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Adaptive Watering System Based Internet Of Things For Evaluating Actual Water Volume In Curly Tomatoes

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Abstract

Irrigation management for curly tomato plants (Solanum lycopersicum L.) grown in polybags requires controlled water application because the limited growing medium may cause rapid soil moisture changes. This study developed an Internet of Things-based adaptive irrigation system with multimodal sensors to evaluate actual water volume. The system integrates an ESP32 microcontroller, soil moisture sensor, DHT22, light intensity sensor, flow sensor, relay, water pump, LCD, and Android-based monitoring application. Irrigation decisions are determined based on soil moisture, irrigation schedule, temperature condition, and daily water target. The system was tested for 21 days with three observations per day, resulting in 63 observations. Evaluation was conducted using sensor data analysis, confusion matrix, actual water volume measurement, and comparison with a fixed duration method. The results showed 14 True Positive, 45 True Negative, 1 False Positive, and 3 False Negative decisions, resulting in 93.65% decision accuracy. The flow sensor recorded a total water volume of 6.539 L per polybag during the 21-day test. Compared with the fixed duration method of 16.800 L per polybag, the adaptive system produced 61.08% lower irrigation volume. These results indicate that the proposed system can operate selectively and support more measurable water management.

Keywords: Internet of Things; adaptive irrigation; multimodal sensor; soil moisture; flow sensor; actual water volume

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INTRODUCTION

Tomato plants are a horticultural crop that is sensitive to water availability. Improper irrigation management can cause the growing medium to become too dry or too wet, which can potentially disrupt plant growth. In polybag cultivation, the volume of growing medium is more limited than in open fields, so changes in moisture levels can occur more rapidly. These conditions require an irrigation system capable of monitoring the actual state of the growing medium and delivering water in a measured manner.

Seyar and Ahamed (2023) emphasize that proper irrigation management is a critical factor in tomato production because rising temperatures can increase evapotranspiration and the plants' water requirements. This study developed an IoT-based precision irrigation system for tomato production using soil moisture sensors, the ThingSpeak platform, and irrigation controls for both indoor and outdoor conditions. The results showed that low-cost sensors can be used as the basis for irrigation scheduling after undergoing a calibration process.

Manual watering and fixed-duration methods are still widely used because they are simple. However, these methods do not always take into account the actual conditions of the growing medium, temperature, air humidity, light intensity, and the actual volume of water delivered. A pump running for the same duration does not necessarily deliver the same volume of water, as flow rate can be influenced by water pressure, pump condition, and resistance in the water lines.

The Internet of Things (IoT) is a relevant approach for developing smart irrigation systems. Through IoT, sensor data can be read in real time, processed by a microcontroller, used as the basis for decision-making, and transmitted to a monitoring application. Several previous studies have developed IoT-based precision irrigation for tomatoes, irrigation scheduling based on soil and plant monitoring, and cloud-based smart irrigation systems (Carucci et al., 2023; Morchid et al., 2024; Seyar & Ahamed, 2023).

Nevertheless, most automatic irrigation systems still focus on ON/OFF control of the pump. Quantitative evaluation of the actual water volume supplied to plants has not always been a primary focus. In fact, measuring the actual water volume is crucial for determining the amount of water plants actually receive and for comparing the performance of adaptive systems with fixed irrigation methods.

This study aims to develop an Internet of Things (IoT)-based adaptive irrigation system with multimodal sensors to evaluate the actual water volume supplied to curly tomato plants. The sensors used include a soil moisture sensor, a DHT22 sensor, a light

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intensity sensor, and a flow sensor. The system was evaluated based on sensor data, pump ON/OFF decisions, decision accuracy using a confusion matrix, actual water volume, and a comparison with the fixed-duration method.

RESEARCH METHODS

System Design

The adaptive irrigation system developed consists of a data acquisition unit, a processing unit, a control unit, a communication unit, and a monitoring unit. This division of units follows the IoT system model used in precision irrigation research, namely the separation of functions among the sensor unit, control unit, irrigation unit, and monitoring unit (Seyar & Ahamed, 2023).

