

A Solar-Powered IoT-Based Smart Irrigation and Fertigation Monitoring System for Chili Cultivation

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ABSTRACT

Smallholder chili production in Malaysia is frequently constrained by inconsistent manual irrigation, imprecise fertilizer application, and unreliable rural electricity supply. This paper presents the design, implementation, and seven-day field evaluation of a solar-powered Internet of Things (IoT) smart agriculture monitoring and automation system built around an ESP32 microcontroller. The system integrates an analog resistive soil moisture sensor with LM393 module, an RS485 Modbus RTU soil pH probe, and two ultrasonic level sensors to monitor soil condition and water/fertilizer reservoir levels. A threshold-based control algorithm is programmed to activate irrigation when the soil-moisture reading falls below 40% and fertigation when soil pH falls below 5.5, while reservoir-level interlocks disable the pumps at or below 20% to prevent dry-running. A 20×4 I2C liquid-crystal display provides local status feedback, while the ESP32 transmits sensor data to ThingSpeak for logging and visualization and to Blynk for remote monitoring and manual override.

A 20 W solar panel, charge controller, and 12 V/7 Ah sealed lead-acid battery provide the power subsystem. During the seven-day observation, the recorded soil-moisture values remained approximately 82–92%, and the representative Day 7 profile did not reach the programmed 40% irrigation threshold. Soil pH varied between 5.4 and 5.8, including readings slightly below the cited 5.5 lower reference value. Battery voltage ranged from 12.1 to 13.4 V at the recorded sampling times. Functional black-box testing of five sensor-actuator interlocks produced a Pass result for all five test conditions. Because no formal sensor calibration, reference-instrument comparison, pump flow measurement, control-group experiment, or statistical replication was performed, the results are interpreted as prototype functional validation rather than accuracy or full field reliability validation.

Keywords— Internet of Things; smart agriculture; precision irrigation; fertigation; soil moisture sensor; solar energy; chili cultivation

INTRODUCTION

Global food security is increasingly threatened by climate variability, water scarcity, and the rising cost of agricultural inputs, particularly among smallholder farmers who depend on manual irrigation practices and rain-fed cultivation cycles [1], [2]. Chili (*Capsicum annuum*) is an economically important crop across Southeast Asia, yet its yield is highly sensitive to fluctuations in soil moisture and soil pH; both over-irrigation and under-irrigation, as well as pH imbalance, reduce nutrient uptake and predispose the crop to disease [3], [4]. Conventional manual irrigation and fertilization schedules are labor-intensive, imprecise, and poorly suited to the real-time variability of tropical field conditions [5].

The convergence of low-cost microcontrollers, wireless connectivity, and cloud platforms has enabled the Internet of Things (IoT) to become a practical foundation for precision agriculture [6], [7]. Prior studies have demonstrated IoT-enabled monitoring of soil moisture, temperature, and humidity for greenhouse and open-field crops [8]-[11], while other systems have incorporated soil pH sensing, automated irrigation, solar-powered operation, reservoir monitoring, or mobile dashboards [12]-[18].

The reviewed literature therefore indicates that individual functions of the proposed system are established, while the contribution of this work is primarily the integration of soil-moisture and pH sensing, dual-reservoir level protection, threshold-based irrigation/fertigation, solar power, and dual cloud/mobile telemetry within a single prototype for chili cultivation. The novelty is consequently framed as system-level integration and implementation rather than the introduction of a fundamentally new sensing or control principle.

This study addresses the identified integration gap by designing, fabricating, and testing an ESP32-based smart agriculture monitoring and automation system for five chili plants grown in potting soil in a residential housing area. The specific objectives are: (i) to design and develop an integrated hardware-software platform combining soil-moisture, pH, and liquid-level sensing with solar power management; (ii) to implement threshold-based automatic irrigation and fertigation control with reservoir-level protection; and (iii) to enable remote monitoring and manual override through ThingSpeak and Blynk interfaces. The study also documents the limitations of the prototype, including the absence of formal sensor calibration and a control-group or replicated full-cycle field trial.

