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IOT ENABLED AND SOLAR POWERED SMART IRRIGATION SYSTEMS FOR SUSTAINABLE FARMING

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KEYWORDS

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Soil Moisture
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ABSTRACT

Rapid urbanization and changing lifestyles have increased the demand for sustainable methods of producing organic vegetables at home to ensure access to healthy, fresh, and nutrient-rich food. Home gardening offers numerous environmental and social benefits, maintaining these gardens manually introduce challenges include inconsistent watering schedules, overuse of water resources, and labors required for maintenance. It monitor the plant health and yield increase the overall efficiency and sustainability of urban gardening systems. Through online monitoring, gardeners can remotely observe soil moisture status, and system perform ance using user-friendly mobile application. Based on the sensor feedback, the microcontroller activates a water pump to deliver water only when necessary, thereby reducing waste and promoting optimal plant growth. The system is powered entirely by a solar panel, ensuring energy efficiency and eliminating dependency on the conventional power grid. The proposed system design is scalable and cost-effective, mafor home vegetable gardens, and greenhouse operations.

1. INTRODUCTION

Agriculture is the backbone of our country, and efficient use of water has become extremely important due to increasing water scarcity, irregular rainfall, and wastage caused by manual irrigation. Many farmers still depend on guesswork to decide when to water their fields. This often results in over-irrigation or under irrigation, affecting crop health and decreasing yield. Water is one of the most critical resources for agriculture and home gardening, yet its efficient utilization has become increasingly challenging due to water scarcity, irregular rainfall, rapid urbanization, and climate variability [7]. Traditional irrigation practices often rely on manual observation and fixed watering schedules, which can result in over-irrigation or under-irrigation, leading to water wastage, nutrient loss, reduced plant health, and lower productivity. These challenges highlight the need for intelligent irrigation solutions capable of monitoring environmental conditions and delivering water precisely when required [14].

Recent advances in the Internet of Things (IoT), sensor technologies, and renewable energy have enabled the development of smart irrigation systems that automate water management while reducing human intervention. Although several IoT-based irrigation solutions have been proposed for conventional agriculture, relatively few systems are specifically designed for urban home and rooftop gardening with integrated water, nutrient, and energy management. The growing popularity of home gardening for producing fresh organic vegetables further emphasizes the importance of sustainable, low-cost, and energy-efficient smart gardening solutions.

This paper presents the design and implementation of a Solar-Powered IoT-Enabled Smart Irrigation System for home garden vegetable cultivation, as illustrated in Figure 1. The proposed system combines soil moisture sensing, temperature and humidity monitoring, water-level detection sensors to continuously assess soil moisture and nutrient availability. An ESP32-based microcontroller processes the sensor data in real time and automatically controls a relay-operated submersible water pump, supplying water and nutrients only when necessary. This intelligent decision-making mechanism minimizes water and fertilizer wastage while maintaining optimal growing conditions for plants. The proposed Solar-Powered IoT-Enabled Smart Irrigation System has a wide range of applications in modern agriculture, urban gardening, and sustainable farming practices. Its intelligent monitoring and automated irrigation capabilities make it suitable for both small-scale and large-scale cultivation.

Agriculture

The system can be deployed in agricultural fields to provide automated and efficient irrigation for a variety of crops, including wheat, rice, pulses, vegetables, and fruit orchards [10]. By continuously monitoring soil moisture and controlling irrigation accordingly, it helps improve crop productivity while reducing water and energy consumption.

Home Gardens, Terrace Gardens, and Greenhouses

The proposed system is well suited for home gardens, rooftop gardens, kitchen gardens, plant nurseries, and greenhouse cultivation. It supports the healthy growth of vegetables, herbs, flowers, and ornamental plants by maintaining optimum soil moisture levels with minimal human intervention [2].

Remote and Rural Farming Areas

Since the system operates using solar energy, it is particularly beneficial in remote villages and off-grid agricultural regions where a reliable electricity supply is unavailable [12]. The renewable energy source ensures uninterrupted operation while reducing dependence on conventional power.

Water Conservation and Sustainable Irrigation

The intelligent irrigation mechanism minimizes water wastage by supplying water only when required. This feature is especially valuable in water-scarce and drought-prone regions, where

efficient water management is essential for sustainable agriculture and environmental conservation [15].

