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Solar-Powered Smart Irrigation for Chilli Plants

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Abstract

The project aims to develop a Solar-power Smart Irrigation System for chilli plants, which are sensitive to water management. This smart water irrigation system should reduce water waste and manual intervention, and encourage the use of renewable energy. It is equipped with multiple sensors, including a soil moisture sensor, a pH sensor, and a close-range ultrasonic water sensor, which are managed by an ESP32 microcontroller to detect real-time soil and environmental conditions. Using the system, water can be optimised for chilli plant growth because it automatically irrigates in accordance with set soil moisture levels. It is solar-powered, using a solar photovoltaic panel and a battery-charging module, making it independent of the grid. It has also used an Internet of Things (IoT) platform, the Blynk application, for real-time tracking and triggering alerts to users via a mobile interface. Empirical observations indicate that this system can ensure the best level of soil moisture, energy efficiency, and non-pollution, and is usable across different sun exposure regimes. It can be helpful for small-scale farming, urban farming, and at-home gardens, and it focuses on the potential of solar energy and smart irrigation for sustainable chilli cultivation.

1. Introduction

Water management is an urgent issue in contemporary agriculture, especially in small-scale agriculture and urban gardening, and a shortage of water resources and energy supply is evident. Traditional irrigation techniques often rely on manual labour and predetermined watering schedules, leading to overuse of water resources and uneven soil moisture. These restrictions underscore the need for an automated, energy-efficient irrigation solution.

Recently, advances in microcontroller-based control systems, sensors, and renewable energy have enabled the introduction of smart irrigation systems that optimise water use based on real-time soil conditions [1]-[9]. By combining soil moisture monitoring with automated control, only the required water is used, and irrigation enhances plant well-being while minimising water waste. Solar energy integration also enhances the system's sustainability, as it can operate without grid power [4]-[7].

The project aims to develop a solar-powered smart irrigation system for chilli plants. The system uses an ESP32 microcontroller to process data from sensors, including a soil moisture sensor, a pH sensor, and a water level sensor, to automatically operate a water pump. Also, an Internet of Things (IoT) platform is implemented to provide real-time monitoring and user engagement via the mobile application. The aim of the proposed system is to provide a cost-effective, self-driven, and environmentally friendly irrigation system suitable for domestic gardens and small food production operations.

2. Methodology

In this project, the methodology has been designed to allow the systematic development, implementation, and testing of a solar-powered smart irrigation system. The system design, hardware integration, software development, and system testing constitute the overall process, as depicted in the block diagrams and flowcharts shown in the following sections.

2.1 System Development Flow

The system has a logical control loop in which, after initialising the ESP32 microcontroller, LCD display, and sensors, it connects to Wi-Fi and the Blynk IoT platform. It works by constantly reading the data of the soil moisture sensor, the level of water sensor, and the pH sensor, and when the soil moisture decreases to a predetermined default threshold, the water pump is turned on, but when the water level is too low, a refill valve is triggered, and a user notification is made. The flow is summarised as follows: update the local display, relay data to the mobile app, and repeat the process to ensure continuous, automated monitoring. Fig. 1 shows the flowchart of the irrigation system's working mechanism.

Fig. 1 *Flowchart of the irrigation system working mechanism.*

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2.2 Hardware Design and Integration

The hardware prototype integrates a power supply unit, a control case, sensors, and actuators into a single unit. The power supply is also a 5W, 5 V solar panel connected to a charging board and a Lithium-Ion battery, providing a sustainable off-grid energy storage component. The ESP32 microcontroller serves as the central processing unit and communicates with the soil moisture sensor, the ultrasonic sensor for tank depth, and the pH sensor to collect environmental data. Relays with a single channel are used to safely isolate the microcontroller from high-power actuators, such as the water pump and solenoid valve. Fig. 2 indicates a block diagram of the system working mechanism.

