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Smart home irrigation: A solar-powered Wi-Fi-based automated drip system with real-time soil moisture sensing

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Abstract: Manual irrigation in home gardening often causes inconsistent watering, unnecessary labor, and inefficient water use. This study developed and evaluated a solar-powered, Wi-Fi-based automated drip irrigation system with real-time soil moisture sensing for small-scale home gardens. The prototype integrated an ESP32 microcontroller, capacitive soil moisture sensors, pH sensor, float sensors, solenoid valves, DC pumps, a 150-W solar panel, a 12.8-V 100-Ah battery, and an Android-based mobile application. Four planting plots were used to test automated irrigation, soil moisture monitoring, water pH monitoring, tank-level detection, drainage monitoring, and mobile-based control. System performance was observed through 15-day plant monitoring and 5-day data logging. Results showed that the system supplied water only when soil moisture dropped below the set threshold and avoided unnecessary pump activation. Evaluations by 20 faculty members, IT experts, agriculturists, and farmers yielded excellent ratings for functionality (4.81), performance (4.74), and usability (4.89), with an overall mean of 4.81. The study demonstrates a low-cost, renewable-energy-based, mobile-controlled irrigation solution suitable for household gardening.

Keywords: automated drip system; ESP32; smart irrigation; soil moisture sensing; solar-powered system

1. Introduction

Home gardening plays an important role in improving household food security in developing countries where population growth and urbanization continue to increase pressure on food systems [1]. By providing direct access to fresh produce, home gardens help improve dietary quality while reducing dependence on external food sources [2]. Studies have shown that home gardens also contribute to local food system resilience by supporting small-scale, household-level food production [3]. In urban and peri-urban settings, home gardens help mitigate food insecurity by improving food availability and accessibility at the household level [4]. These gardens also support environmental sustainability through improved soil management and efficient use of limited resources [2]. Despite these benefits, food stability remains a challenge when gardening practices are inefficient or poorly managed [4], [5], [6]. This highlights the need for improved methods that support sustainable and reliable home food production.

Irrigation management remains one of the most critical challenges in home gardening. Many households continue to rely on manual watering practices based on routine schedules or visual assessment rather than actual soil conditions [7]. Such practices often result in overwatering or underwatering, which negatively affects plant growth and leads to unnecessary water consumption [7]. Time constraints further limit the ability of gardeners to consistently monitor and adjust irrigation, especially for households balancing gardening with work and family responsibilities [8].

Recent advancements in agricultural technology have introduced automated solutions to address these limitations. Internet of Things (IoT)-based irrigation systems enable real-time monitoring of soil moisture and environmental conditions through the use of sensors and microcontrollers [9]. These systems allow irrigation to be applied only when necessary, improving water-use efficiency and reducing manual labor [10]. Research has demonstrated that smart irrigation systems can significantly enhance plant health by maintaining optimal soil moisture levels [11]. The adoption of automation in agriculture has become increasingly important due to demographic changes such as an aging population and a declining agricultural workforce [12]. Automation improves productivity by reducing physical labor and increasing operational accuracy in agricultural tasks [12]. Agriculture has historically benefited from technological innovations developed across scientific disciplines, leading to continuous transformation of farming practices [13]. Current research suggests that continued technological advancements will further reshape agricultural systems at both large-scale and household levels [14].

Soil moisture has been consistently identified as a key parameter influencing plant growth and productivity. Maintaining appropriate moisture levels prevents water stress and supports efficient nutrient uptake. Different vegetable crops and herbs require specific moisture conditions, making real-time monitoring essential for effective irrigation control [15], [16]. These findings emphasize the importance of adaptive irrigation systems capable of responding to plant-specific requirements. Despite the availability of smart irrigation technologies, adoption among home gardeners remains limited. High cost, technical complexity, and lack of awareness discourage households from using automated irrigation systems [10]. As a result, inefficient irrigation practices persist, leading to water wastage, inconsistent plant growth, and increased labor demands. This reveals a clear need for a smart irrigation solution that is affordable, simple to use, and suitable for home garden environments.

Accordingly, this study aims to design, develop, and evaluate a Smart Home Irrigation System that integrates real-time soil moisture sensing, automated drip irrigation, and mobile-based monitoring powered by solar energy. The study specifically seeks to assess the system's functionality, performance, and usability in maintaining optimal soil moisture conditions for selected home garden plants while improving water-use efficiency and reducing manual labor. The significance of this study lies in its contribution to sustainable home gardening and efficient water management. By addressing irrigation inefficiency rather than water scarcity alone, the proposed system promotes responsible water use and reduces unnecessary water loss. The integration of solar energy further enhances sustainability by lowering operational costs and minimizing reliance on conventional power sources [17], [18]. From a practical perspective, the system offers a low-maintenance and user-friendly solution for home gardeners. From a research perspective, this study offers practical evidence on how solar-powered, IoT-based irrigation systems perform in controlled home garden settings.

2. Material and methods

This study followed a structured research design composed of seven sequential phases: preliminary survey and problem identification, design, development, implementation, data collection, evaluation, and final output, as shown in Figure 1. The preliminary survey and problem identification phase established the need for the study by determining common difficulties in home gardening, particularly manual watering, inconsistent irrigation, overwatering, underwatering, and limited time for plant maintenance. The findings from this phase served as the basis for defining the system requirements and identifying the major functions needed in the proposed smart irrigation system.