Smart Agriculture and IoT-Based Farming

The system supports IoT-enabled monitoring and control through wireless connectivity, allowing users to view real-time soil moisture, irrigation status, and other environmental parameters on a mobile application or web dashboard. Future enhancements can incorporate cloud computing, artificial intelligence, weather forecasting, and predictive analytics to further improve irrigation scheduling and precision farming practices [11, 17].

2. MATERIALS AND METHODS

The entire system is powered by a photovoltaic solar panel, making it energy-efficient, environmentally friendly, and independent of the conventional power grid. IoT connectivity enables users to remotely monitor sensor readings, receive notifications, and control irrigation through a mobile application, thereby improving convenience and operational efficiency [5, 19] . By integrating smart sensing, automated irrigation, renewable energy, and online monitoring, the proposed system provides an economical and scalable solution for sustainable home gardening.

The developed system is particularly suitable for cultivating organic vegetables such as tomato, chili, cauliflower, lady finger (okra), brinjal (eggplant), French beans, coriander, potato, onion, and garlic. Intelligent water and nutrient management supports healthier plant growth, enhances vegetable productivity, conserves water and energy, reduces labor requirements, and promotes year-round cultivation [2, 8]. Consequently, the proposed IoT-enabled solar-powered smart gardening system contributes to sustainable urban agriculture, improves household food security, and encourages environmentally responsible production of nutritious organic vegetables [3, 10]. The following hardware and components were used in the development of the IoT-based automated irrigation system given in table 1.

TABLE 1: COMPONENTS USED FOR PROPOSED SYSTEM

Component	Functions
Solar Panel (10W 12V)	Powers the entire system independently, no external electricity required
Solar Charge Controller	regulates voltage and charges a battery
Battery (Li-ion)	outputs stable power to the ESP and the relay module
ESP32 Microcontroller	To process sensor data and controlling the water pump
Soil Moisture Sensor	Detects soil moisture to determine when watering is needed
Mini Water Pump	Pumps water from the reservoir to vegetable plants
Relay Module	Switches the pump ON/OFF based on sensor data
Breadboard & Jumper Wires	Connects and supports circuit setup
Water Tubing	Store water to distribute through pump to vegetable plants
Small Farming Tray Setup	placing the soil-moisture sensor inside the soil for demonstration
Bluetooth Module	Allows local wireless control through a mobile app

3. METHODOLOGY

The proposed Solar-Powered IoT-Enabled Smart Irrigation System operates through four integrated stages: soil moisture measurement, intelligent automation, solar energy management,

and feedback-based irrigation control [15, 16]. Initially, a soil moisture sensor continuously measures the water content of the soil using the principle of electrical resistance or capacitance, where dry soil exhibits higher resistance and wet soil exhibits lower resistance. The measured sensor values are transmitted to the ESP32 microcontroller, which compares the moisture level with a predefined threshold and automatically controls a relay module to switch the water pump ON or OFF, thereby ensuring irrigation only when required. The entire system is powered by a photovoltaic solar panel that converts sunlight into electrical energy, which is stored in a rechargeable battery and supplies uninterrupted power to the microcontroller, sensors, and water pump [7, 20]. During operation, the system continuously monitors soil conditions through a closed-loop feedback mechanism, dynamically adjusting irrigation based on real-time sensor data to maintain optimum soil moisture, minimize water wastage, reduce energy consumption, and promote healthy plant growth. The overall methodology is illustrated through the proposed block diagram of proposed System Design shown in figure 1 and figure 2 shows the system flow for operational sequence, and intelligent decision-making process.

The proposed Solar-Powered IoT-Enabled Smart Irrigation System follows a systematic methodology that integrates soil sensing, intelligent automation, renewable energy, and feedback-based irrigation control [1, 18]. The objective is to optimize water utilization, reduce manual intervention, and ensure healthy growth of home garden vegetables through real-time monitoring and automated decision-making [18. The overall methodology consists of four sequential stages.