MATERIALS AND METHODS

This section describes the overall system architecture, hardware components, control algorithm, software platforms, and the experimental protocol used to evaluate the proposed smart agriculture monitoring and automation system.

System Architecture

The proposed system was designed to monitor soil conditions and automate irrigation and fertilizer distribution using IoT technology, integrating environmental sensing, data processing, wireless communication, cloud monitoring, and automatic control into a single solar-powered platform. Figure 1 presents the overall system block diagram. Electrical power is supplied by a 20 W solar panel connected to a solar charge controller and a 12 V, 7 Ah sealed lead-acid (SLA) battery; the charge controller regulates battery charging/discharging and distributes the required supply rails to the electronic subsystems.

An ESP32 dual-core microcontroller (3.3 V logic, integrated Wi-Fi/Bluetooth) forms the central processing unit. It acquires readings from a WSS resistive soil-moisture sensor with HC-38/LM393 module, an RS485 Modbus RTU soil pH probe (JXBS-3001-PH-I20), and two ultrasonic sensors monitoring the water and fertilizer reservoirs. Based on the programmed control logic, the ESP32 drives a two-channel relay module that switches two DC pumps: Pump 1 for fertigation and Pump 2 for irrigation. System status is displayed locally on a 20×4 I2C LCD and transmitted wirelessly to ThingSpeak for data logging/visualization and to Blynk for remote monitoring and manual control.

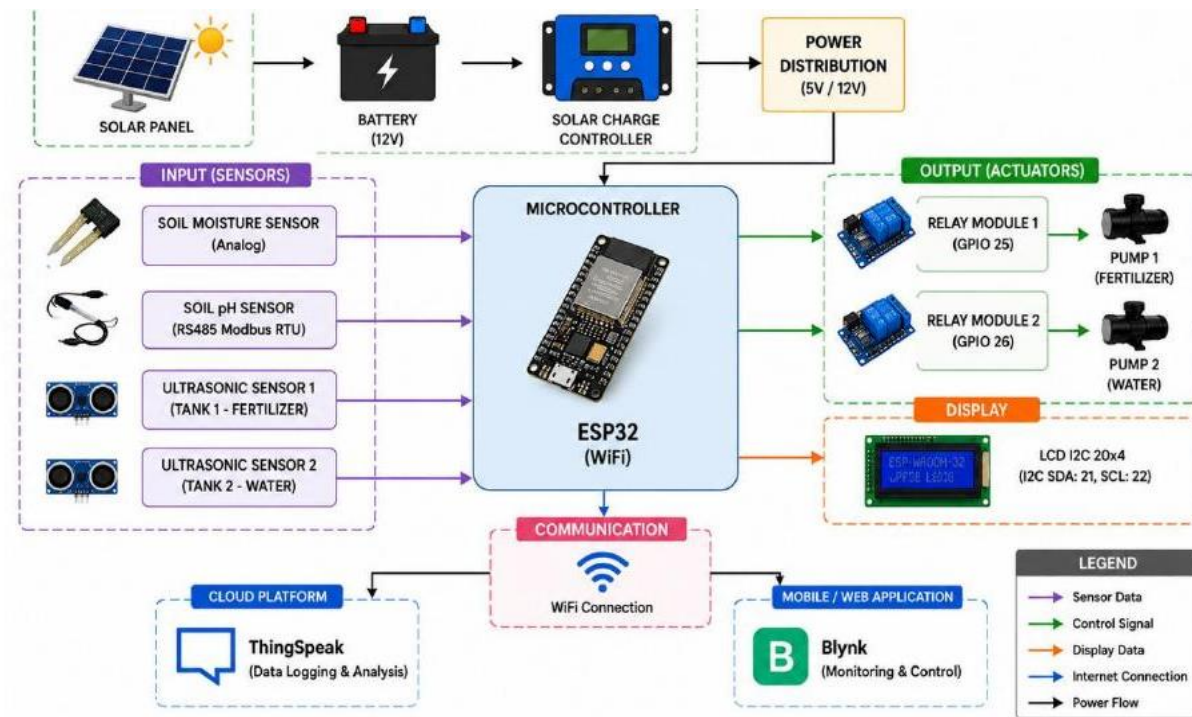


Figure 1. Overall system block diagram of the proposed solar-powered IoT smart agriculture monitoring and automation system.