The data acquisition unit includes a soil moisture sensor to measure growing medium moisture, a DHT22 to measure air temperature and humidity, a light intensity sensor to measure lighting conditions, and a flow sensor to measure the volume of water flowing during irrigation. The processing unit uses an ESP32 as the main microcontroller. The ESP32 reads sensor data, evaluates the irrigation schedule, checks temperature conditions, groups soil moisture values, calculates the daily water target, determines whether to turn the pump ON or OFF, and sends data to the monitoring app. The relay functions as an electronic switch to turn the water pump on or off.

The hardware design is illustrated through a wiring diagram to clarify the connections between the ESP32, soil moisture sensor, DHT22, light intensity sensor, flow sensor, relay, water pump, LCD, and power source. The system also includes an Android app to monitor temperature, air humidity, light intensity, growing medium moisture, water volume, system mode, and pump status in real time.

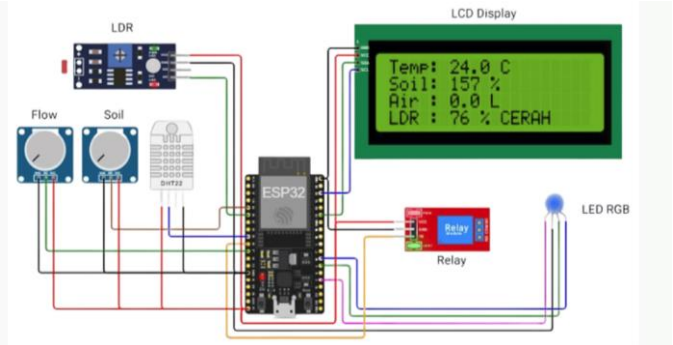


Figure 1. Wiring diagram of an IoT-based adaptive irrigation system

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Figure 2. Hardware prototype of the adaptive irrigation system



Figure 3. Android app interface for monitoring system parameters

Table 1. Main Components of an Adaptive Irrigation System

Components	Functions
ESP32	Main microcontroller, sensor data processor, and data transmitter to the monitoring application.

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Soil moisture sensor	Reads the moisture content of the growing medium as the primary indicator of soil conditions.
DHT22	Reads air temperature and humidity as environmental parameters.
Light intensity sensor	Reads light intensity as a supplementary environmental parameter.
Flow sensor	Measures the actual volume of water dispensed during watering.
Relay and water pump	Controls and delivers water to the growing medium.

Sensor Calibration

Sensor calibration was performed prior to testing to ensure that sensor readings accurately reflected the actual conditions of the growing medium and water flow. In the reference journal, a low-cost soil moisture sensor was calibrated by comparing its readings to those of a more accurate moisture sensor; the relationship between the readings was then analyzed using regression (Seyar & Ahamed, 2023). In line with this approach, this study used an initial calibration to establish operational categories for growing medium moisture.

The calibration results for the soil moisture sensor showed a range of readings from very wet to very dry, with values of 82%, 76%, 68%, 60%, 55%, and 49%. The SM threshold of <40% is not set as the absolute lowest reading value but as the system's operational dry/critical threshold to prioritize irrigation when the growing medium experiences a more extreme drop in moisture. The flow sensor was calibrated by observing the relationship between flow duration and the measured water volume.

Irrigation Decision Model

The irrigation decision model uses a threshold-based adaptive decision approach. Pump activation is determined not only by soil moisture values but also by the irrigation schedule, temperature conditions, and daily water targets. Irrigation is only permitted during the morning schedule from 6:00 a.m. to 8:00 a.m. and the afternoon schedule from 4:00 p.m. to 6:00 p.m. Outside of these schedules, the pump remains OFF. Additionally, the pump is not activated when the temperature is still in the "hot" category.

