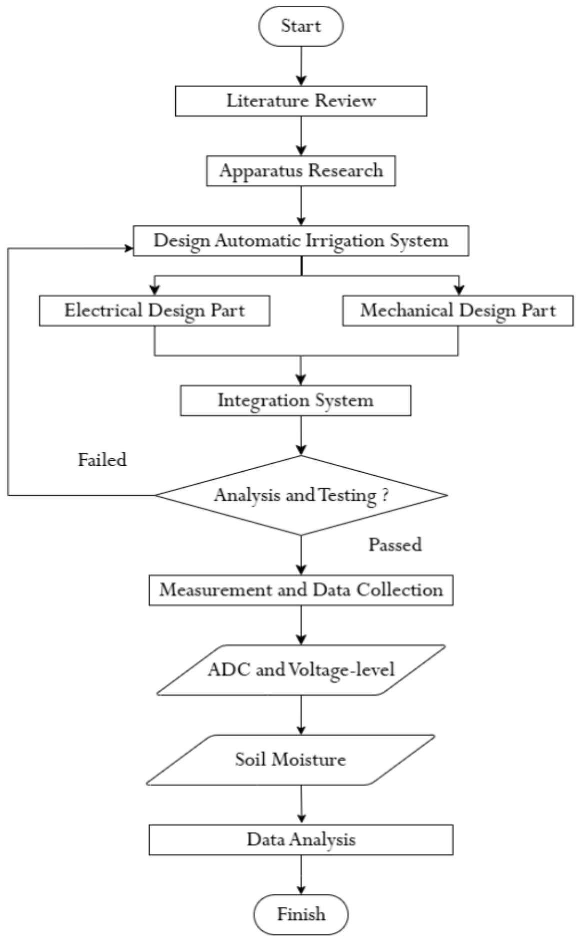


Figure 1. Research Flow of a Smart Irrigation System

The next step involves selecting components, including soil moisture and temperature sensors, the ESP32 microcontroller, valves, and relays, and designing the system architecture and control logic. Mechanical design covers pipe layout, water containers, and sensor placement. Afterward, electrical and mechanical parts are integrated and tested to ensure proper functionality. Data are then collected and analyzed to assess system efficiency, reliability, and water-saving performance, completing the research process.

2. Electrical Schematic Design

The block diagram in Figure 2 illustrates an IoT-based smart irrigation system comprising several key components. The YL-69 soil moisture sensor detects soil water content and sends analog data to the ESP32, while the DHT21 measures temperature and humidity through a one-wire connection. ESP32 processes these inputs to determine the plant's water needs and transmits the data via Wi-Fi to the Blynk IoT app for real-time monitoring. Powered by a solar panel with a voltage controller, the system operates independently in the field. The relay module controls the irrigation valve based on soil moisture levels, ensuring efficient and sustainable irrigation management.

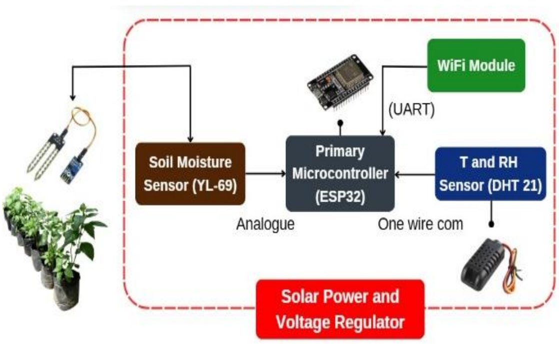


Figure 2. Block Diagram of an Smart Irrigation System

The circuit in Figure 3 illustrates the integration of various components with the ESP32 microcontroller for automated environmental monitoring and irrigation control. The YL-69 soil moisture sensor detects soil water content, while the DHT21 sensor measures temperature and humidity. Data from these sensors is processed by the ESP32 and displayed in real time on an LCD screen. LED indicators display system status, valve operation, and sensor alerts, ensuring easy monitoring of performance. This configuration forms an efficient IoT-based irrigation system capable of maintaining ideal soil and environmental conditions while supporting wireless connectivity and cloud integration for remote supervision and data logging. Moreover, the ESP32's built-in Wi-Fi enables seamless data transmission to online dashboards, allowing users to remotely monitor conditions.