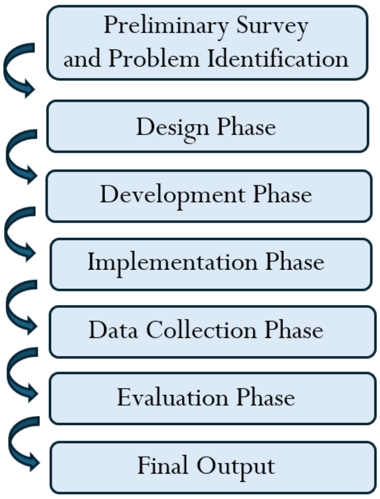


Figure 1. Research design framework of the Smart Home Irrigation system

The design phase focused on planning the overall structure of the Smart Home Irrigation system. This included the arrangement of the planting plots, selection of electronic and mechanical components, solar-power configuration, water distribution layout, and control logic for automated irrigation. The system was designed to integrate real-time soil moisture sensing, pH monitoring, water tank level detection, drainage monitoring, and mobile-based monitoring and control. The development phase involved the fabrication and assembly of the prototype. During this phase, the ESP32 microcontroller was programmed, the sensors were connected and tested, the pumps and solenoid valves were installed, and the Android-based mobile application was developed for system monitoring and user interaction. Calibration and troubleshooting were also conducted to ensure that the soil moisture sensors, pH sensor, float sensors, pumps, and valves operated according to the intended system logic.

The implementation phase involved deploying the completed prototype in an outdoor home garden setting. The system was operated using four planting plots to observe its actual performance under real environmental conditions. During this phase, the automated irrigation function was tested based on the soil moisture readings and the programmed threshold values. The data collection phase focused on recording relevant system outputs, including soil moisture levels, irrigation responses, water tank status, drainage condition, and data logs from the mobile application. These data were used to determine whether the system could provide water only when required and maintain appropriate soil moisture conditions for the selected plants.

The evaluation phase assessed the system in terms of functionality, performance, and usability. Functionality referred to the ability of the system to perform its intended automated irrigation and monitoring tasks. Performance focused on the responsiveness, stability, and reliability of the sensors, pumps, valves, and solar-powered operation. Usability evaluated the clarity, convenience, and ease of use of the Android-based mobile application. The final output of the study was a solar-powered, Wi-Fi-based automated drip irrigation system with real-time soil moisture sensing and mobile monitoring for small-scale home gardening.

2.1 Design of the automated solar-powered drip irrigation system

The Automated Solar-Powered Drip Irrigation System was designed as an integrated off-grid irrigation platform combining renewable energy, embedded control, and precision water delivery. The design objective was to develop a compact, mobile, and energy-autonomous system capable of delivering zone-specific irrigation based on real-time soil conditions. The overall physical configuration of the prototype is presented in Figure 2, while the components are illustrated in Figure 3.

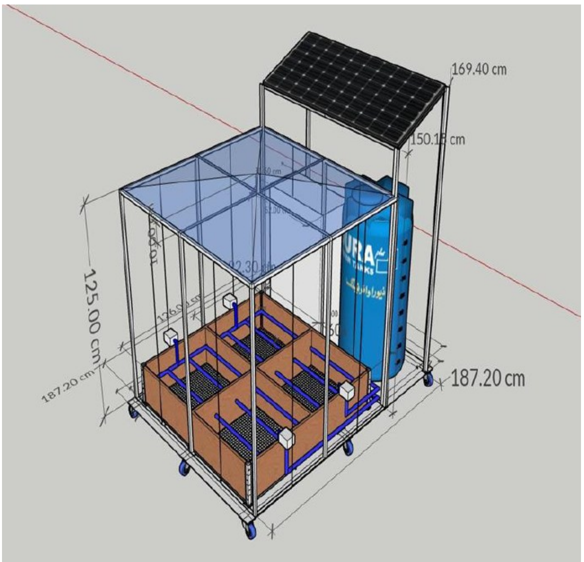


Figure 2. Structural layout of the automated solar-powered drip irrigation prototype

Figure 3. System Components

The structural design adopts a modular framework composed of a metal support platform mounted on caster wheels to ensure portability and ease of maintenance. The upper section supports a 150 W solar panel installed at an inclined angle to maximize solar energy capture. Energy generated from the panel is regulated through a solar charge controller and stored in a 12.8 V lithium battery, enabling continuous off-grid operation. A DC-DC buck converter stabilizes voltage levels supplied to low-power electronic components, ensuring operational reliability. Solar sizing was determined using Peak Sun Hour (PSH) analysis to match local environmental conditions and calculated load demand [17], [18]. This renewable configuration aligns with emerging sustainable irrigation practices and intelligent agricultural energy systems [19].