Step 1: Soil Moisture Measurement

The irrigation process begins with continuous monitoring of soil moisture using a soil moisture sensor [4]. The sensor determines the moisture content by measuring the electrical resistance or capacitance of the soil. Dry soil exhibits higher electrical resistance, whereas wet soil has lower resistance. The measured analog values are transmitted to the ESP32 microcontroller for further processing. Additional sensors such as temperature, humidity, water-level sensors can also be integrated to monitor environmental conditions and nutrient availability

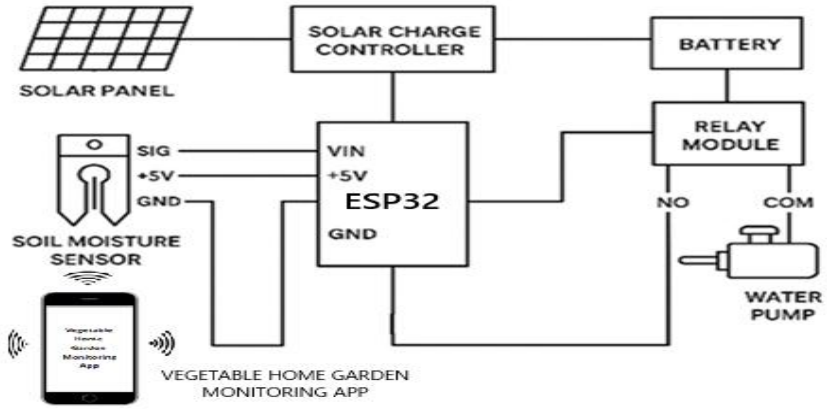


Fig.1: Proposed System Design

Step 2: Intelligent Automation Using ESP32

The ESP32 microcontroller acts as the central processing unit of the system. It continuously reads sensor data and compares the measured soil moisture with a predefined threshold value. If the moisture level falls below the specified limit, the controller activates the relay module to switch ON the submersible water pump. When the desired moisture level is

achieved, the relay automatically switches OFF the pump, thereby preventing over-irrigation and conserving water.

Step 3: Solar Energy Generation and Power Management

The system is powered by a photovoltaic solar panel that converts sunlight into electrical energy. The generated energy is stored in a rechargeable battery, ensuring uninterrupted operation during cloudy conditions and nighttime. This renewable energy source eliminates dependence on conventional electricity and enhances the sustainability of the irrigation system.

Step 4: Feedback Control and IoT Monitoring

The proposed system employs a closed-loop feedback mechanism that continuously monitors soil conditions during irrigation. Sensor readings are updated in real time and transmitted to the BlynkIoT platform through the ESP32 Wi-Fi module. Users can monitor soil moisture, pump status, battery condition, and irrigation performance remotely using a smartphone or web dashboard. Based on the feedback received from the sensors, the controller dynamically adjusts irrigation, ensuring efficient water and nutrient management while minimizing energy consumption.

Efficient irrigation management is critical for sustaining agricultural productivity under increasing water scarcity and climate variability. This study presents a solar-powered, IoT-enabled intelligent irrigation system enhanced with data-driven optimization techniques for selected vegetable crops such as Tomato, chili, cauliflower, lady finger, brinjal, French beans, coriander, potato, onion, garlic, Cucumber, carrot, cabbage, broccoli, spinach, beetroot, ginger, green pea, ridge guard, bitter guard, capsicum, drumstick, calabash, fenugreek, and dill leaves etc. The proposed system integrates soil moisture sensing, an ESP32-based control unit, and photovoltaic energy harvesting to enable autonomous irrigation.