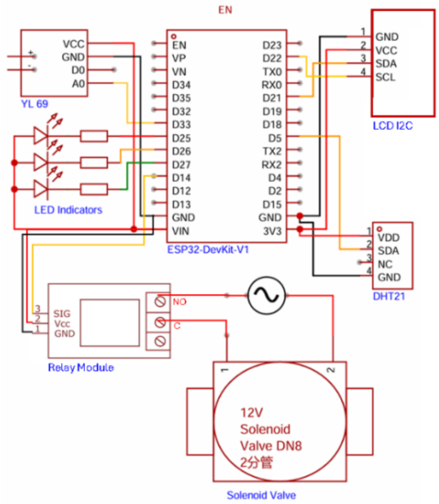


Figure 3. System Circuit

3. Workflow and Testing

The system workflow, as shown in Figure 4, begins by initializing the ESP32 and sensors (YL-69 and DHT21) to collect data on soil moisture, temperature, and humidity. The ESP32 processes and transmits the data to the Blynk app via Wi-Fi for real-time monitoring. This study focuses on designing an efficient smart irrigation system that integrates sensors and utilizes data communication.

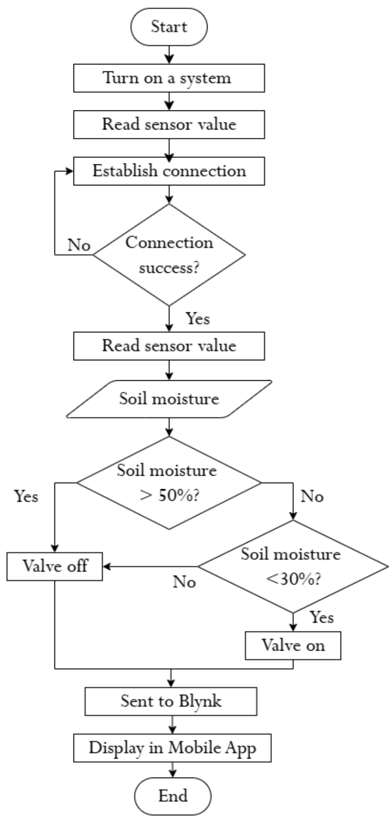


Figure 4. Workflow of a Smart Irrigation System

According to Setyowati et al., (2020), the sensor voltage was calculated using equation (1). Since the ESP32 microcontroller utilizes a 12-bit analog-to-digital converter (ADC) with values ranging from 0 to 4095, the conversion from the analog reading to voltage is expressed as follows

$$V_{sensor} = \frac{analog\ read}{4095} \times 3.3V \quad (1)$$

whereas V_{sensor} is the soil moisture sensor in voltage-level (mV), and analog read is an analog-to-digital number, 4095 is the analog maximum value, and 3.3V is the maximum voltage value.

The calibration of the YL-69 soil moisture sensor in this study resulted in a third-order polynomial equation. In mathematical expression, that defines the relationship between soil moisture (%) and sensor voltage (V) in equation (2)

$$y = 5.97x^3 + 63.95x^2 - 232.8x + 308.98 \quad (2)$$

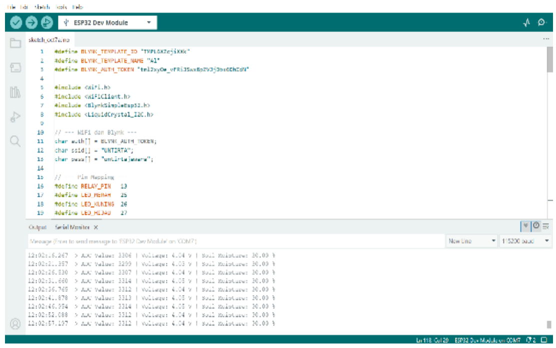
whereas y is soil moisture (%) and x is the soil moisture sensor in voltage-level (mV).