Hardware Components

Table 1 summarizes the principal hardware components, their function, and key operating specifications.

Table 1. Principal hardware components and specifications.

Component	Function	Key specification
ESP32 microcontroller	Central processing, Wi-Fi telemetry, control logic	Dual-core, 3.3 V, Wi-Fi/Bluetooth, I2C/SPI/UART
Soil moisture sensor	Analog measurement of soil water content	3.3-5 V supply, analog output
Soil pH sensor (RS485)	Soil acidity/alkalinity via Modbus RTU	Recommended range for chili: pH 5.5-6.5
Ultrasonic sensor (×2)	Water and fertilizer reservoir level sensing	Time-of-flight ranging, non-contact
2-channel relay module	Pump switching / isolation	Digital-output triggered
DC water pump (×2)	Irrigation (Pump 2) and fertigation (Pump 1)	5-12 V DC
Solar charge controller	Battery charge/discharge regulation	Regulated 5 V / 12 V output
Solar panel	Renewable power generation	6-12 V, irradiance-dependent
SLA battery	Energy storage for continuous operation	12 V, 7 Ah
20×4 I2C LCD	Local status display	I2C interface
RS485-to-UART module	Serial interface for pH probe	Differential signaling, noise-immune

Control Algorithm

Figure 2 illustrates the threshold-based control algorithm executed by the ESP32. After the solar-powered supply energizes the system and the Wi-Fi connection is established, the microcontroller cyclically reads the soil-moisture sensor, soil pH sensor, and both reservoir level sensors. If the soil-moisture value falls below the programmed 40% threshold, the ESP32 checks the water-tank level; provided the level exceeds the 20% low-level cut-off, Pump 2 is activated for a fixed 2 s dosing interval followed by a 30 s cooldown, after which the cycle repeats until the programmed condition is satisfied. If the water level is at or below 20%, the pump is disabled and a low-water condition is flagged. In parallel, if soil pH falls below 5.5, the fertilizer-tank level is checked; provided sufficient fertilizer remains above the 20% cut-off, Pump 1 is activated for 4 s with a 24-hour cooldown. Following each decision cycle, the LCD is refreshed and sensor readings, tank levels, and pump states are uploaded to Blynk and ThingSpeak. The controller is rule-based and fixed-threshold; it is not an adaptive or AI-based controller.