The irrigation structure consists of four independent planting plots, each configured as a separate irrigation zone. Water is stored in a centralized tank positioned to maintain structural balance and is distributed through a controlled piping network connected to dedicated pumps and solenoid valves. The zonal configuration allows precise and flexible water allocation tailored to localized soil conditions, reducing unnecessary water discharge commonly associated with manual irrigation methods [7]. Horizontal drip lines installed across each plot promote uniform water distribution and minimize surface runoff, enhancing irrigation efficiency. The control architecture is centered on an ESP32 microcontroller, which functions as the system's processing and communication unit. Soil moisture in each plot is continuously monitored using capacitive soil moisture sensors that measure dielectric variations to estimate volumetric water content. Calibration was performed under controlled dry and saturated soil conditions to establish threshold reference values, which were programmed into the controller to enable automated irrigation triggering. This demand-based activation prevents overwatering and supports optimal plant growth conditions [15], [16].

In addition to soil monitoring, system protection and operational safety are reinforced through auxiliary sensors. A float sensor installed in the water tank prevents dry pump operation, while a second float sensor monitors drainage accumulation to avoid overflow conditions. An analog pH sensor measures water irrigation quality to ensure compatibility with plant growth requirements. These sensing elements collectively enhance system responsiveness and safeguard long-term component durability. Actuation is achieved through 12 V DC pumps and solenoid valves controlled via a relay interface that electrically isolates high-current devices from the low-voltage microcontroller circuitry. This configuration ensures safe switching while maintaining energy efficiency. The irrigation process operates automatically based on programmed thresholds but remains user-accessible through an Android-based mobile application. The application provides real-time visualization of soil moisture levels, pump activity, and tank status, reflecting current IoT-enabled irrigation frameworks that promote remote monitoring and operational transparency [20].

2.2 Development of the multi-plot integrated prototype

Following the completion of the system design, a functional multi-plot prototype was fabricated to validate structural integrity, control integration, and multi-zone irrigation performance. Prior to physical assembly, a three-dimensional digital model was developed using SketchUp to define spatial arrangement, component alignment, hydraulic routing, and load distribution. The digital modeling stage ensured dimensional consistency and structural stability while minimizing fabrication errors. The ESP32 microcontroller was configured as the centralized processing unit responsible for integrating sensing, actuation, and communication subsystems. Firmware was developed to implement a closed-loop control mechanism in which real-time soil moisture readings from four independent plots were continuously acquired, compared against calibrated threshold values, and processed to trigger corresponding pump and solenoid valve activation. This logic enabled demand-driven irrigation rather than fixed time-based scheduling. Microcontroller-based irrigation systems have been shown to enhance control precision and water-use efficiency compared to conventional timer-based methods [11].

To validate multi-zone capability, the controller was tested for simultaneous acquisition of four soil moisture sensor inputs and independent actuation of four irrigation channels. Signal stability, switching latency, and relay response were evaluated to ensure that concurrent operations did not introduce delay, cross-interference, or control instability. Each irrigation zone operated autonomously under centralized logic, confirming that sensor inputs were correctly mapped to their corresponding hydraulic outputs. Four plant types were cultivated in separate plots to simulate variable moisture requirements and assess adaptive irrigation performance. Soil moisture thresholds were programmed according to recommended plant-specific ranges, recognizing that proper moisture regulation directly influences plant growth and yield performance [15], [16]. This configuration demonstrated that the prototype achieved centralized monitoring while maintaining independent irrigation control per zone, fulfilling the multi-plot integration objective. The fabricated multi-plot prototype is presented in Figure 4, showing the front, side, and back views of the assembled structure, including the solar panel mounting system, centralized water tank, structural frame, and drip irrigation layout.


Front view
Sideview
Back view

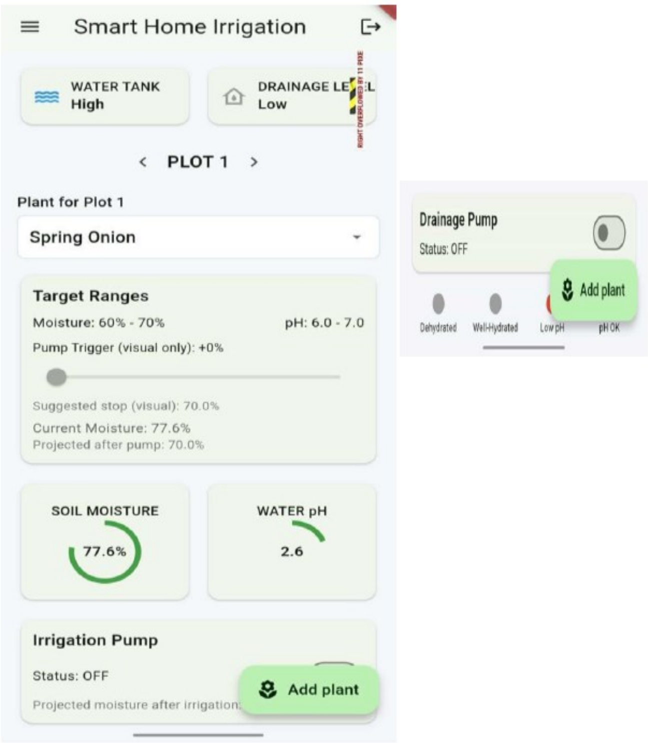
Figure 4. Fabricated multi-plot integrated prototype with control and irrigation subsystems

2.3 Implementation and testing

Following fabrication, the automated drip irrigation system was installed in an outdoor environment to simulate real-world operating conditions. The installation was performed in an area with adequate solar exposure to allow proper evaluation of photovoltaic energy harvesting and system autonomy. The system was configured for continuous operation over a 15-day monitoring period to assess functional stability under variable environmental conditions. Programming validation and hardware integration were conducted prior to and during system deployment. The finalized control configuration, including the ESP32 microcontroller, relay module, sensor terminals, and power regulation components, is presented in Figure 5.