This equation was derived through a calibration process using the Gravimetric Water Content method, where soil samples were weighed both before and after drying to determine their actual moisture content.

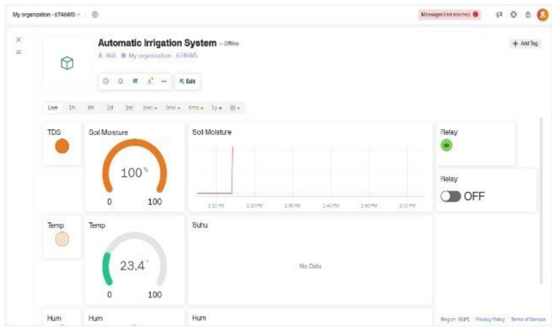
During calibration, the sensor output voltage was recorded for each known soil moisture level. The collected data were then plotted to form a correlation curve between voltage and soil moisture, expressed as a third-order polynomial equation. The polynomial equation was obtained from the calibration process described by Setyowati et al., (2020) with the smallest average error of about 2.92%. The equation closely represents the actual soil condition, which is essential for reliable intelligent irrigation control.

4. Software Design

After completing the hardware setup, software development was carried out using the Arduino IDE to program the ESP32 microcontroller. As shown in Figure 5(a), essential libraries such as WiFi.h, BlynkSimpleEsp32.h, and DHT.h were implemented to enable stable communication between the sensors, relay module, and Blynk platform. The ESP32 processes data from the YL-69 soil moisture sensor and DHT21 temperature-humidity sensor, activating the solenoid valve via the relay when soil moisture falls below a set threshold. Figure 5(b) displays the Blynk interface for real-time monitoring and control, showing temperature, humidity, and soil moisture data, as well as providing options for both manual and automatic operation. This seamless integration enhances irrigation accuracy, promotes better water-use efficiency, and significantly improves overall user interaction within the smart irrigation system.



(a)

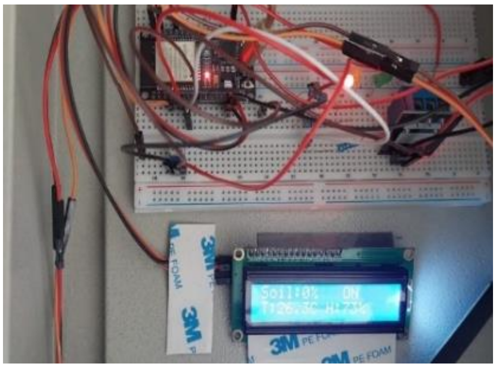


(b)

Figure 5. Design of (a) Programming ESP32 Microcontroller-based, and (b) Blynk Interface for Real-time Monitoring

5. Operating and Data Collecting Process

In this smart irrigation system, the Arduino IDE Serial Monitor collected sensor data and converted ADC readings into soil moisture percentages. Figure 6(a) shows data collection in the electrical component, while Figure 6(b) illustrates field implementation. When soil moisture dropped below the threshold, the ESP32 activated the solenoid valve. This integration optimized water use and maintained ideal soil conditions for efficient irrigation.



(a)

(b)

Figure 6. Data Collection in (a) Electrical Component (b) System Implementation in The Field

RESULTS AND DISCUSSION

Experimental Correlation Between Voltage Output and Soil Moisture Content

The experimental results presented in Figure 7 show the correlation between the voltage output of the soil moisture sensor and the corresponding soil moisture content. Voltage readings varied between approximately 2.0 V and 3.5 V, which, based on the calibration equation, correspond to soil moisture values ranging from approximately 29% to 55%. The plotted data indicate an inverse relationship, where higher voltage readings are associated with lower soil moisture levels. This behavior reflects the sensor's operational principle, in which reduced soil conductivity under drier conditions leads to increased voltage output. Overall, the results confirm the sensor's effectiveness in detecting soil moisture variations, providing reliable input data for automatic irrigation control systems.