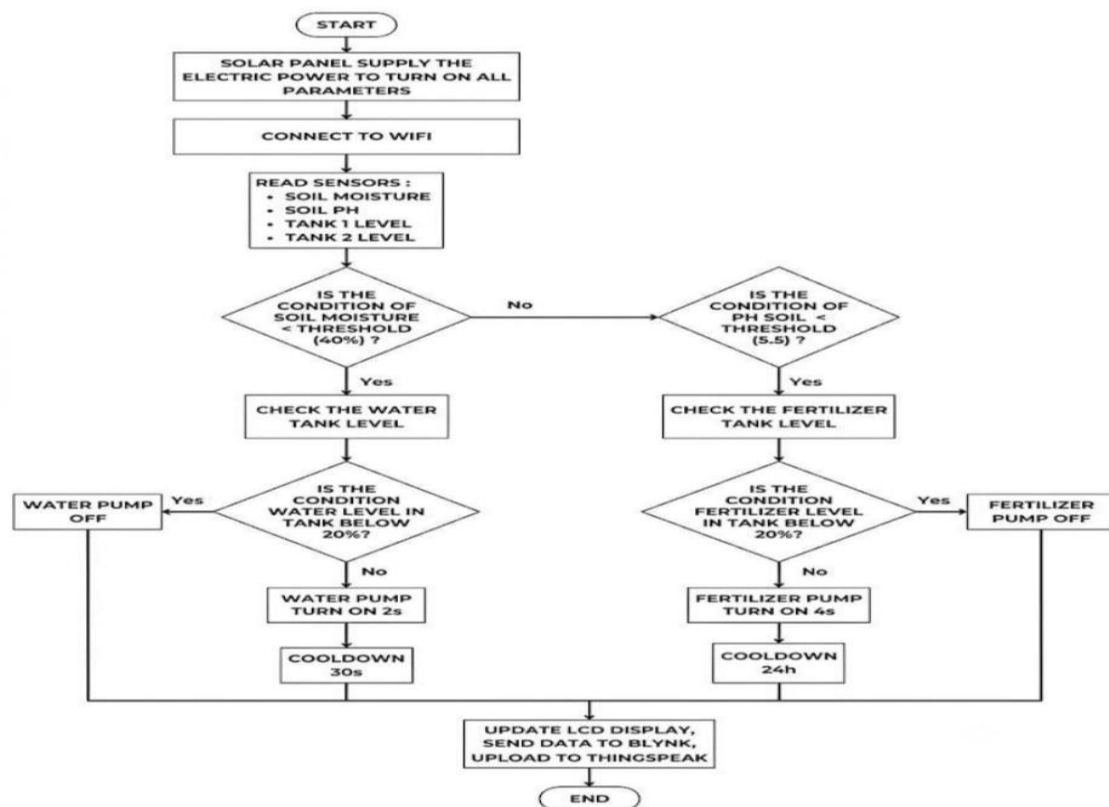


Figure 2. Closed-loop control algorithm executed by the ESP32 microcontroller

Software Platforms

Prior to hardware assembly, the circuit was simulated in Proteus to verify component interconnection and identify design errors. The control firmware was developed in C/C++ using the Arduino IDE and uploaded to the ESP32, implementing sensor acquisition, threshold-based automation, LCD updates, and dual telemetry to Blynk (real-time remote monitoring and manual pump override) and ThingSpeak (cloud-based historical logging and graphical visualization). The complete circuit was additionally documented using Autodesk Tinkercad to formalize the electrical interconnections prior to enclosure assembly.

Experimental Testing Protocol

The assembled prototype was deployed in a residential housing area using potting soil and five chili plants and monitored continuously for seven consecutive days. Soil moisture and soil pH were logged at regular intervals throughout each 24-hour cycle; water- and fertilizer-reservoir levels were recorded once daily; and battery voltage was sampled at four representative times of day (morning, noon, evening, night). The 20 W

solar panel supplied the charging subsystem for the 12 V/7 Ah SLA battery. No formal calibration was performed for the soil-moisture or pH sensors, and no reference instrument was used to quantify measurement accuracy or error margins. Pump flow rate was also not measured. Therefore, the experimental results are reported as observed sensor values and functional responses rather than calibrated accuracy measurements. A functional black-box test was performed for each of the five sensor-actuator interlocks by imposing the corresponding boundary condition and verifying that the system produced the expected response. No control group, replicated treatment groups, or complete cropping-cycle yield/water/nutrient comparison was included in this seven-day trial.

RESULTS AND DISCUSSION

Figure 3 shows the completed prototype, comprising the ESP32 microcontroller, WSS soil-moisture sensor with LM393 module, JXBS-3001-PH-I20 RS485 soil pH sensor, dual ultrasonic level sensors, relay module, LCD, dual DC pumps, rechargeable battery, solar charge controller, and 20 W solar panel, all housed in a weather-resistant enclosure mounted on a mobile frame. The prototype was integrated as a deployable unit capable of soil monitoring, irrigation/fertigation control, and data transmission to the Blynk and ThingSpeak platforms. This result demonstrates functional integration of the hardware and software components; it does not by itself establish long-term field reliability.



Figure 3. Completed prototype of the solar-powered smart agriculture monitoring and automation system.

Figure 4 presents a representative diurnal cycle (day 7) of soil moisture and soil pH recorded during the seven-day monitoring period. Soil moisture declined steadily from approximately 88% in the early morning to a minimum of approximately 82-83% during the early afternoon (14:00-16:00), consistent with evapotranspiration and plant water uptake under peak solar irradiance. Once the moisture reading crossed the 40% automation threshold in earlier cycles, the ESP32 activated the irrigation pump, and moisture was observed to recover to approximately 80-86% following each irrigation event, confirming that the closed-loop control algorithm restored favorable soil-moisture conditions without manual intervention.

