

# IoT-based smart irrigation protocol for water efficiency and soil moisture stabilization in lowland horticulture

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## ABSTRACT

Conventional irrigation in horticultural land continues to face challenges related to water wastage and soil moisture instability, particularly in Indonesia's lowland regions. This study proposes a smart irrigation system based on the internet of things (IoT) with a closed-loop control mechanism to enhance water use efficiency and maintain optimal soil moisture. The system was designed using NodeMCU ESP8266, soil moisture sensor, DHT11 sensor, 12V water pump, and Blynk platform for remote monitoring. Sensor calibration was performed using gravimetric method and linear regression, yielding a conversion equation of  $Y = 78.00 - 0.8391X$  with a correlation coefficient of  $r = -0.965$ . Experimental testing over three days was conducted on bird's eye chili, corn, and water spinach plants, comparing the IoT system against manual irrigation. Results demonstrated that the system maintained average soil moisture of 55.23% compared to 43.53% in conventional methods, saved up to 25.9% water, and increased Water Use Efficiency by 62.7%. These findings indicate that the IoT irrigation system is effective, economical, and has potential to support sustainable precision agriculture.

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## 1. INTRODUCTION

The horticultural agriculture sector plays a strategic role in maintaining food security and national economic stability, particularly in developing countries with tropical climate characteristics such as Indonesia. Commodities such as bird's eye chili (*Capsicum frutescens*), corn (*Zea mays*), and water spinach (*Ipomoea aquatica*) are economically valuable crops that contribute to food availability and inflation control. However, horticultural productivity in lowland areas still faces various constraints, especially concerning water management that remains inefficient and dependent on manual irrigation methods. Most small-scale agricultural lands employ experience-based visual approaches by farmers to determine irrigation timing and volume, resulting in uneven water distribution, increased risk of water wastage, and soil moisture instability. Climate variability and changing rainfall patterns further exacerbate these conditions and potentially reduce harvest quality [1].

The development of Internet of Things (IoT) technology opens significant opportunities in transforming conventional agricultural systems toward data-driven precision agriculture. The integration of sensors, microcontrollers, and communication networks enables real-time environmental condition monitoring and automatic irrigation decision-making [2]. Various previous studies have reported that IoT-based irrigation systems can improve water use efficiency and crop growth stability through closed-loop control mechanisms [3, 4]. Additionally, artificial intelligence and IoT-based (AIoT) approaches have been implemented to determine adaptive irrigation patterns that are more responsive to environmental conditions [5]. Despite promising results, most of these systems still possess high technical complexity, relatively large network infrastructure requirements, and implementation costs that are less affordable for small-scale farmers.

Based on these conditions, this study proposes a smart irrigation system based on IoT with a closed-loop control mechanism designed using low-cost and readily available components. The system utilizes NodeMCU ESP8266 microcontroller, resistive soil moisture sensor as the primary control variable, and lightweight cloud platform for remote monitoring via smartphone. The uniqueness of the proposed approach lies in the direct integration of linear regression-based sensor calibration model into the water pump control logic, ensuring irrigation decisions are based not only on raw sensor values but on actual soil moisture estimates.

The main contributions of this research include the design of a simple and economical IoT irrigation system architecture for small-scale horticultural agriculture, development of a soil moisture sensor calibration model directly integrated into the automatic control system, and experimental evaluation of water use efficiency, soil moisture stability, and Water Use Efficiency. Through this approach, this research is expected to bridge the gap between smart irrigation system development in academic environments and actual needs in smallholder agriculture, while supporting the implementation of precision agriculture and sustainable water resource management in Indonesia.

## 2. LITERATURE REVIEW

The application of Internet of Things (IoT) technology in the agricultural sector has developed rapidly alongside increasing demands for efficient and sustainable food production systems. Wolfert et al. emphasized that the integration of sensors, communication networks, and data analytics constitutes the main foundation in developing precision agriculture based on smart farming, where operational decisions are made based on real-time environmental data [2]. In the context of irrigation, soil moisture sensor data becomes the primary variable for determining irrigation volume and timing adaptively.