Figure 5. Control unit and sensor integration during operational testing

This configuration reflects the physical integration of sensing, control, and actuation subsystems during operational testing. The firmware was programmed to continuously acquire soil moisture readings from four independent zones, compare them against calibrated threshold values, and activate the corresponding pump and solenoid valve when required. Debugging procedures were performed to verify stable signal acquisition, correct channel mapping, and reliable relay switching without electrical interference. Continuous operational monitoring was carried out throughout the 15-day implementation period. A representative mobile application interface used for data acquisition is shown in Figure 6.



WATER TANK High

DRAINAGE LE L Low

Plant for Plot 1: Spring Onion

Target Ranges
Moisture: 60% - 70%
pH: 6.0 - 7.0
Pump Trigger (visual only): +0%
Suggested stop (visual): 70.0%
Current Moisture: 77.6%
Projected after pump: 70.0%

SOIL MOISTURE 77.6%

WATER pH 2.6

Irrigation Pump
Status: OFF
Projected moisture after irrigation:

Drainage Pump
Status: OFF

Figure 6. Sample mobile application data log during 15-day monitoring period

The system logged soil moisture percentage per plot, pump activation status, tank level indicators, drainage level status, and pH readings. These parameters were recorded to evaluate system responsiveness, irrigation triggering behavior, and energy sustainability during field deployment. Irrigation response behavior was examined by allowing soil moisture levels to reach programmed thresholds and observing automated actuator activation. Multi-zone operation was configured to run concurrently, enabling independent irrigation control per plot. Solar charging performance and battery voltage levels were monitored to assess off-grid operational capability during the implementation phase.

2.4 Performance evaluation and system assessment

The performance evaluation of the Automated Solar-Powered Drip Irrigation System was conducted to determine its functional accuracy, operational stability, responsiveness, energy sustainability, and overall usability. Assessment focused on three primary dimensions: functionality, performance, and usability. Functional evaluation verified the system's ability to autonomously execute programmed tasks, including accurate soil moisture detection, threshold-based activation of pumps and solenoid valves per irrigation zone, proper float sensor operation for tank and drainage monitoring, and real-time pH measurement without false triggering or control instability. Performance evaluation examined irrigation response time, defined as the interval between moisture threshold detection and actuator activation, multi-zone processing capability without signal interference, consistency of sensor readings during the 15-day monitoring period, and stability of the solar-powered energy subsystem through battery voltage regulation and sustained charge replenishment. The system's load profile and solar sizing computations were validated against actual operational behavior to confirm uninterrupted off-grid functionality. Usability assessment evaluated the Android-based mobile application in terms of interface clarity, real-time data visualization, responsiveness of control commands, and accessibility of system logs. Expert evaluators from agriculture, electronics, and information technology fields utilized a structured rating instrument to quantify system effectiveness, and mean scores were computed and interpreted using predefined interval classifications.

3. Results and discussion

The results cover the validation of the system design, operational testing of the multi-plot prototype, analysis of soil moisture regulation during field deployment, and structured evaluation of system effectiveness. Solar energy performance, irrigation activation behavior, and multi-zone control stability were examined using recorded monitoring data and comparative moisture logs. Visual documentation of the installed prototype during the 15-day outdoor testing period was included to demonstrate structural and operational condition over time. Soil moisture readings, pump activation records, and stability trends across selected monitoring days were analyzed to assess closed-loop control consistency. In addition, functionality, performance, and usability were evaluated through structured assessment instruments, and weighted mean scores were computed to determine overall system acceptability.

3.1 Design performance of the automated solar-powered drip irrigation system

The automated irrigation framework was implemented using a 150W solar photovoltaic panel, lithium battery storage, charge controller, ESP32 microcontroller, four solenoid valves, four pumps, and independent soil moisture sensors per plot. The energy modeling performed during the design phase was validated during actual operation. Throughout the monitoring period, the solar subsystem maintained stable battery voltage levels, and no power interruptions were recorded. This confirms that the selected photovoltaic capacity was sufficient to sustain continuous sensor monitoring, wireless communication, and pump activation cycles.

The independent irrigation configuration allowed flexible water distribution per zone. Data logs showed that pump activation occurred only in plots where soil moisture fell below programmed threshold values, demonstrating proper threshold-based irrigation logic. The integration of four solenoid valves and four pumps enabled zone isolation, preventing simultaneous water discharge when not required. Real-time soil moisture readings were accurately displayed on the Android Studio mobile application. The user interface successfully reflected percentage moisture levels, pump status, and water tank conditions without transmission delay. The water storage tank maintained adequate supply levels, and drainage remained minimal, indicating efficient drip irrigation distribution.