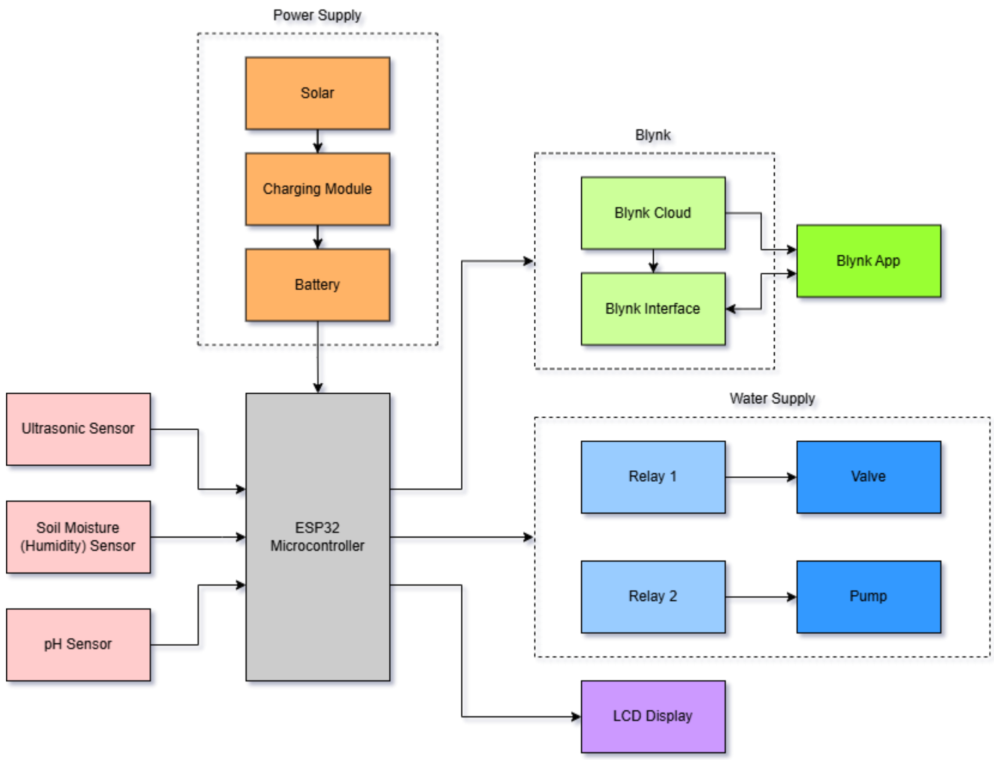

Fig. 2 *Block diagram of the system working mechanism.*

2.3 Software Development

The system develops software with the Arduino IDE, a programming environment that runs on the ESP32 to implement control algorithms and communication protocols. The code logic sets automation levels: the pump is turned on when the soil moisture is below 30% and off when it is above 60%; the refill valve is turned on when the water level is below 30%. The software also supports the Blynk mobile application, providing a user interface of virtual widgets to visualise current data in real-time and to send push notifications for alerts or to control a system.

2.4 System Operation

The system is intended to be autonomous. Therefore, it has a 24-hour power supply, which it uses solar power kept in the battery to operate during the day and night. The system also automatically controls irrigation based on real-time soil moisture sensor feedback, so they do not need to use manual watering schedules. At the same time, it tracks the quality and quantity of water and displays status messages on the local LCD and the Blynk dashboard at a different location, so users can monitor the process through the app.

2.5 Testing and Validation

The methodology covers rigorous testing of the real prototype to confirm the stability of power generation and the accuracy of the sensors. The concept of solar integration was confirmed by testing the dependence of voltage on irradiance; the correlations remained constant at irradiance levels above 700 W/m2. The functionality testing ensured the actuators responded appropriately to sensor thresholds, such as activating the pump when moisture reached 30, and the IoT aspect was capable of relaying real-time data and activation alerts to the end-user's smartphone.

3. Result and Discussion

In this section, the author presents the performance of the created solar-powered smart irrigation system based on experimental testing and the system's behaviour. The assessment focuses on the sensor's accuracy, irrigation response, power efficiency, and IoT observation capabilities.