Bwambale et al. stated that closed-loop control strategies based on soil moisture sensors can significantly improve water use efficiency compared to open-loop systems [3]. Generally, this mechanism can be modeled with a functional relationship between sensor output and actual soil moisture using a linear regression approach:

$$Y = a + bX \quad (1)$$

where  $X$  represents sensor output voltage and  $Y$  represents actual soil moisture percentage. This model enables the system to determine threshold values for automatically activating or deactivating irrigation actuators, allowing water supply to be adjusted to actual soil conditions. A similar approach was used in the SIP! report, which obtained the calibration function:

$$Y = 78,00 - 0,8391X \quad (2)$$

with a high correlation coefficient ( $r \approx -0,965$ ), indicating a strong inverse relationship between sensor voltage and soil moisture.

Morchid et al. developed an IoT-based irrigation management system with cloud computing support and data telemetry to enhance agricultural water resource security [4]. Performance evaluation of smart irrigation systems is generally conducted by comparing water volume used, which can be calculated through the equation:

$$V = Q \times t \quad (3)$$

where  $V$  is water volume (liters),  $Q$  is flow rate (liters/minute), and  $t$  is irrigation time (minutes). This parameter is used to assess water savings between automatic and conventional systems.

Furthermore, energy consumption of electric pump-based irrigation systems is typically analyzed using the equation:

$$E = P \times t \quad (4)$$

where  $E$  is electrical energy (Wh),  $P$  is pump power (Watts), and  $t$  is operating time (hours). In the SIP! system, this analysis was used to evaluate the trade-off between water savings and increased energy consumption due to electric pump and microcontroller usage.

An artificial intelligence and IoT-based approach (AIoT) was developed by Ariawan to determine adaptive irrigation patterns based on environmental conditions [5]. Irrigation system performance in the context of plant growth is often expressed using the Water Use Efficiency (WUE) parameter, formulated as:

$$WUE = \frac{Y_p}{ET} \quad (5)$$

where  $Y_p$  represents crop yield or biomass and  $ET$  represents total water volume used (liters). This parameter becomes an important indicator in assessing how effectively water is converted into plant growth, and was also used in the SIP! system evaluation.

Additionally, Al Faroby et al. reported that the implementation of IoT-based smart irrigation systems in greenhouse environments can improve water efficiency and horticultural crop growth quality [6]. However, application in open land with more dynamic climate variations and soil characteristics still requires more adaptive control systems and integrated sensor calibration models.

Based on this review, it can be concluded that IoT-based irrigation systems generally rely on three main mathematical models: (1) linear regression-based soil moisture sensor calibration model, (2) water and energy consumption calculation model, and (3) water use efficiency evaluation model through WUE parameters. Although widely used separately, the integration of these three models directly into automatic control mechanisms is still rarely reported.

Therefore, this research proposes a low-cost IoT irrigation system that integrates sensor calibration models, resource consumption calculations, and WUE evaluation in a unified closed-loop control algorithm, enabling the system to not only adapt to soil conditions but also be quantitatively evaluated in terms of efficiency and sustainability of resource use.

### 3. RESEARCH METHODOLOGY

This research employs a research and development approach with quantitative experimental design to develop and evaluate a smart irrigation system based on Internet of Things (IoT) with closed-loop control mechanism. The research focus includes prototype system design, sensor and actuator integration, control software development, and system performance testing compared to conventional irrigation methods on horticultural crops.

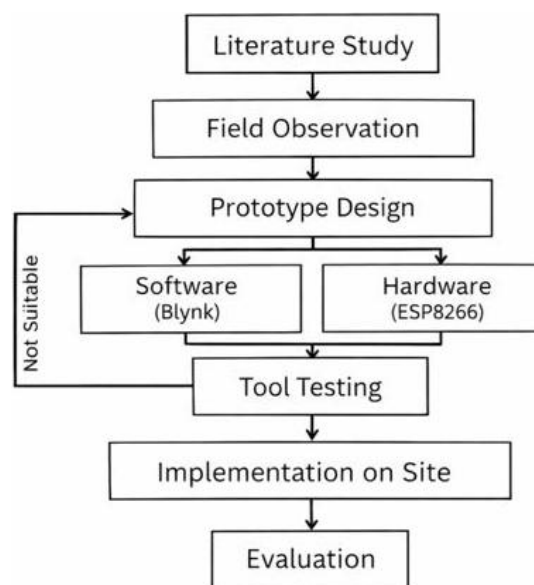


Figure 1. Research flow diagram of smart irrigation protocol (SIP!).