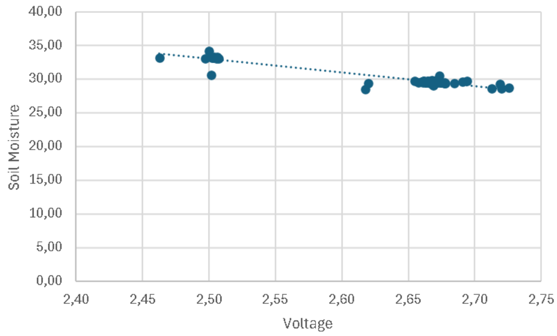


Figure 7. Experimental Correlation Between Voltage Output and Soil Moisture Content

Performance

The downward trend demonstrates the sensor's ability to capture moisture variations without signal distortion consistently. At the early stage, soil moisture was relatively stable (around 53%); then, it decreased gradually after 18:00, dropping below 30%. This pattern reflects the influence of evapotranspiration and surface evaporation, processes that dominate water loss in the soil plant atmosphere continuum as reported by Raza et al., (2023). This finding suggests that the sensor responded primarily to evapotranspiration-induced moisture loss, confirming the validity of the recorded data.

The voltage-to-moisture conversion applied in this study was based on a third-order polynomial equation from Setyowati et al., (2020) that compared sensor readings with gravimetric measurements. That model reported an average error of 2.92%, confirming its reliability for field estimation. By applying this validated calibration, the obtained values accurately represent actual soil conditions without direct gravimetric verification.

In terms of performance characteristics, the YL-69 resistive soil moisture sensor demonstrated adequate sensitivity and response linearity to changes in volumetric water content, with accuracy levels typically within ±5% and precision errors below 6%, as supported by laboratory calibration results from Adla et al., (2020). According to the same study, the YL-69 demonstrated a mean absolute error (MAE) of 4.13% and a root mean square error (RMSE) of 5.54%, which indicates that the sensor maintains consistent readings under controlled temperature and salinity variations. The observed decline to 25% moisture demonstrates that the system can effectively trigger irrigation when the threshold (e.g., 30%) is reached, ensuring optimal soil moisture maintenance for plant growth. These results confirm the sensor's suitability for real-time applications in innovative and sustainable irrigation systems.

Irrigation Control Strategy Based on Soil Moisture Thresholds

The soil moisture thresholds shown in Table 1, where the soil moisture is below 30% and above 50%, were determined based on the critical limits of soil water availability for plants. When the measured soil moisture falls below 30%, the soil is approaching the permanent wilting point (*PWP*), a condition where water is held too tightly by soil particles for plant roots to absorb. At this stage, plants begin to show signs of water stress, such as leaf wilting and reduced photosynthetic activity. Therefore, the system activates the relay (On) and opens the valve to irrigate the soil until sufficient moisture is fully restored and stabilized.

In contrast, when soil moisture exceeds 50%, the soil nears the field capacity (*FC*), which represents the maximum amount of water the soil can retain after gravitational drainage. Supplying additional water beyond this point would not increase plant-available water; instead, it would lead to waterlogging and nutrient leaching. Hence, the irrigation system turns the relay (Off) and closes the valve to prevent excessive water use.

The use of both upper and lower thresholds is essential for maintaining an efficient irrigation cycle. If only one limit were used, such as a single low threshold, the valve might stay open continuously, leading to unnecessary water loss. By defining a lower threshold (30%) to initiate irrigation and an upper threshold (50%) to terminate it, the system creates a controlled hysteresis range that ensures the soil moisture remains within the optimal zone for plant growth while conserving water.