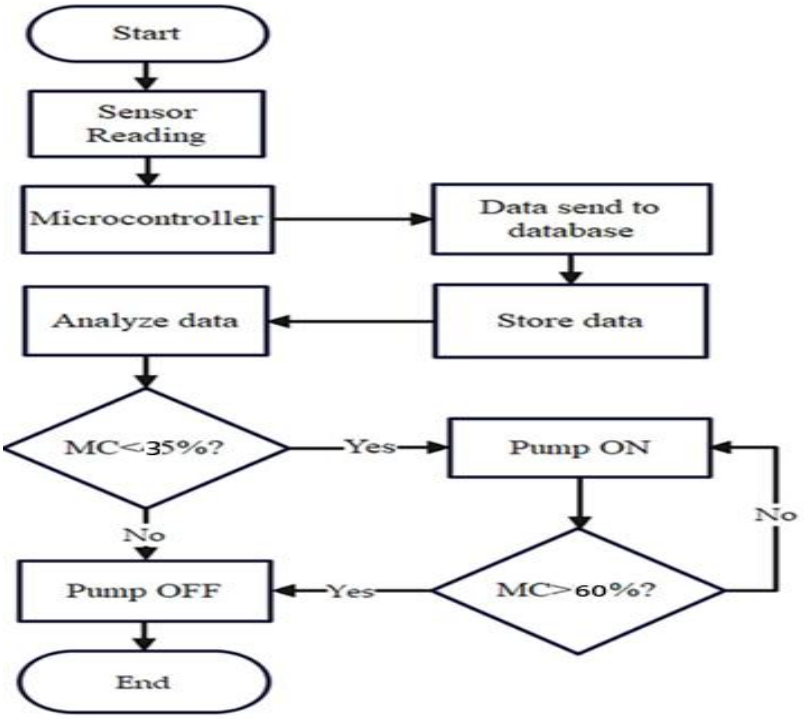


Fig.2: Flow Diagram

4. RESULTS AND DISCUSSION

The prototype of the proposed system is constructed by first arranging the model farm on a flat surface and placing the soil-moisture sensor inside the soil shown in fig.3contains names of different components used for setup. The sensor wires are connected to the ESP32 microcontroller, which receives soil moisture readings continuously. A solar panel is connected to a solar charge controller, which regulates voltage and charges a battery. The battery outputs stable power to the ESP and the relay module. The mini water pump is attached to the relay so the microcontroller can turn the pump ON/OFF automatically. Water flows through tubing to the demo farm until the soil reaches the required moisture level.



Fig.3: Physical Layout of Proposed System Prototype

4.1 Proposed System Architecture and Operational Modules

Experimental evaluation demonstrates that the proposed system significantly enhances irrigation performance by reducing water consumption, improving irrigation efficiency, and minimizing dependence on conventional electrical energy through solar-powered operation [9]. Furthermore, the integration of mobile App and IoT-based monitoring enhances decision-making capabilities, making the system suitable for scalable deployment in precision agriculture and smart urban gardening [5].The proposed Solar-Powered IoT-Enabled Smart Irrigation System is organized into five functional modules that work together to provide intelligent, energy-efficient, and automated irrigation for home garden vegetable cultivation.

Module 1: Solar Power Generation

The system is powered by a photovoltaic solar panel that converts solar energy into electrical energy. The generated power is stored in a rechargeable battery to ensure continuous operation during periods of low sunlight or at night, thereby reducing dependence on the conventional power grid.

Module 2: Soil and Environmental Monitoring

A soil moisture sensor continuously measures the moisture content of the soil and transmits the readings to the ESP32 microcontroller. Additional sensors, such as temperature, humidity, water-level, and EC/TDS sensors, may also be incorporated to monitor environmental conditions and nutrient availability for efficient irrigation management.

Module 3: Intelligent Decision-Making

The ESP32 microcontroller processes the sensor data in real time and compares the measured soil moisture with a predefined threshold value. When the moisture level falls below the threshold, the controller activates a relay module to switch the irrigation pump ON. If the soil moisture is within the desired range, the pump remains OFF, preventing unnecessary irrigation and conserving water.

Module 4: Automated Irrigation

Once activated, the submersible water pump delivers water through the irrigation tubing to the home garden. Water is supplied only until the soil reaches the desired moisture level, ensuring optimal hydration while minimizing water loss and promoting healthy plant growth.

Module 5: Automatic Pump Control

The irrigation process is continuously monitored by the microcontroller. As soon as the soil moisture reaches the preset threshold, the relay automatically switches the pump OFF. This closed-loop control mechanism prevents over-irrigation, improves water-use efficiency, and reduces energy consumption.

4.2 IoT Integration Using the Blynk Platform

To provide real-time monitoring and remote accessibility, the proposed system is integrated with the BlynkIoT platform, enabling users to supervise and control irrigation through a smartphone or web-based dashboard. The ESP32 microcontroller communicates with the Blynk Cloud via Wi-Fi, allowing sensor data and system status to be accessed from any location with an internet connection. The Blynk application provides a user-friendly interface through which users can monitor real-time soil moisture levels, observe the operational status of the irrigation pump, check the battery voltage and solar power status, and receive notifications whenever the soil moisture falls below the specified threshold, demonstration setup given in fir. 4(a). In addition to automatic irrigation, users can manually operate the water pump whenever required, providing greater flexibility and control over the irrigation process.