Research stages were conducted systematically, encompassing literature study, initial observation of land and plant conditions, hardware and software design of the IoT system, soil moisture sensor calibration, prototype testing, system implementation in experimental plots, and performance evaluation based on quantitative parameters and visual observation. The complete research stage flow is shown in Figure 1.

The smart irrigation system was designed using NodeMCU ESP8266 microcontroller as the data processing center, resistive soil moisture sensor as the primary control variable, DHT11 temperature-humidity sensor as supporting environmental parameter, and 12V diaphragm pump controlled through relay module. Sensor data is processed locally by the microcontroller and transmitted in real-time to the Blynk platform via Wi-Fi network to enable remote monitoring using smartphones. Water distribution to plants is conducted through drip irrigation system to enhance irrigation precision and reduce water loss due to runoff.

The system's working architecture follows the Input-Process-Output concept, where sensor data serves as input, NodeMCU as processing unit, and pump relay along with Blynk interface as output. The functional structure of the system is shown in Figure 2.

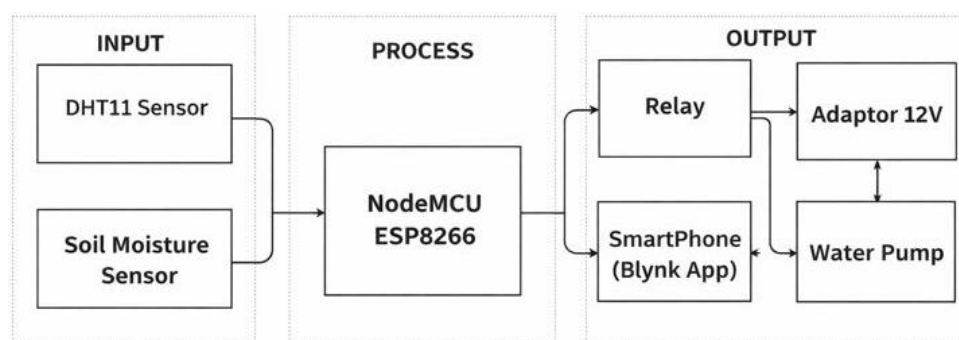


Figure 2. IoT smart garden device prototype flow diagram.

Soil moisture sensor calibration was performed using gravimetric method to obtain an accurate relationship between sensor output and actual soil conditions. Calibration results were then integrated into the controller software on the microcontroller, enabling the system to automatically determine active or inactive pump conditions based on established moisture thresholds. This approach ensures irrigation decisions do not depend on raw sensor values but on more representative soil condition estimates.

Experimental testing was conducted over three days at the mini farm of MAN 2 Pekanbaru City using three types of horticultural crops: bird's eye chili (*Capsicum frutescens*), corn (*Zea mays*), and water spinach (*Ipomoea aquatica*). The experiment was divided into two treatment groups: plants irrigated using the SIP! system and control group irrigated manually using conventional methods. Both groups were placed under similar soil and environmental conditions to maintain comparison validity.

Performance parameters analyzed included average daily soil moisture, water volume used, system electrical energy consumption, Water Use Efficiency (WUE), and visual plant conditions including leaf color, freshness, and soil surface texture. Data analysis was conducted descriptively and comparatively by comparing all these parameters between the SIP! system and conventional methods to assess the efficiency, stability, and feasibility of the developed automatic irrigation system.