Table 1. Soil Moisture Threshold Settings for the Smart Irrigation System

Measured Value (%)	Threshold Value (%)	Relay	Action
29	<30%	On	Valve Open
51	>50%	Off	Valve Close

According to Liu & Ma, (2024), the field capacity typically occurs at around 33 kPa of soil suction, while the permanent wilting point occurs near 1500 kPa, representing the boundaries of plant-available water. This difference, known as the available water capacity (*AWC*), defines the portion of soil moisture that plants can effectively use. Therefore, setting irrigation control thresholds between 30% and 50% corresponds to maintaining soil moisture within this range of available water, optimizing plant health, and irrigation efficiency.

Smart Irrigation System Testing Based on Soil Moisture Threshold

Based on Table 2 of Smart Irrigation System Testing Based on Soil Moisture Threshold, the relationship between ADC values, voltage, and soil moisture percentage demonstrates the system's automatic response to varying soil conditions. The ADC readings ranged from 2447 to 2480, corresponding to voltage levels between 2.50 and 2.73 volts. When the soil moisture dropped below approximately 30%, the irrigation system was activated ("On"), indicating the threshold level that triggers water delivery. Conversely, when the moisture level exceeded 30%, the system automatically turned off ("Off") to prevent unnecessary irrigation. This behavior reflects the effectiveness of the control logic in maintaining optimal soil moisture levels. The slight variations in voltage and ADC readings indicate stable sensor performance and consistent calibration. Overall, the table confirms that the smart irrigation system can efficiently regulate water use based on real-time soil moisture data.

Table 2. Performance Test of IoT-Based Smart Irrigation System

ADC	Voltage (Volt)	Soil Moisture (%)	Action
2448	2,51	33,24	Off
2448	2,50	30,58	Off
2447	2,62	28,53	On
2449	2,73	28,75	On
2448	2,71	28,62	On
2451	2,72	28,64	On
2451	2,72	29,26	On
2449	2,68	29,40	On
2449	2,68	29,48	On
2480	2,67	30,53	On

Comparison of Conventional and Sensor-Based Drip Irrigation Performance

A comparative analysis between conventional manual irrigation and drip irrigation, integrated with the YL-69 soil moisture sensor, is presented in Table 3. Several parameters, including irrigation efficiency, total water volume, potential water loss, and estimated crop yield were evaluated. The calculation of water requirements was based on SNI 7745:2012 (BSN, 2012), which outlines the Penman–Monteith method for reference crop evapotranspiration. The data were obtained under the assumption of Total Available Water (*TAW*) and Readily Available Water (*RAW*) as the basis for determining irrigation thresholds. Variables required for the calculation included reference evapotranspiration (*ETo*), crop coefficient (*Kc*), rooting depth (*Zr*), depletion fraction (*p*), and adequate rainfall (*Peff*). These variables were considered equivalent to both irrigation methods, allowing for direct comparison.

The estimation of crop water requirements in this study followed the procedure outlined in SNI 7745, which applies the Penman–Monteith method to calculate reference evapotranspiration (*ETo*). Crop evapotranspiration (*ETc*) was then obtained by multiplying ETo by the crop coefficient (*Kc*), which represents the growth stage-specific water demand of the crop. Tan et al., (2021) state that the integration of the soil moisture coefficient (*Ks*) and canopy coefficient (*Kc*) with the reference evapotranspiration (*ETo*) derived from the Penman–Monteith equation enables a comprehensive assessment of crop water demand under varying environmental stresses, thereby supporting more efficient irrigation management. This parameter served as the primary basis for determining irrigation water needs in both conventional and sensor-assisted drip irrigation systems.

Irrigation efficiency under conventional practices reached only 60 – 70%, primarily due to uneven distribution and uncontrolled water application. The use of sensor-assisted drip irrigation increased efficiency to 90 – 95% by regulating water delivery according to soil moisture feedback, thereby minimizing excess application. According to Lee et al., (2025), this improvement aligns with precision agriculture advancements, where soil moisture sensor integration in drip systems reduces water application by 30 – 50% compared to flood methods, enabling uniform root-zone delivery and minimizing over-irrigation in water-scarce environments.