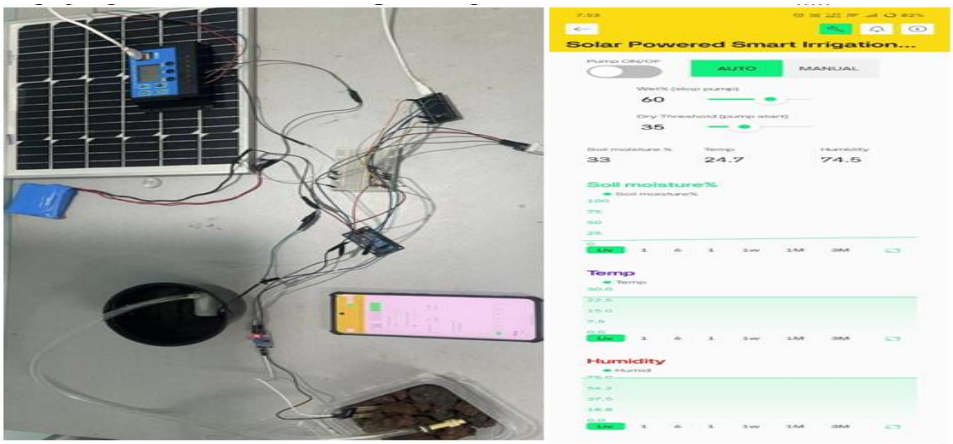
4.3 Operational Workflow of the Blynk System

The ESP32 continuously acquires sensor data and uploads the information to the Blynk Cloud through a Wi-Fi connection. The cloud platform synchronizes the data with the Blynk mobile application and web dashboard, allowing users to monitor live sensor readings. When the soil moisture decreases below the predefined threshold, the system automatically activates the irrigation pump and simultaneously sends a notification to the user's mobile device. If necessary, users can manually override the automatic operation using the virtual control buttons available in the Blynk application. This combination of intelligent automation and remote monitoring significantly improves irrigation efficiency, reliability, and user convenience.

4.4 QR Code-Based Dashboard Access

To simplify system demonstration and evaluation, the developed prototype incorporates a QR code that provides direct access to the Blynk dashboard. By scanning the QR code using a smartphone, users, teachers, or evaluators can instantly access the live monitoring interface without requiring manual configuration or programming.

The dashboard displays real-time soil moisture values, irrigation pump status, battery and solar power information, and other sensor readings, shown in fig. 4(b). It also enables manual pump control and provides live updates as environmental conditions change. This feature enhances system usability, demonstrates the practical implementation of IoT technology in smart agriculture, and offers an interactive platform for monitoring and controlling the irrigation system in real time.



(a) Setup of Proposed System (b) Mobile App for System

Fig.4: Live Demonstration of Proposed System Operation using Mobile App

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Bluetooth Module	Allows local wireless control through a mobile app

5. CONCLUSION

This project presents the successful design and implementation of a Solar Powered IoT-Enabled Smart Irrigation System for home vegetable gardens, providing an intelligent, energy-efficient, and sustainable solution for urban agriculture. The system continuously monitors soil moisture levels and automatically controls irrigation based on predefined moisture thresholds specific to different vegetables, thereby preventing both under-irrigation and over-irrigation. This precision irrigation approach ensures optimum soil moisture for healthy plant growth while significantly reducing water wastage. The integration of soil moisture sensors, a

microcontroller, Bluetooth-based mobile monitoring, and a solar photovoltaic power system enables reliable, low-cost, and eco-friendly operation without dependence on continuous grid electricity. The system minimizes human intervention, reduces maintenance effort, and supports the cultivation of fresh, organic, and nutrient-rich vegetables within limited urban spaces.

Furthermore, the proposed system encourages sustainable water management, renewable energy utilization, and smart gardening practices, making it an ideal solution for households, rooftop gardens, balconies, kitchen gardens, schools, and community gardens. Its modular and scalable architecture allows easy adaptation to different crops, soil types, and environmental conditions. Overall, the proposed smart irrigation system contributes to water conservation, improved vegetable productivity, reduced operational costs, and environmentally responsible food production. Future enhancements may include Wi-Fi/cloud connectivity for remote monitoring, weather-based irrigation scheduling, artificial intelligence for crop-specific decision-making, automated nutrient and fertilizer dosing, disease prediction, and comprehensive data analytics to further improve the efficiency, reliability, and sustainability of smart home gardening systems.

6. DECLARATIONS

6.1 Use of AI Technology
The authors not used AI-based tools for editing purposes.

6.2 Conflicts of Interest Declaration
All authors declare that they have no conflicts of interest.

6.3 Informed Consent Declaration
No, my research did not involve human participants.

6.4 Funding
This work received no external funding.

6.5 Data Availability Statement
Data will be available on request.

6.6 Ethics and Consent Human Participants
No human participants were involved in study, Not Applicable.

6.7 Consent to publish Identifiable Images
Images and photos created by author.

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