#### 4. RESULTS AND DISCUSSION

The smart irrigation system prototype based on Internet of Things (IoT) was successfully implemented using NodeMCU ESP8266, soil moisture sensor, DHT11 sensor, relay module, 12V diaphragm pump, and Blynk application as remote monitoring interface. The system was capable of reading sensor data in real-time, comparing soil moisture values with a 40% threshold, and automatically controlling the water pump. Temperature, air humidity, soil moisture, and pump status data can be monitored directly through the Blynk application, eliminating the need for users to be physically present at the location to know system conditions.

Soil moisture sensor calibration results using gravimetric method showed a strong negative linear relationship between sensor output voltage and actual soil moisture. From ten soil samples tested, a conversion equation of  $Y=78,0-0,8391X$  was obtained with a correlation coefficient of approximately  $-0.965$ . This model was used as the basis for automatic control system decision-making. The 40% moisture threshold value was converted to a sensor voltage of 45.29 mV as the water pump activation trigger point. This regression relationship is visualized in the correlation graph of voltage against soil moisture presented below.

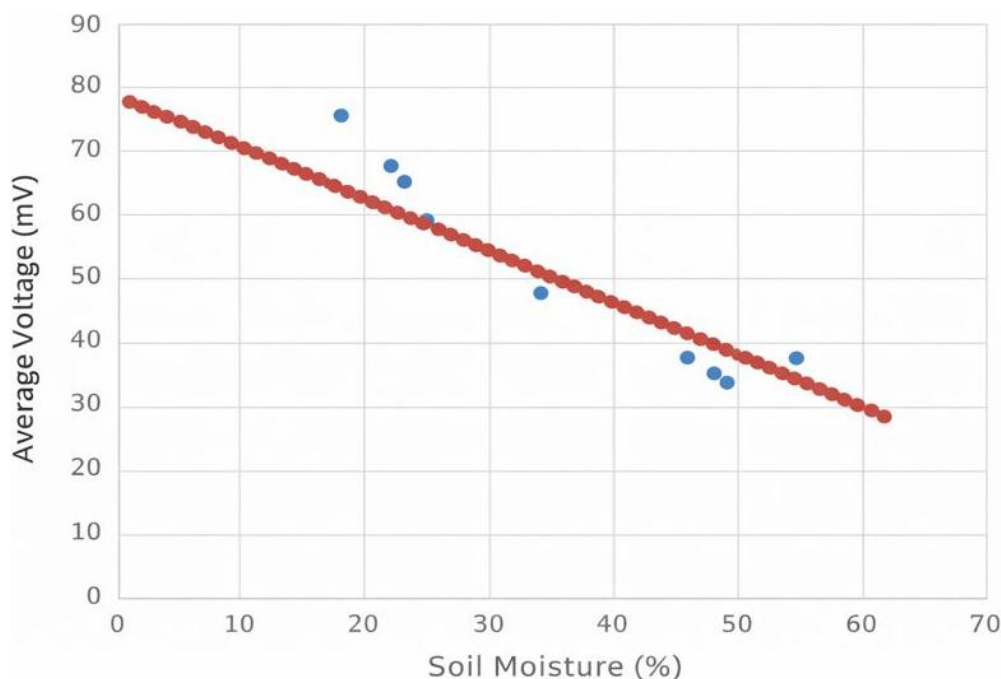


Figure 3. Correlation graph between sensor voltage (mV) and actual moisture (%).

Field testing was conducted over three days comparing the SIP! system and conventional irrigation methods on bird's eye chili, corn, and water spinach plants. Quantitative measurement results are presented in Table 1, which includes parameters of soil moisture, water volume, energy consumption, and Water Use Efficiency (WUE).

Table 1. Daily average IoT sensor data and monitoring.

Day-	System	Soil moisture (%)	Water volume used (L)	Energy consumption (Wh)	WUE (g/L)
1	SIP!	54.3	12	28	6.1
2		54.7	12	28	6.3
3		56.7	12	28	6.5
1	Conventional	43.2	16.2	0	3.8
2		43.7	16.2	0	3.8
3		43.7	16.2	0	3.9

The SIP! system maintained soil moisture in the range of 54.3-56.7% with an average of 55.23%, while the conventional system only achieved an average of 43.53%. This difference indicates that the automatic system is more stable in maintaining soil conditions above the optimal threshold.