3.2 Performance of the multi-plot integrated prototype

The operational performance of the developed multi-plot irrigation prototype was evaluated over a 15-day continuous outdoor deployment period. The installed system during this monitoring interval is presented in Figure 7. The images illustrate the physical condition of the structural framework, irrigation layout, and planting plots at regular three-day intervals, providing visual documentation of system stability and sustained functionality under real environmental exposure.

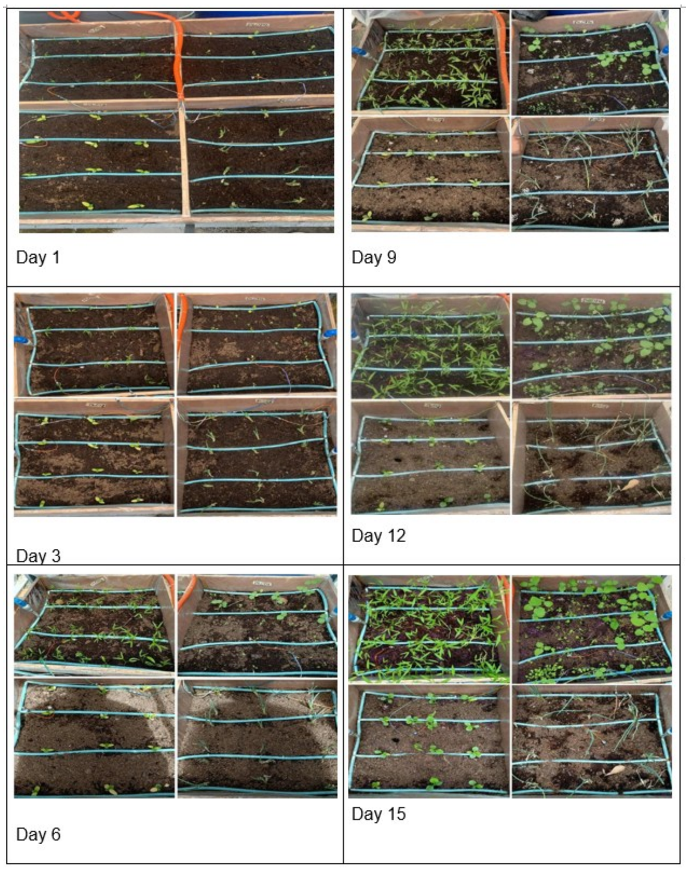
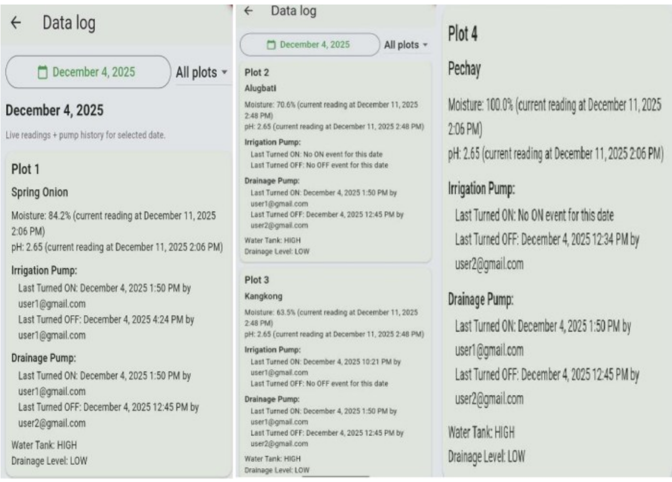


Figure 7. Installed prototype in outdoor testing environment (day 1 to day 15 with 3-day gap)

Throughout the monitoring period, the structural frame remained mechanically stable, with no observed displacement, deformation, or hydraulic leakage. Electrical components and wiring maintained secure connections, and no operational interruptions were recorded. The solar panel maintained its orientation and structural integrity despite outdoor conditions, supporting uninterrupted energy harvesting. The progressive images in Figure 7 further demonstrate consistent plant condition across the four irrigation zones, indicating that soil moisture levels were maintained within programmed threshold ranges. No signs of excessive water accumulation, surface runoff, or soil desiccation were observed, confirming balanced irrigation delivery. The uniform wetting pattern across plots suggests that the drip distribution network operated effectively and that multi-zone control was sustained without interference. Operational continuity was maintained across the entire 15-day duration, with no recorded system shutdown, control failure, or power interruption. The repeated documentation at three-day intervals provides visual confirmation of consistent system performance and validates the durability of the integrated structural, hydraulic, control, and renewable energy subsystems.

3.3 Implementation efficiency and operational stability

Implementation efficiency and operational stability were evaluated using comparative soil moisture logs recorded on Day 1 (December 4, 2025), Day 3 (December 6, 2025), and Day 5 (December 7, 2025), presented in Figures 8, 9, and 10. On Day 1 (Figure 8), soil moisture values were recorded at 84.2% (Plot 1 - Spring Onion), 70.6% (Plot 2 - Alugbati), 63.5% (Plot 3 - Kangkong), and 100.0% (Plot 4 - Pechay). Pump activation events were logged on this day, indicating that irrigation occurred in response to threshold detection. Tank levels were recorded as HIGH, while drainage levels remained LOW, confirming adequate water supply and absence of overflow.