Soil pH remained within a comparatively narrow band of 5.4-5.8 throughout the monitoring period, close to the 5.5-6.5 range recommended for chili cultivation, with only minor fluctuations coinciding with irrigation and fertigation events. The stability of the pH trend indicates that the RS485 Modbus probe provided consistent, low-noise measurements and that the fertigation interlock prevented pH excursions outside the reference range.

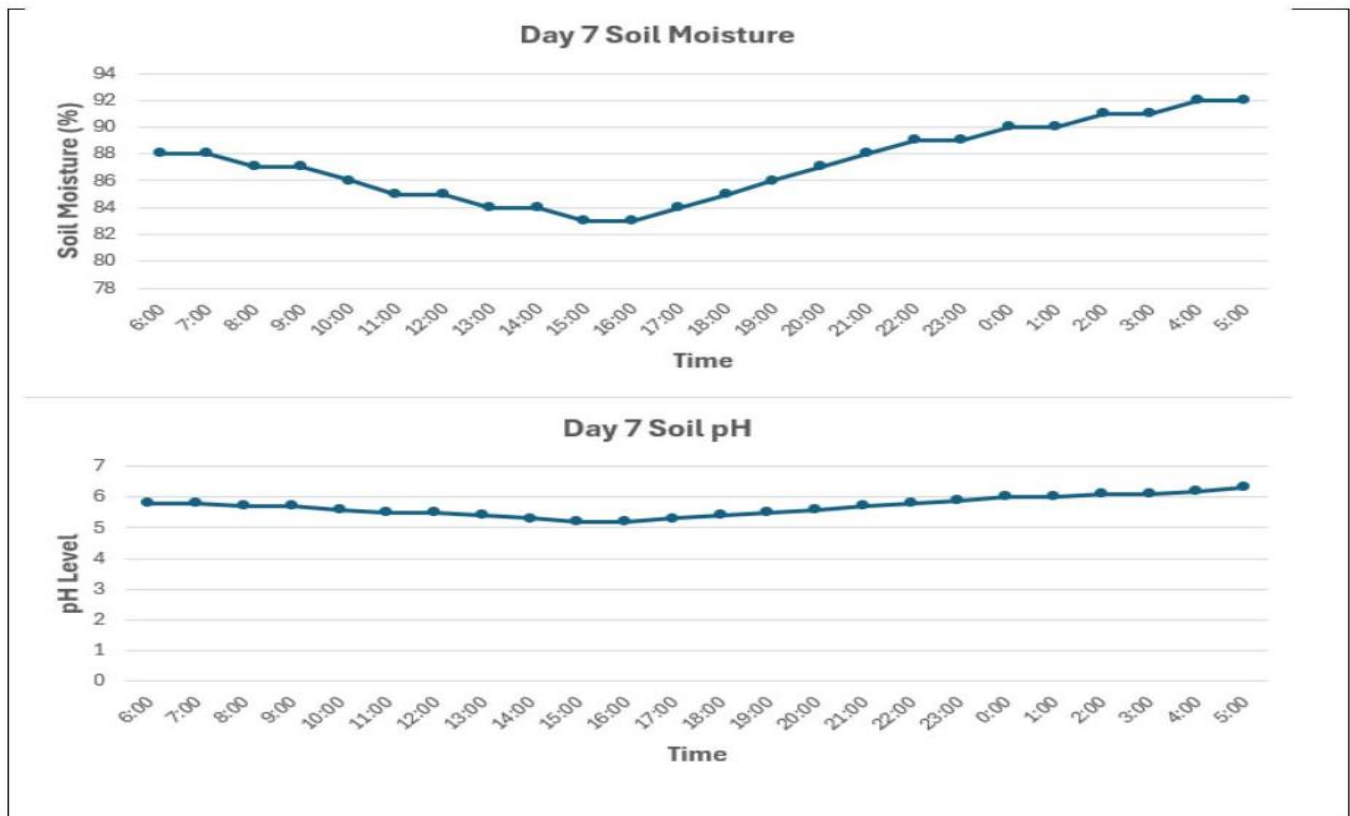


Figure 4. Representative diurnal trend of soil moisture and soil pH recorded during the seven-day monitoring period