In terms of water consumption, the SIP! system used 12 liters per day, while the conventional method required 16.2 liters per day, resulting in savings of approximately 4.2 liters or equivalent to 25.9%. This comparison is visualized in the daily water consumption graph.

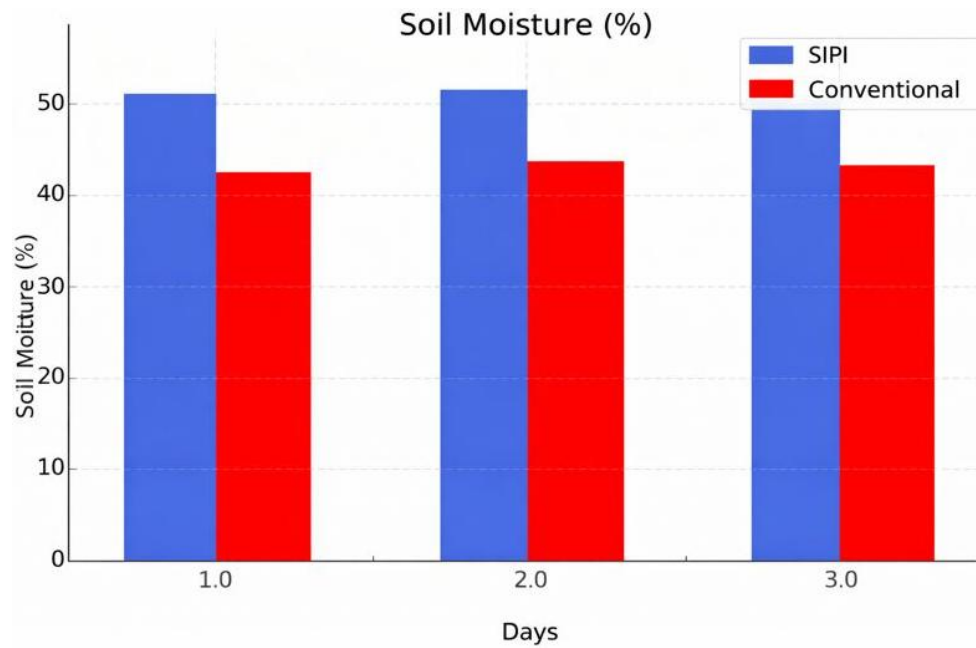


Figure 4. Soil moisture percentage graph for SIP! and conventional systems.

Meanwhile, the SIP! system required electrical energy of 288 Wh per day due to adapter and water pump usage, while the conventional system did not require additional electrical energy. This energy consumption difference is displayed in the following graph.