3.1 Sensor Performance Analysis

The system used three main sensors to acquire environmental information, which were handled by the ESP32 microcontroller to ensure accurate, reliable measurements. The soil moisture sensor was an analogue sensor that provided real-time feedback on soil humidity by continually monitoring soil moisture content. According to the programmed control logic, the water pump came on when the moisture content was below the dry threshold of 30 per cent and stopped when the moisture content was above the wet threshold of 60 per cent. The ultrasonic sensor measured the distance to the sensor and the pinacol surface in the storage tank, then converted the distance to a percentage (water quantity) to determine water levels. Once the water level fell below 30, the system recognised a low-level scenario and activated the refill mechanism. Moreover, the pH sensor checked the quality of irrigation water and sent alert messages when the measured pH deviated outside the recommended testing range of 7.5 to 8.5, ensuring that the water provided did not harm plant growth.

3.2 Irrigation System Response

The irrigation system was found to be an efficient, autonomous system, as it reacted rationally to real-time sensor inputs without human input. Once the soil moisture dropped below 30 per cent, the ESP32 activated the water pump via a relay module, triggering it to start. A hysteresis control strategy was used to eliminate rapid switching and minimise mechanical wear by automatically turning the pump off when the moisture level exceeded 60. At the same time, the self-monitored the reservoir water level; the ultrasonic sensor noted that the tank had dropped below 30 per cent, the solenoid valve was then activated to fill the tank. This was a safety mechanism that prevented dry-pumping conditions and ensured a constant water supply for irrigation. All in all, these reactions supported the idea that the system could maintain optimal soil conditions and defend parts of the system.

3.3 Solar Power and Energy Performance

The interaction between the solar panel, the charging module, and the battery storage unit was used to determine the performance of the power supply subsystem. Fig. 3 shows the 5 V, 5 W solar panel, which serves as the main energy source for the system. The measurements of solar irradiance were also taken during a normal operating day. We analysed the availability of solar power, as shown in Fig. 4, and the numerical figures are provided in Table 1. The findings showed an evident change in irradiance levels over time, with the highest levels recorded during the midday hours.

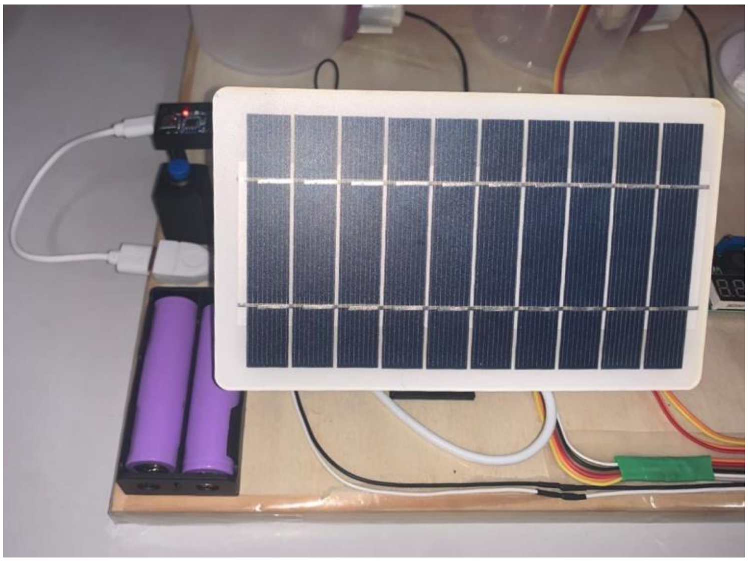

Fig. 3 *The 5 V, 5 W solar panel used as the primary energy source for the solar-powered irrigation system.*

Table 1 *Solar irradiance data recorded over time during system operation.*

Time	Irradiance
8:00	100
9:00	200
10:00	300
11:00	500
12:00	700
13:00	900
14:00	1000
15:00	800
16:00	600
17:00	400