Total water volume applied in conventional irrigation was 450 mm throughout the cultivation period, whereas sensor-based drip irrigation reduced the requirement to 270 mm. This reduction reflects the optimization of water application by maintaining soil moisture within the effective root zone. Similarly, Vinutha et al., (2024) reported in their study that comparable field trials on spinach cultivation demonstrated conventional surface irrigation volumes exceeding 290 mm per season, while sensor-based drip systems operating at optimal thresholds reduced applications to as low as 117 mm, achieving water savings of up to 60% without compromising yield.

Potential water loss under manual irrigation was recorded at 30 – 40%, resulting from runoff, percolation, and evaporation. According to Attaluri (2025) and Irsal et al., (2023), this substantial reduction mirrors the efficiency gains achieved in pressurized drip systems, which restrict losses to approximately 10% through targeted root-zone water delivery, in contrast to 30 – 50% losses observed in conventional surface irrigation, thereby maximizing plant uptake and minimizing environmental impacts such as soil erosion. Similarly, Mekong River Commission (2022) and Supriadi et al., (2018) reinforced these findings, noting that field validations conducted in arid and semi-arid regions further demonstrate that sensor-equipped drip irrigation effectively reduces non-productive losses (e.g., evaporation and percolation) to below 10%, achieving up to 50% overall water savings compared to manual irrigation systems, while maintaining or even enhancing crop yields under variable climatic.

Estimated crop yield under conventional irrigation maintained baseline productivity at 100%, while sensor-assisted drip irrigation enhanced yield potential to 100 – 115%. This finding is further supported by Lakhiar et al., (2024), who noted that such stability in soil moisture, as observed in IoT-integrated precision irrigation systems, effectively mitigates water stress–induced reductions in photosynthesis and nutrient uptake, leading to documented yield increases of up to 35% compared to traditional scheduling methods. Consistent with these results, Meriç, (2025) reported that empirical trials on vegetable crops demonstrated sensor-driven drip irrigation achieving 12.05% higher yields than evapotranspiration-based conventional drip systems, primarily due to sustained root-zone hydration that enhances transpiration efficiency and overall plant biomass accumulation rate.

Table 3. Comparative Parameters of Conventional and Sensor-Based Drip Irrigation Systems

Parameter	Conventional (Manual Irrigation)	Drip Irrigation with YL-69 Soil Moisture Sensor
Irrigation Efficiency	60 – 70%	90 – 95%

Total Water Volume (mm)	450	270
Potential Water Loss	High (30– 40%)	Low (<10%)
Estimated Crop Yield (%)	100	100 – 115

Overall, the integration of the YL-69 soil moisture sensor in drip irrigation systems demonstrates superior performance compared to conventional irrigation. The system ensures precise water management, optimizes plant-available water, and aligns with the standards established by SNI-based calculation methods.

CONCLUSION AND RECOMMENDATION

The IoT-based smart irrigation system developed using the ESP32 microcontroller and YL-69 soil moisture sensor proved effective in optimizing water use by maintaining soil moisture within the optimal 30–50% range through accurate real-time monitoring and automated control. Calibration using the gravimetric method ensured high measurement accuracy, resulting in a water efficiency improvement of up to 90 – 95% and a reduction in total water consumption by approximately 40% compared to conventional irrigation methods. These results demonstrate that IoT-based automation significantly enhances water-use efficiency and promotes sustainable agricultural practices. Nevertheless, the current system still relies on fixed threshold-based control, limiting its adaptability to dynamic environmental conditions. Future work should focus on integrating intelligent algorithms, such as machine learning or fuzzy logic, to enable predictive irrigation management, improve decision-making accuracy, and further enhance the efficiency and sustainability of precision agriculture.

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