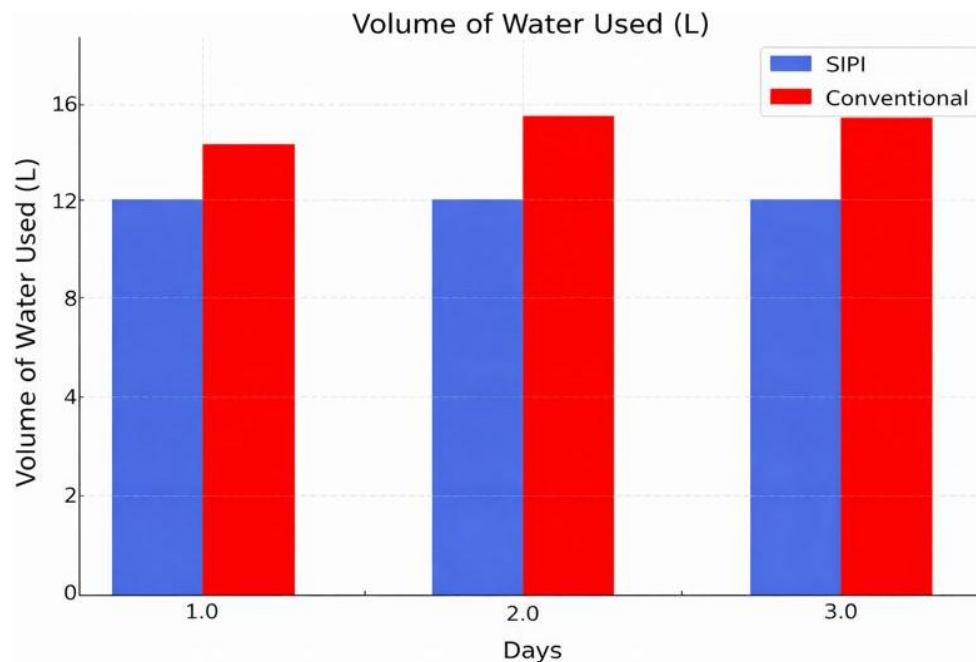


Figure 5. Water consumption graph for SIP! and conventional systems.

Despite additional energy consumption, this value remains tolerable considering water savings, reduced manual labor, and overall irrigation efficiency improvement. Performance improvement is most significantly evident in the Water Use Efficiency parameter. The SIP! system's WUE value increased from 6.1 to 6.5 g/L during the testing period, while the conventional method remained only in the range of 3.8-3.9 g/L. Average efficiency improvement reached 62.7%, as shown in the following graph.

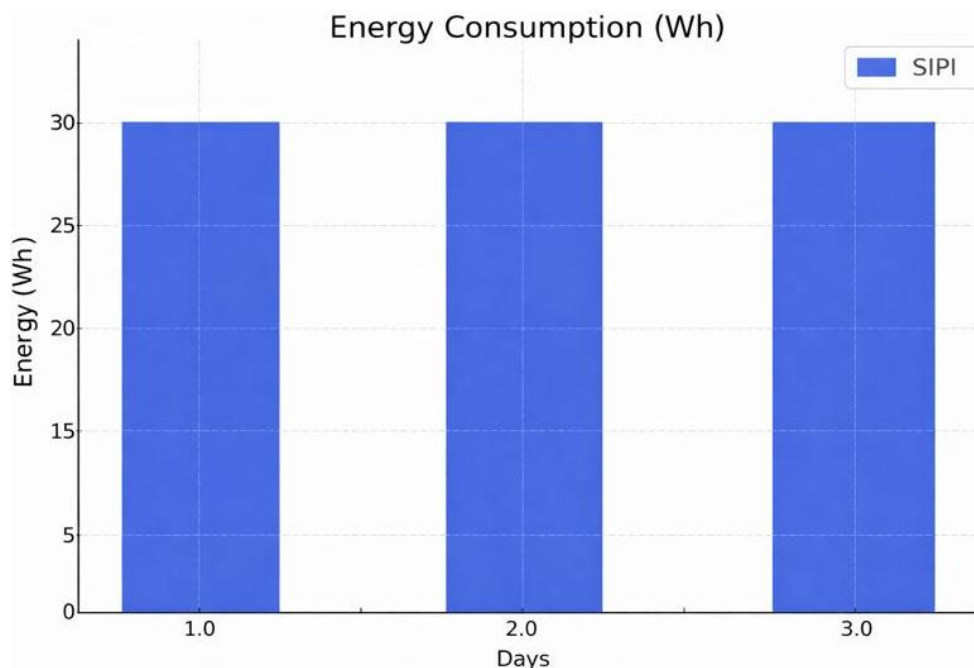


Figure 6. Energy consumption graph for SIPI and conventional systems.

These results demonstrate that irrigation based on actual soil needs enables far more effective water conversion to plant growth compared to fixed-schedule irrigation. In addition to quantitative measurements, visual observations also showed consistent differences between the two systems. Plants under the SIPI system exhibited bright green leaves, stronger stems, and moist soil conditions around the root area without waterlogging. Conversely, plants under the conventional system showed mild water stress symptoms, such as slightly wilted leaves during daytime, yellowing leaf color, and drier, cracking soil surface.