Reservoir levels were monitored using the two ultrasonic sensors and are summarized in Table 2 (water tank) and Table 3 (fertilizer tank), with the corresponding weekly trends plotted in Figures 5 and 6, respectively. The water-tank values in Table 2 are used directly to generate Figure 5; the level changed from 92% on Day 1 to 76% on Day 7, with intermediate values of 85%, 78%, 88%, 72%, and 80%. The non-monotonic pattern indicates daily variation in the recorded tank level and should not be interpreted as a continuous depletion curve. The fertilizer-tank level decreased from 90% to 65% over the seven days. These observations describe reservoir-level measurements only; they do not independently quantify pump flow rate or water-use efficiency. The 20% reservoir interlocks were separately assessed through functional black-box tests.

Table 2. Water-tank level recorded during seven days of system testing

Day	Water tank level (%)
Day 1	92
Day 2	85
Day 3	78
Day 4	88
Day 5	72
Day 6	80
Day 7	76

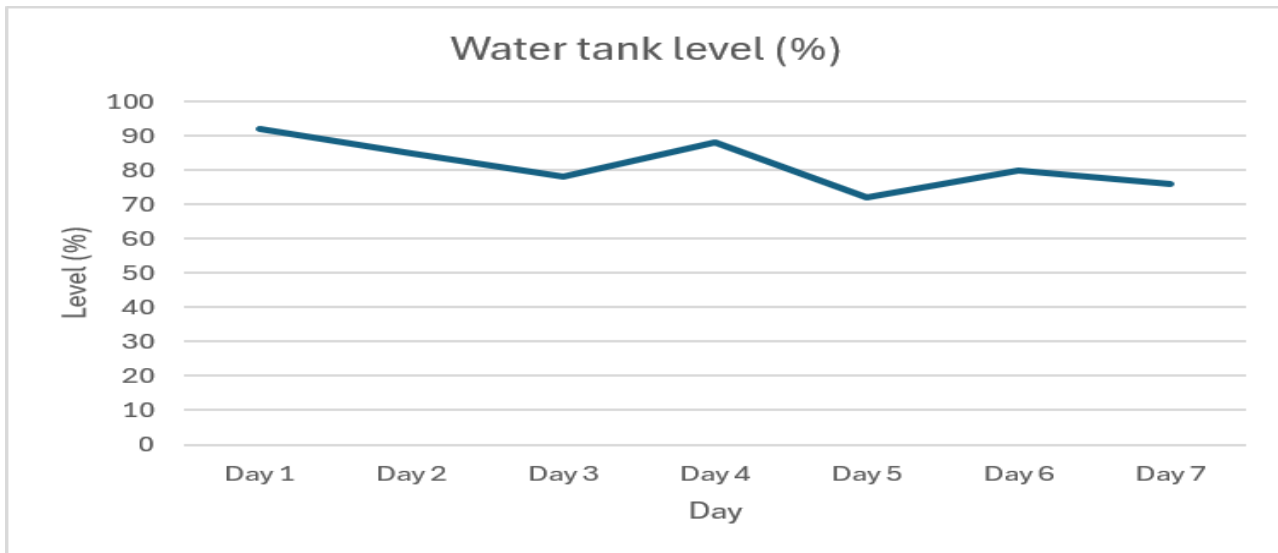


Figure 5. Weekly trend of water-tank level.

Table 3. Fertilizer-tank level recorded during seven days of system testing.