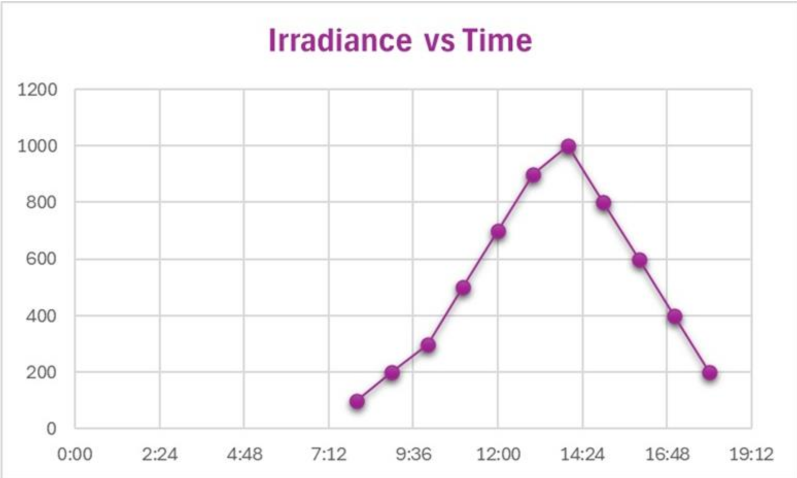

Fig. 4 *Variation of solar irradiance with time over a typical operating day.*

A close correlation between solar irradiance and the solar panel output voltage was observed, as illustrated in Fig. 5. At irradiance levels above 700 W/m2, the panel maintained a consistent voltage of 5.0-5.6 V, which was acceptable for charging and system operation. Table 2 shows the solar panel's output power at varying irradiance levels; the panel's power increases with increasing sunlight intensity. The charging unit controlled the voltage delivered to the Lithium-Ion battery, avoided overvoltage, and ensured safe storage of the energy. The battery was able to store surplus energy during peak sunlight hours, allowing the system to continue operating even during low irradiance times, such as early mornings and late afternoons.

Table 2 *Output power of the solar panel under different irradiance levels.*

Test	Solar Irradiance (W/m^2)	PV Output Voltage (V)
1	100	2.1
2	200	3
3	300	3.8
4	400	4.3
5	500	4.6
6	600	4.8
7	700	5
8	800	5.2
9	900	5.4
10	1000	5.6

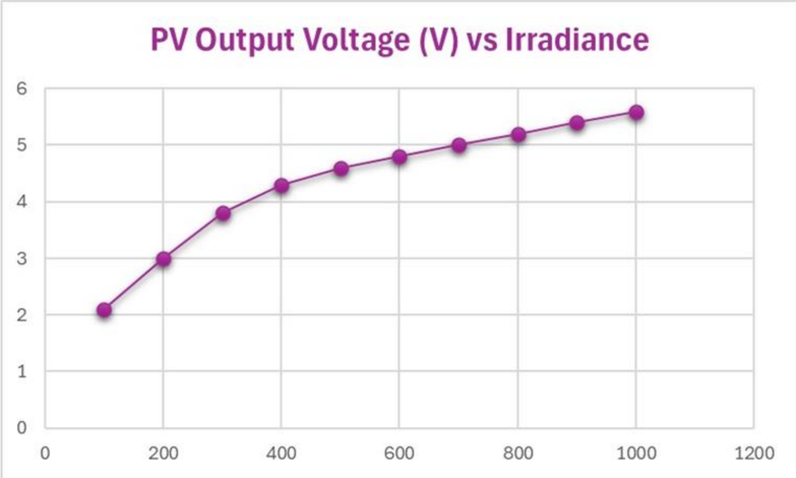

Fig. 5 *Relationship between solar irradiance and output voltage of the 5 V, 5 W solar panel.*

3.4 IoT Monitoring and User Interface

The Blynk mobile app was used for remote monitoring and for user interaction with the system, and it provided a user-friendly interface for graphical data visualisation. The virtual widgets that display key system parameters, including soil moisture level, water tank level, and pH, enable the user to monitor system conditions at their convenience. Stable wireless communication between the ESP32 microcontroller and the Blynk cloud platform was maintained during system operation to ensure data transmission quality. Moreover, the system was set to automatically push a notification to the user's smartphone if abnormal conditions were observed, such as a low water level or a pH level outside the acceptable thresholds. This was an advantage since corrective measures were taken promptly, and the system usually became more reliable.