The variables used in the decision model include A for dry soil conditions, B for moist soil conditions, C for the active watering schedule, D for the unmet daily water

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target, E for non-hot temperatures, and Y for the pump decision. Logically, the pump decision is expressed in Equation (1).

$$Y = C \wedge E \wedge [A \vee (B \wedge D)] \ldots\ldots\ldots (1)$$

Table 2. Logic variables for the irrigation decision

Simbol	Notes	Value 1	Value 0
A	Dry soil	SM < 40%	SM ≥ 40%
B	Moist soil	40% ≤ SM ≤ 79%	SM < 40% or SM ≥ 80%
C	Active watering schedule	6:00 a.m.–8:00 a.m. or 4:00 p.m.–6:00 p.m.	Outside schedule
D	Daily water target not met	Daily volume < target	Daily volume ≥ target
E	Temperature is not hot	Temperature is in the “not hot” category	High temperature
Y	Pump decision	ON	OFF

System Testing and Data Analysis

Testing was conducted on curly tomato plants in 40 x 40 cm polybags over a period of 21 days. Data were collected three times a day—in the morning, at noon, and in the afternoon—resulting in 63 observations. The parameters observed included soil moisture, air temperature, relative humidity, light intensity, system decisions, pump ON duration, and water volume per polybag.

Irrigation decision analysis was performed using a confusion matrix. True Positive (TP) indicates a condition where the system irrigates when irrigation is indeed necessary. True Negative (TN) indicates a condition where the system does not irrigate when irrigation is not necessary. False Positive (FP) indicates a condition where the pump is ON even though irrigation is not necessary, while False Negative (FN) indicates a condition where the pump is OFF even though irrigation is necessary.

System accuracy was calculated using Equation (2). The actual water volume was analyzed based on flow sensor data, while the comparison for the fixed duration was made using a reference volume of 800 mL/polybag/day.

$$\text{Accuracy} = (TP + TN) / (TP + TN + FP + FN) \times 100\% \ldots\ldots (2)$$

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RESULTS AND DISCUSSION

Sensor Reading Results

Based on testing over 21 days, soil moisture values ranged from 49% to 82%, air temperature ranged from 25.2°C to 34.1°C, relative humidity ranged from 56% to 89%, and light intensity ranged from 26% to 97%. These ranges indicate that the sensors were able to detect variations in growing medium and environmental conditions throughout the testing period.

The sensor readings showed logical patterns. Temperature and light intensity tended to increase during the day, while relative humidity tended to decrease as temperature rose. Soil moisture served as the primary indicator of growing medium conditions, while temperature, relative humidity, and light intensity functioned as supporting parameters for assessing environmental conditions.

Table 3. Summary of Sensor Readings

Parameters	Value range	Interpretation
Soil moisture	49%-82%	The growing medium varies from relatively dry to wet.
Air temperature	25,2°C-34,1°C	Temperature varies depending on the time of observation, with the highest values typically occurring during the day.
Air humidity	56%-89%	Air humidity tends to decrease as temperature rises.
Light intensity	26%-97%	Light intensity is higher during the day and decreases in the afternoon.

Irrigation Decision Evaluation

Based on 63 observations, the system produced 14 true positives, 45 true negatives, 1 false positive, and 3 false negatives. A summary of the system's decision evaluation is shown in Table 4.

Table 4. Irrigation decision evaluation based on the confusion matrix

Category	Condition	System decision	Number of observations
True Positive (TP)	Requires watering	ON	14
True Negative (TN)	Does not require watering	OFF	45

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False Positive (FP)	Does not require watering	ON	1
False Negative (FN)	Requires watering	OFF	3
Total			63

The system's decision accuracy was calculated at 93.65% based on the formula (14 + 45) / 63 × 100%. This value indicates that the system demonstrated a high level of compliance with internal decision rules during testing.

However, the system has not yet achieved 100% accuracy because false positives (FP) and false negatives (FN) still occur. FPs pose the risk of unnecessary watering, while FNs pose the risk of delayed watering when the growing medium needs water. These findings indicate that the system still requires refinement of its decision logic and sensor validation in future research.