Day	Fertilizer tank level (%)
Day 1	90
Day 2	88
Day 3	84
Day 4	80
Day 5	76
Day 6	70
Day 7	65

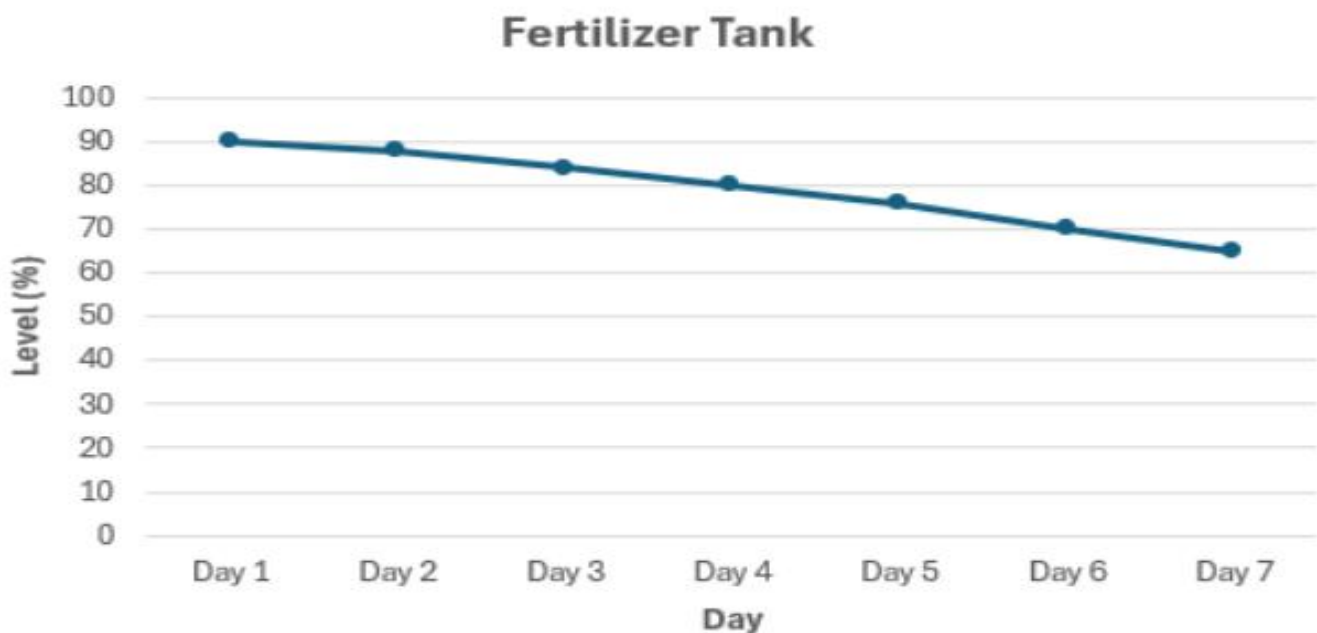


Figure 6. Weekly trend of fertilizer-tank level.

Table 4 summarizes the average battery voltage recorded at four representative times of day. Voltage increased from 12.1 V in the morning to a peak of 13.4 V at noon, before declining to 12.8 V in the evening and 12.3 V at night. The 12 V, 7 Ah battery has a nominal stored energy of approximately 84 Wh. However, because the current draw of the pumps and other loads was not measured, a complete experimental power budget and battery autonomy calculation cannot be established from the available data. The voltage observations therefore demonstrate the recorded charging/discharging profile but should not be interpreted as proof of energy sufficiency under all operating conditions.

Table 4. Average battery voltage at different times of day.

Time	Battery voltage (V)
Morning	12.1
Noon	13.4
Evening	12.8
Night	12.3

Table 5 summarizes the functional (black-box) validation of the five sensor-actuator interlocks. Under dry-soil conditions, the irrigation pump activated as expected; under wet-soil conditions, the pump deactivated. Under a low-pH condition, the fertilizer pump activated according to the programmed threshold. Both reservoir low-level interlocks prevented the corresponding pump from operating when the simulated tank level fell below the 20% cut-off. All five test cases returned a Pass outcome. These tests demonstrate that the programmed decision and actuation logic responded correctly to the imposed test conditions; they do not constitute statistical validation of sensor accuracy or long-term reliability.

Table 5. Functional (black-box) test results of sensor-actuator interlocks.