3.5 Overall System Evaluation

The developed smart irrigation prototype operated effectively as an integrated system, combining renewable solar energy, sensor-based monitoring, automated control logic, and IoT connectivity. The complete physical assembly of the prototype is shown in Fig. 6. System evaluation confirmed stable power management, accurate sensor readings, and reliable actuation of irrigation components. The system successfully maintained optimal soil moisture levels while minimising water wastage and reducing manual intervention. Furthermore, its ability to operate independently of the electrical grid demonstrated its suitability for deployment in resource-constrained and remote agricultural environments. Overall, the prototype proved to be a practical and sustainable solution for small-scale chilli cultivation.

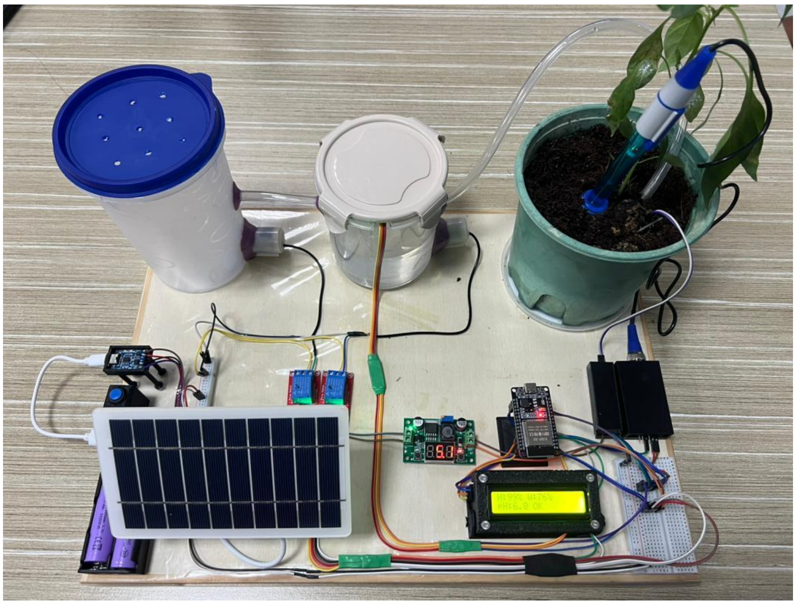

Fig. 6 *Overall prototype of the smart irrigation system.*

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4. Conclusion

This project achieved its goal of designing and installing a Solar-Powered Smart Irrigation System for chilli plants to overcome the challenges of manual irrigation, water waste, and reliance on non-renewable energy. The system also includes automated control systems with soil moisture sensors powered by solar energy, making it affordable and environmentally friendly to grow. It measures water, pH, and soil water in real time, and adjusts irrigation according to plant needs. Remote monitoring and notifications can be improved in usability with the IoT using the Blynk application, requiring minimal physical supervision. Performance reviews show that the system optimises soil moisture and minimises water waste, enhancing the efficient, healthy growth of plants. Further development might involve the introduction of more environmental sensors, data logging, and scanning across larger areas of agriculture.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Inshyrah Harlina Alyea Laila Md Armaludin, Mohammad Faiz Liew Abdullah;* ***data collection:*** *Inshyrah Harlina Alyea Laila Md Armaludin;* ***analysis and interpretation of results:*** *Inshyrah Harlina Alyea Laila Md Armaludin, Mohammad Faiz Liew Abdullah;* ***draft manuscript preparation:*** *Inshyrah Harlina Alyea Laila Md Armaludin, Mohammad Faiz Liew Abdullah. All authors reviewed the results and approved the final version of the manuscript.*

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