Actual Water Volume and Comparison with Fixed Duration

A flow sensor was used to record the actual water volume during each irrigation event. Over the 21-day testing period, the system performed 15 irrigation events with a total water volume of 6,539 L per polybag. The average water volume per event was 0.436 L per polybag, while the average daily water volume was 0.311 L per polybag per day.

The use of a flow sensor enhances the system evaluation because water volume is not merely estimated based on the duration the pump is active. With a flow sensor, the actual volume of water discharged can be recorded and used as the basis for evaluating water usage. This principle is the key distinguishing factor of this study compared to systems that evaluate only the ON/OFF control of the pump.

Table 5. Summary of Actual Water Volume

Components	Value
Number of watering events	15 events
Total water volume per polybag	6,539 L
Average volume per event	0.436 L
Average daily volume	0.311 L or 311.38 mL
Estimated total for 10 polybags	65.39 L over 21 days

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Table 6. Comparison of Adaptive and Fixed-Duration Systems

Method	Total volume per polybag	Notes
Adaptive system	6,539 L	Watering is based on the actual condition of the growing medium and system settings.
Fixed duration	16,800 L	Watering remains at 800 mL per polybag per day.
Difference	10,261 L	The volume for fixed-duration watering is greater than that of the adaptive system.
Reduction	61,08%	The adaptive system delivers water more selectively.

The comparison results show that the adaptive system produces a watering volume that is 61.08% lower than the fixed-duration method. This reduction occurs because the system does not water at a fixed rate every day. On days when the growing medium is still sufficiently moist, the pump remains OFF, resulting in a water volume of 0 mL. Conversely, under certain conditions, the system can provide more water than the fixed-duration method if the conditions of the growing medium and the environment indicate a greater need for watering.

Thus, the advantage of the adaptive system is not merely that it provides less water, but that it is capable of adjusting water delivery based on the actual conditions of the growing medium. This demonstrates that the system can operate selectively and precisely.

Comparison with Related Research

The study by Seyar and Ahamed (2023) is closely related to this research because both developed IoT-based irrigation systems for tomato plants using soil moisture sensors. That study focused on determining soil moisture thresholds and comparing surface and subsurface drip irrigation, then evaluating agronomic parameters such as germination, roots, shoots, and tomato yield.

The main difference in this study lies in the focus of the evaluation. This study does not directly test agronomic parameters but emphasizes system performance, the accuracy of ON/OFF decisions, the measurement of actual water volume using a flow sensor, and a comparison of volume with fixed-duration irrigation. Thus, this study complements previous research in terms of system data evaluation and actual water usage at the polybag scale.

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Potential Impacts and Limitations

The use of an adaptive irrigation system has the potential to support more precise water management and help maintain more controlled growing media conditions. Theoretically, sufficient water availability can support more stable plant growth. However, this study did not directly measure agronomic parameters such as plant height, number of leaves, number of flowers, number of fruits, fruit weight, fruit size, fruit quality, or plant health.

Therefore, this study does not conclude that the system directly improves plant health or fruit quality. The impact that can be stated is the system's potential to support water management and the stability of growing media conditions. Further agronomic trials are needed to assess the system's effect on plant growth and yield.

CONCLUSION

An Internet of Things-based adaptive irrigation system with multimodal sensors was successfully designed and tested on curly tomato plants grown in polybags. The system is capable of monitoring growing medium and environmental conditions, making irrigation decisions, controlling the pump, and measuring the actual water volume using a flow sensor.

An evaluation of the decisions showed that the system produced TP = 14, TN = 45, FP = 1, and FN = 3, with a decision accuracy of 93.65%. These results indicate that the system has a high level of compliance with its internal decision rules, although decision errors still occur.

The flow sensor recorded a total water volume of 6.539 L per polybag over 21 days. Compared to the fixed-duration method, which used 16,800 L per polybag, the adaptive system resulted in a 61.08% lower irrigation volume. This system has the potential to support more precise water management, but its direct impact on fruit growth and quality needs to be tested in further research.

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