December 4, 2025
Live readings + pump history for selected date.

Plot 1
Spring Onion
Moisture: 84.2% (current reading at December 11, 2025 2:06 PM)
pH: 2.65 (current reading at December 11, 2025 2:06 PM)
Irrigation Pump:
Last Turned ON: December 4, 2025 1:50 PM by user1@gmail.com
Last Turned OFF: December 4, 2025 4:24 PM by user1@gmail.com
Drainage Pump:
Last Turned ON: December 4, 2025 1:50 PM by user1@gmail.com
Last Turned OFF: December 4, 2025 12:45 PM by user2@gmail.com
Water Tank: HIGH
Drainage Level: LOW

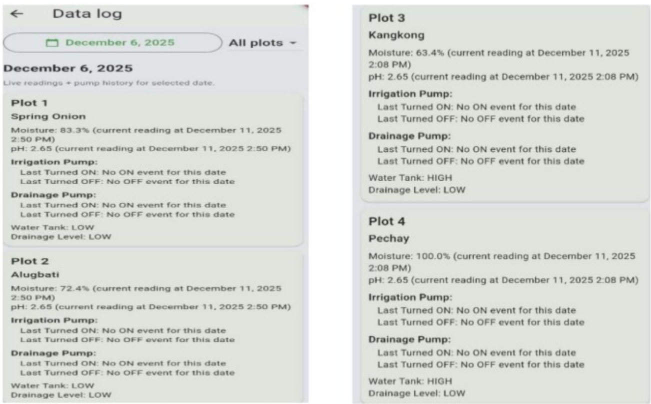
Plot 2
Alugbati
Moisture: 70.6% (current reading at December 11, 2025 2:48 PM)
pH: 2.65 (current reading at December 11, 2025 2:48 PM)
Irrigation Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: No OFF event for this date
Drainage Pump:
Last Turned ON: December 4, 2025 1:50 PM by user1@gmail.com
Last Turned OFF: December 4, 2025 12:45 PM by user2@gmail.com
Water Tank: HIGH
Drainage Level: LOW

Plot 3
Kangkong
Moisture: 63.5% (current reading at December 11, 2025 2:48 PM)
pH: 2.65 (current reading at December 11, 2025 2:48 PM)
Irrigation Pump:
Last Turned ON: December 4, 2025 10:21 PM by user1@gmail.com
Last Turned OFF: No OFF event for this date
Drainage Pump:
Last Turned ON: December 4, 2025 1:50 PM by user1@gmail.com
Last Turned OFF: December 4, 2025 12:45 PM by user2@gmail.com
Water Tank: HIGH
Drainage Level: LOW

Plot 4
Pechay
Moisture: 100.0% (current reading at December 11, 2025 2:06 PM)
pH: 2.65 (current reading at December 11, 2025 2:06 PM)
Irrigation Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: December 4, 2025 12:34 PM by user2@gmail.com
Drainage Pump:
Last Turned ON: December 4, 2025 1:50 PM by user1@gmail.com
Last Turned OFF: December 4, 2025 12:45 PM by user2@gmail.com
Water Tank: HIGH
Drainage Level: LOW

Figure 8. Day 1 soil moisture and irrigation log (December 4, 2025)

By Day 3 (Figure 9), moisture values were 83.3%, 72.4%, 63.4%, and 100.0% across the four plots. No irrigation ON events were recorded for this date, demonstrating that soil moisture levels remained above programmed thresholds and no additional watering was required. The absence of unnecessary pump activation confirms effective demand-based irrigation control. On Day 5 (Figure 10), moisture readings remained within similar ranges at 83.9%, 72.1%, 66.9%, and 100.0%. Pump activation records were limited and corresponded strictly to moisture threshold conditions. Drainage levels remained LOW, and no hydraulic imbalance or overflow was observed.



December 6, 2025
Live readings + pump history for selected date.

Plot 1
Spring Onion
Moisture: 83.3% (current reading at December 11, 2025 2:50 PM)
pH: 2.65 (current reading at December 11, 2025 2:50 PM)
Irrigation Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: No OFF event for this date
Drainage Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: No OFF event for this date
Water Tank: LOW
Drainage Level: LOW

Plot 2
Alugbati
Moisture: 72.4% (current reading at December 11, 2025 2:50 PM)
pH: 2.65 (current reading at December 11, 2025 2:50 PM)
Irrigation Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: No OFF event for this date
Drainage Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: No OFF event for this date
Water Tank: LOW
Drainage Level: LOW

Plot 3
Kangkong
Moisture: 63.4% (current reading at December 11, 2025 2:08 PM)
pH: 2.65 (current reading at December 11, 2025 2:08 PM)
Irrigation Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: No OFF event for this date
Drainage Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: No OFF event for this date
Water Tank: HIGH
Drainage Level: LOW

Plot 4
Pechay
Moisture: 100.0% (current reading at December 11, 2025 2:08 PM)
pH: 2.65 (current reading at December 11, 2025 2:08 PM)
Irrigation Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: No OFF event for this date
Drainage Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: No OFF event for this date
Water Tank: HIGH
Drainage Level: LOW

Figure 9. Day 3 Soil moisture and irrigation log (December 6, 2025)

December 7, 2025
Live readings + pump history for selected date.