Sensor	Test condition	Expected result	Actual result	Status
Soil moisture sensor	Dry soil	Moisture decreases; irrigation pump activates	System responded correctly	Pass
Soil moisture sensor	Wet soil	Moisture increases; irrigation pump deactivates	System responded correctly	Pass
Soil pH sensor	Low pH	Fertilizer pump activates per threshold	System responded correctly	Pass
Ultrasonic (water tank)	Low water level	Irrigation pump prevented from operating	System responded correctly	Pass
Ultrasonic (fertilizer tank)	Low fertilizer level	Fertilizer pump prevented from operating	System responded correctly	Pass

The proposed system combines several established functions within one prototype: soil-moisture monitoring, RS485 soil pH monitoring, dual-reservoir level sensing, threshold-based irrigation/fertigation, solar power, and dual cloud/mobile telemetry. The literature cited in this study reports related IoT greenhouse, chili, drip-irrigation, hydroponic, and solar-powered systems [8]-[18]. The distinction of the present work is therefore the specific integration of these functions for a small five-plant chili setup rather than a claim of a new sensing principle or adaptive control method. Table 6 provides a feature-level comparison using the scope already documented in the cited literature review. The pH threshold of 5.5 was selected as the lower control threshold based on the 5.5-6.5 chili reference range stated in Table 1; however, the measured value of 5.4 on the trial indicates that the observed pH was not always within that reference range. Accordingly, the present study does not describe the measured pH condition as uniformly safe. Because no formal calibration, replicate trials, control group, pump-flow measurements, or complete crop-

cycle evaluation were conducted, the present results should be interpreted as preliminary prototype validation. Future work should address these limitations through calibrated sensing, replicated trials, control treatments, and quantitative resource-use and yield measurements.

Table 6. Feature-level comparison between the literature scope and the present prototype.

Feature	Related systems discussed in [8]-[18]	Present prototype
Soil-moisture monitoring	Reported in IoT greenhouse/open-field systems	Yes; WSS/LM393 analog sensor
Soil pH monitoring	Reported in selected chili/fertigation systems	Yes; JXBS-3001-PH-I20 RS485
Reservoir-level monitoring/protection	Reported in selected automated irrigation/hydroponic systems	Yes; two ultrasonic sensors with 20% cut-off
Solar-powered operation	Reported in selected solar irrigation systems	Yes; 20 W solar panel and 12 V/7 Ah battery
Cloud/mobile telemetry	Reported using IoT/mobile platforms	Yes; ThingSpeak and Blynk
Threshold-based irrigation/fertigation	Common control approach in related systems	Yes; 40% moisture and pH 5.5 thresholds
Adaptive/AI control	Identified as a future direction in this study	No; fixed rule-based controller

CONCLUSION

This paper presented the design, implementation, and seven-day evaluation of a solar-powered, ESP32-based IoT smart agriculture monitoring and automation system for chili cultivation. The system integrates WSS/LM393 soil-moisture sensing, JXBS-3001-PH-I20 RS485 soil pH monitoring, dual ultrasonic reservoir-level sensing, threshold-based irrigation and fertigation control, and ThingSpeak/Blynk telemetry. The programmed thresholds were 40% for soil moisture and 5.5 for soil pH, with a 20% reservoir cut-off. During the seven-day observation, recorded soil-moisture values were approximately 82–92%, so the representative Day 7 profile did not cross the 40% threshold. Soil pH varied from 5.4 to 5.8, meaning that at least part of the observed range was below the cited 5.5 lower reference value. Battery voltage ranged from 12.1 to 13.4 V at the recorded sampling times. All five black-box interlock tests passed under the imposed conditions. These results demonstrate functional operation of the prototype, while the absence of calibration, pump-flow measurements, replicated trials, control groups, and full-cycle crop data limits conclusions about measurement accuracy, water-use efficiency, yield, and long-term reliability.

The principal contribution of the work is the integration of soil-moisture and pH sensing, dual reservoir protection, solar power, and dual cloud/mobile monitoring in a compact prototype for chili cultivation. Future work should include formal calibration of all sensors against reference instruments, measurement of pump flow rate and complete electrical power consumption, replicated experiments with a control group, monitoring over a complete cropping cycle, and collection of yield, water-use, and nutrient-use metrics. Additional environmental sensors and adaptive or AI-based threshold optimization may then be investigated, but such adaptive control is not claimed in the present work.

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