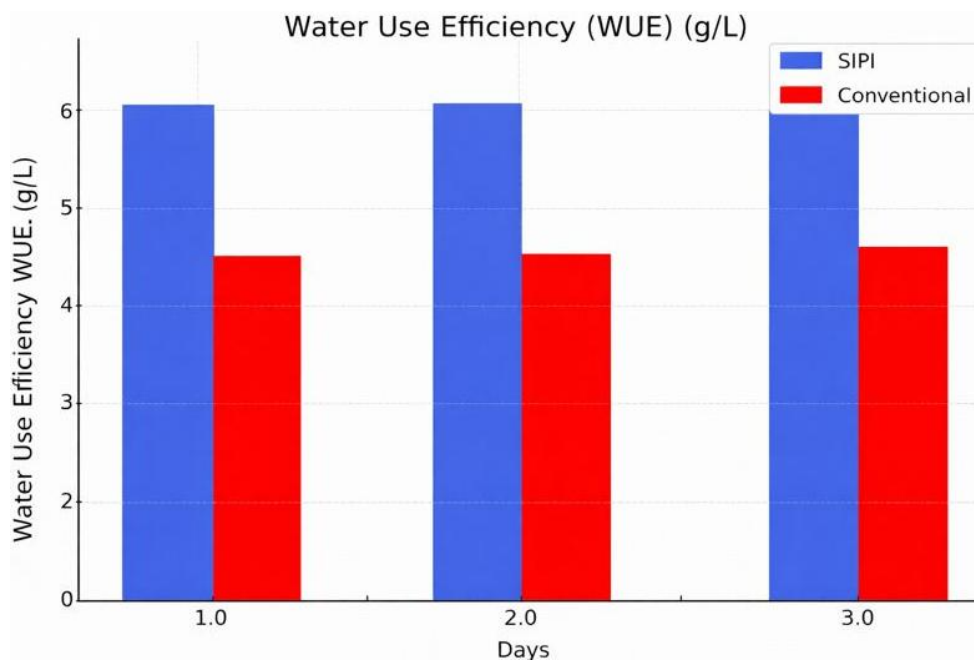


Figure 7. Water use efficiency (WUE) graph for SIPI and conventional systems.

Overall, this research demonstrates that the integration of calibrated soil moisture sensors, closed-loop control algorithms, and drip irrigation systems can improve water use efficiency while

maintaining soil condition stability. The main advantage of the SIP! system lies in its ability to perform precision irrigation based on actual soil conditions, rather than time estimates or fixed volumes. WUE improvement of more than 60% indicates that IoT-based approaches have great potential to support precision agriculture and sustainable water resource management, particularly in lowland regions with limited water availability and dominance of small-scale agriculture.

## 5. CONCLUSION

This research has successfully designed, implemented, and evaluated a smart irrigation system based on Internet of Things (IoT) with closed-loop control mechanism for horticultural agriculture applications in lowland regions. The developed system uses NodeMCU ESP8266, soil moisture sensor, DHT11 sensor, water pump, and Blynk platform as remote monitoring interface, enabling automatic plant irrigation based on actual soil conditions.

Sensor calibration results showed a strong negative linear relationship between sensor voltage and actual soil moisture, enabling the system to make more accurate irrigation decisions. Field testing over three days on bird's eye chili, corn, and water spinach plants demonstrated that the SIP! system maintained average soil moisture of 55.23%, more stable compared to conventional methods which only achieved 43.53%. Additionally, daily water consumption was successfully reduced from 16.2 L to 12 L, equivalent to savings of 25.9%.

In terms of water use productivity, the Water Use Efficiency (WUE) value of the SIP! system increased to an average of 6.30 g/L, approximately 62.7% higher compared to the conventional system. Although the system requires additional electrical energy consumption of 288 Wh per day, benefits including water savings, improved soil condition stability, and reduced dependence on manual labor make this system technically and operationally feasible.

Overall, this research proves that IoT-based smart irrigation systems with integrated sensor calibration and automatic control have great potential to be implemented as efficient, economical, and sustainable precision agriculture solutions, particularly for small-scale farmers in Indonesia. Future research can focus on long-term testing, integration of renewable energy sources such as solar panels, and development of artificial intelligence-based adaptive control algorithms to enhance system performance under various environmental conditions.

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