Plot 1
Spring Onion
Moisture: 83.9% (current reading at December 11, 2025 2:51 PM)
pH: 2.65 (current reading at December 11, 2025 2:51 PM)
Irrigation Pump:
Last Turned ON: December 7, 2025 9:26 AM by user2@gmail.com
Last Turned OFF: December 7, 2025 9:26 AM by user2@gmail.com
Drainage Pump:
Last Turned ON: December 7, 2025 9:26 AM by user2@gmail.com
Last Turned OFF: December 7, 2025 9:26 AM by user2@gmail.com
Water Tank: LOW
Drainage Level: LOW

Plot 2
Alugbati
Moisture: 72.1% (current reading at December 11, 2025 2:51 PM)
pH: 2.65 (current reading at December 11, 2025 2:51 PM)
Irrigation Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: No OFF event for this date
Drainage Pump:
Last Turned ON: December 7, 2025 9:26 AM by user2@gmail.com
Last Turned OFF: December 7, 2025 9:26 AM by user2@gmail.com
Water Tank: LOW
Drainage Level: LOW

Plot 3
Kangkong
Moisture: 66.9% (current reading at December 11, 2025 2:51 PM)
pH: 2.65 (current reading at December 11, 2025 2:51 PM)
Irrigation Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: December 7, 2025 9:25 AM by user2@gmail.com
Drainage Pump:
Last Turned ON: December 7, 2025 9:26 AM by user2@gmail.com
Last Turned OFF: December 7, 2025 9:26 AM by user2@gmail.com
Water Tank: LOW
Drainage Level: LOW

Plot 4
Pechay
Moisture: 100.0% (current reading at December 11, 2025 2:08 PM)
pH: 2.65 (current reading at December 11, 2025 2:08 PM)
Irrigation Pump:
Last Turned ON: No ON event for this date
Last Turned OFF: No OFF event for this date
Drainage Pump:
Last Turned ON: December 7, 2025 9:26 AM by user2@gmail.com
Last Turned OFF: December 7, 2025 9:26 AM by user2@gmail.com
Water Tank: HIGH
Drainage Level: LOW

Figure 10. Day 5 soil moisture and irrigation log (December 7, 2025)

The temporal stability of moisture regulation is illustrated in Figure 11. The moisture stability trend indicates that variation across the three monitoring days remained within a narrow deviation range (approximately ±2-3%). This minimal fluctuation demonstrates stable closed-loop control and sustained soil moisture regulation. Multi-zone operation remained consistent, with no cross-channel interference, switching delay, or mis-triggering events observed across the monitoring period. The pH value remained constant at 2.65 across all logged days, indicating stable sensor acquisition and uninterrupted data transmission. No system shutdown, communication loss, actuator malfunction, or energy interruption was recorded during the evaluation interval.

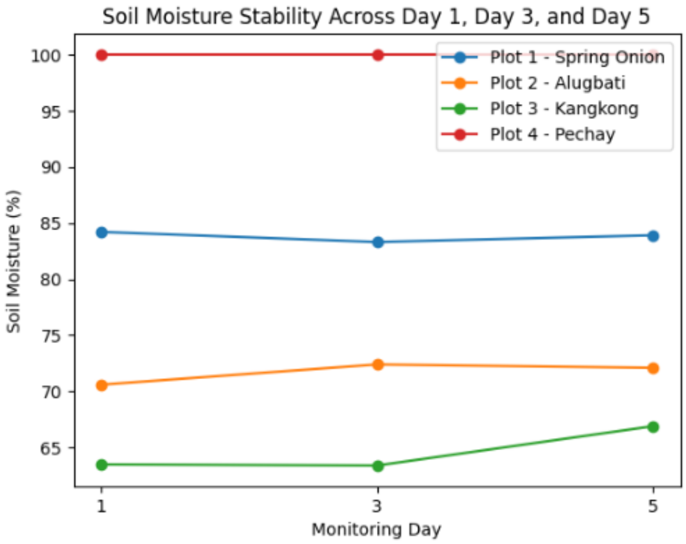


Figure 11. Soil moisture stability trend across day 1, day 3, and day 5

3.4 Evaluation of functionality, performance, and usability

The evaluation results of the Automated Solar-Powered Drip Irrigation System are presented in Table 1, which summarizes the assessment across four respondent groups: Faculty, IT Experts, Farmers, and Agriculturists. The system obtained consistently high ratings in functionality, performance, and usability across all categories, with overall weighted means ranging from 4.80 to 4.83. According to the equivalent point interval interpretation shown in Table 2, all computed means fall within the 4.21-5.00 range, corresponding to an "Excellent" verbal rating.

Table 1. Summary of evaluation result by respondent category

Respondent group	No. of respondents	Functionality	Performance	Usability	Overall weighted mean	Descriptive rating
Faculty	5	4.60	4.92	4.92	4.80	Excellent
IT Experts	5	4.84	4.64	4.92	4.80	Excellent
Farmers	5	4.96	4.68	4.8	4.81	Excellent
Agriculturists	5	4.84	4.72	4.92	4.83	Excellent
Overall mean	20	4.81	4.74	4.89	4.81	Excellent

Faculty respondents assigned an overall weighted mean of 4.80, with performance and usability both rated at 4.92, indicating strong system responsiveness and user interaction capability. IT Experts reported an overall weighted mean of 4.80, with functionality rated at 4.84 and usability at 4.92, suggesting high confidence in system architecture, control logic, and interface design. Farmers provided an overall weighted mean of 4.81, with functionality rated highest at 4.96, reflecting favorable perception of irrigation reliability and practical applicability in agricultural use. Agriculturists recorded the highest overall weighted mean of 4.83, with usability and functionality both rated at 4.92 and 4.84, respectively, indicating strong acceptance from technically knowledgeable agriculturists.

Table 2. Equivalent point interval and verbal interpretation of the mean

Numerical scale	Equivalent point interval	Verbal interpretation
5	4.21-5.00	Excellent
4	3.41-4.20	Very Good
3	2.61-3.40	Good
2	1.81-2.60	Fair
1	1.00-1.80	Poor

The consolidated results in Table 3 show an overall mean of 4.81 for functionality, 4.74 for performance, and 4.89 for usability, with a grand overall mean of 4.81. The usability dimension obtained the highest mean score (4.89), demonstrating that the mobile monitoring interface and control accessibility were highly satisfactory to users. Performance, while slightly lower at 4.74, remained within the "Excellent" category, indicating stable system responsiveness and efficient irrigation execution under real operating conditions.

Table 3. Results of the overall mean of functionality, performance, and usability of the smart home

	Functionality	Performance	Usability	Overall
Mean	4.81	4.74	4.89	4.81
Interpretation	Excellent	Excellent	Excellent	Excellent

The consistency of high ratings across diverse respondent groups suggests strong cross-disciplinary acceptance of the system. The absence of any dimension falling below the "Excellent" threshold confirms that the integrated sensing, renewable energy subsystem, control architecture, and user interface collectively met both technical and practical expectations. Overall, the evaluation results validate the system's reliability, operational efficiency, and user-centered design, supporting its suitability for sustainable and automated home irrigation applications.

4. Conclusion

This study successfully designed, developed, and validated a solar-powered, Wi-Fi-based automated drip irrigation system for home gardening applications. The system operated using a 150 W photovoltaic panel, a 12.8 V-100 Ah (1280 Wh) $LiFePO_4$ battery, and a 15 A MPPT charge controller, which sustained continuous operation without recorded power interruptions during the monitoring period. The ESP32 microcontroller accurately processed inputs from four capacitive soil moisture sensors and independently controlled four pumps and four solenoid valves, enabling reliable multi-zone irrigation. During the 15-day field evaluation, soil moisture levels were consistently maintained within the recommended 60-80% range depending on crop requirement, and irrigation was activated strictly at preset threshold values. No redundant pump activation was observed when moisture remained within acceptable limits, confirming efficient threshold-based control and reduced water wastage. Wireless communication remained stable with no recorded data loss, and the system achieved an overall expert evaluation rating of 4.81 out of 5.00 (Excellent) in functionality, performance, and usability. The findings demonstrate that integrating real-time sensing, automated drip irrigation, and renewable energy provides a technically reliable, energy-autonomous, and cost-feasible solution for improving irrigation precision and minimizing manual intervention in small-scale home gardening.

Future development may integrate closed-loop pH regulation to complement the existing 0-14 pH monitoring capability and incorporate additional environmental sensors such as temperature, humidity, and light intensity to enable adaptive irrigation control. Extended field testing of at least 90 days across multiple crop types and seasonal conditions is also recommended to quantify measurable water savings and yield improvements. A modular control architecture capable of supporting more than four irrigation zones may be developed for semi-commercial applications, while inclusion of an offline communication mode such as Bluetooth or local access point control would improve reliability in areas with unstable Wi-Fi connectivity. Finally, conducting a detailed cost–benefit and payback period analysis is recommended to evaluate economic feasibility and support broader household and small-farm adoption.

Author's declaration

Author contribution

Dominic Olango Cagadas: Conceptualization, Methodology, Software, Investigation, Formal Analysis, Writing – Original Draft. **Cran Leigh Mae Adis Salamanca**: Investigation, Validation, Formal Analysis, Writing – Original Draft, Writing – Review & Editing.

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Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The dataset includes system testing records, soil moisture monitoring logs, prototype evaluation results, and summarized survey responses. However, some raw data are not publicly available to protect participant privacy and confidentiality.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical clearance

This research has obtained ethical approval from the Department of Electronics Technology, University of Science and Technology of Southern Philippines. All procedures involving human participants were conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from all individual participants included in the study prior to their participation.

AI statements

The authors used AI for limited language polishing, grammar improvement, coherence checking, and assistance in preparing responses to reviewer comments. The AI tool was not used to generate research data, analyze results, create tables, produce figures, modify images, or replace the authors' intellectual contribution. The authors manually reviewed, revised, and verified all AI-assisted text against the original study data and manuscript content. The authors take full responsibility for the accuracy, integrity, and final content of the article.

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Researcher and Lecturer Society as the publisher, and the Editor of Innovation in Engineering state that there is no conflict of interest towards this article publication.

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