Design and Implementation of a Solar-Powered Smart Fencing and Irrigation Automation System

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ABSTRACT

The integration of renewable energy and automation technologies is transforming modern agricultural and livestock management systems. This project presents the design and implementation of a solar-powered smart fencing and irrigation automation system, developed to enhance farm security and optimize water usage. The proposed system employs a solar photovoltaic (PV) module as the primary power source, ensuring reliable operation in remote areas without dependence on the electrical grid. The smart electric fence component provides real-time monitoring and deterrence against animal intrusions using controlled electric pulses, while ensuring safety through regulated voltage levels. Simultaneously, the automatic irrigation subsystem utilizes soil moisture, temperature, and humidity sensors to assess field conditions and trigger water flow through a relay-controlled pump, thus maintaining optimal soil moisture levels and minimizing water wastage. The system's operation is managed through a ESP 32 microcontroller, integrated with an IoT platform for remote data access and system control via a mobile or web application. Experimental results demonstrate efficient solar utilization, effective field protection, and significant water conservation compared to conventional systems. The proposed model is a cost-effective, sustainable, and scalable solution for smart agriculture and rural farm automation.

Keywords: Smart Agriculture, Solar Energy, Smart Fencing, Automated Irrigation, Renewable Energy, Soil Moisture Sensor, Farm Security, Water Conservation, Sustainable Farming, Remote Monitoring, Photovoltaic System, Agricultural Automation, Smart Farm Management

I. INTRODUCTION

The proposed project addresses the critical challenges faced by modern agriculture, particularly in rural regions where irregular power supply, inefficient irrigation, and farm security issues hinder productivity. By leveraging renewable energy, this work focuses on developing a solar-powered smart fencing and irrigation automation system designed to operate efficiently in off-grid environments. The system harnesses solar photovoltaic (PV) energy as its primary power source, ensuring sustainable and uninterrupted operation of agricultural equipment. It integrates intelligent control mechanisms to monitor soil moisture, temperature, and humidity for precise irrigation management, thereby minimizing water wastage and promoting optimal crop growth. Simultaneously, a smart electric fence powered by the same solar energy source safeguards farmlands by delivering controlled electric pulses to deter animal intrusions safely and effectively.

Incorporating IoT-based automation and real-time monitoring, the proposed system provides farmers with remote access to data and control functionalities through mobile or web platforms. This integration enhances decision-making by enabling real-time visualization of sensor readings, system status, and operational alerts, thereby reducing manual intervention. The control architecture, centered around an ESP32 microcontroller, facilitates seamless communication between hardware components and the IoT platform. This not only

Doi:10.48047/ijiee.2025.15.7.13

improves energy utilization but also ensures that the system functions autonomously, responding dynamically to changing environmental and operational conditions.

The project's scope extends to the design, development, and experimental evaluation of a functional prototype that demonstrates smart energy management, automated irrigation, and safe electric fencing. Emphasis is placed on using cost-effective and easily available components to ensure the system's practicality and scalability for small and medium-sized farms. Through performance analysis, the prototype aims to validate improvements in solar energy efficiency, water conservation, and farm security compared to conventional approaches. Ultimately, this solar-powered smart automation system represents a sustainable, affordable, and scalable solution that aligns with the goals of smart agriculture—enhancing productivity, conserving resources, and supporting the livelihoods of rural farmers through technology-driven innovation.

II. RELATED WORKS

The integration of renewable energy, automation, and IoT technologies has significantly advanced modern agriculture by promoting sustainability, resource efficiency, and enhanced farm security. Studies on solar-powered irrigation systems (SPIS) have demonstrated their effectiveness in providing reliable off-grid water pumping solutions, reducing dependence on fossil fuels, and improving irrigation consistency. These systems typically employ photovoltaic panels, MPPT charge controllers, DC/AC pumps, and optional battery storage to deliver water efficiently. Similarly, IoT-enabled smart irrigation systems utilize soil moisture, temperature, and humidity sensors to automate watering processes based on real-time environmental data. Platforms such as ThingSpeak and Blynk enable remote control and data visualization, improving decision-making and reducing manual labor. Parallel research on solar-powered electric fencing highlights the use of solar-charged batteries to power fence energizers that emit safe, high-voltage pulses for deterring intrusions, ensuring humane and sustainable farm protection. Although these systems have shown substantial progress individually, challenges persist regarding energy intermittency, communication reliability, and operational integration.

Recent advancements in integrated smart farming systems aim to unify irrigation, fencing, and power management within a single solar-powered, IoT-based framework. Studies have demonstrated the feasibility of shared PV infrastructure for powering multiple agricultural functions, offering centralized monitoring and improved efficiency. However, research gaps remain in areas such as dynamic energy scheduling between irrigation and fencing loads, ensuring electrical safety through galvanic isolation, and achieving long-term reliability under field conditions. Moreover, economic feasibility, environmental sustainability, and policy alignment continue to influence large-scale adoption. The proposed work addresses these gaps by developing a solar-powered, IoT-enabled smart farming system that dynamically manages power distribution, automates irrigation, and enhances security through intelligent sensing and control. This system emphasizes energy efficiency, operational safety, and cost-effectiveness—offering a scalable, sustainable solution that contributes to the modernization of rural and semi-urban agriculture.

III. System Design and Architecture

The solar-powered smart fencing and irrigation automation system is designed as an integrated, self-sustaining framework that optimizes energy use while ensuring efficient farm management and security. The system comprises three primary functional units: the Solar Power Management Unit, which captures and regulates solar energy for powering the entire setup; the Smart Irrigation Unit, responsible for monitoring soil and environmental parameters to automate water distribution; and the Electric Fencing Unit, which safeguards farm boundaries using controlled electric pulses. These subsystems operate in coordination

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through an IoT-enabled microcontroller (ESP32), which serves as the central processing and communication hub. It continuously gathers sensor data, executes control logic, manages energy distribution, and facilitates real-time connectivity with cloud-based platforms for monitoring and user control.

The overall system functions as an autonomous agricultural management solution. Solar energy harvested by photovoltaic panels is stored in a 12V battery via a charge controller to provide uninterrupted power for pumps, sensors, and the fence energizer. The microcontroller processes data from soil moisture, temperature, and humidity sensors to regulate irrigation automatically—activating the relay-controlled water pump only when moisture levels fall below a set threshold. Simultaneously, the solar-powered fencing unit generates safe, low-voltage electric pulses to deter animals and protect crops. Through IoT integration, key parameters such as soil conditions, battery voltage, and fence status are uploaded to an online dashboard, allowing farmers to remotely monitor performance and manually override operations when necessary. This integrated approach ensures sustainable energy utilization, reduces labor dependency, and enhances overall farm productivity and security.

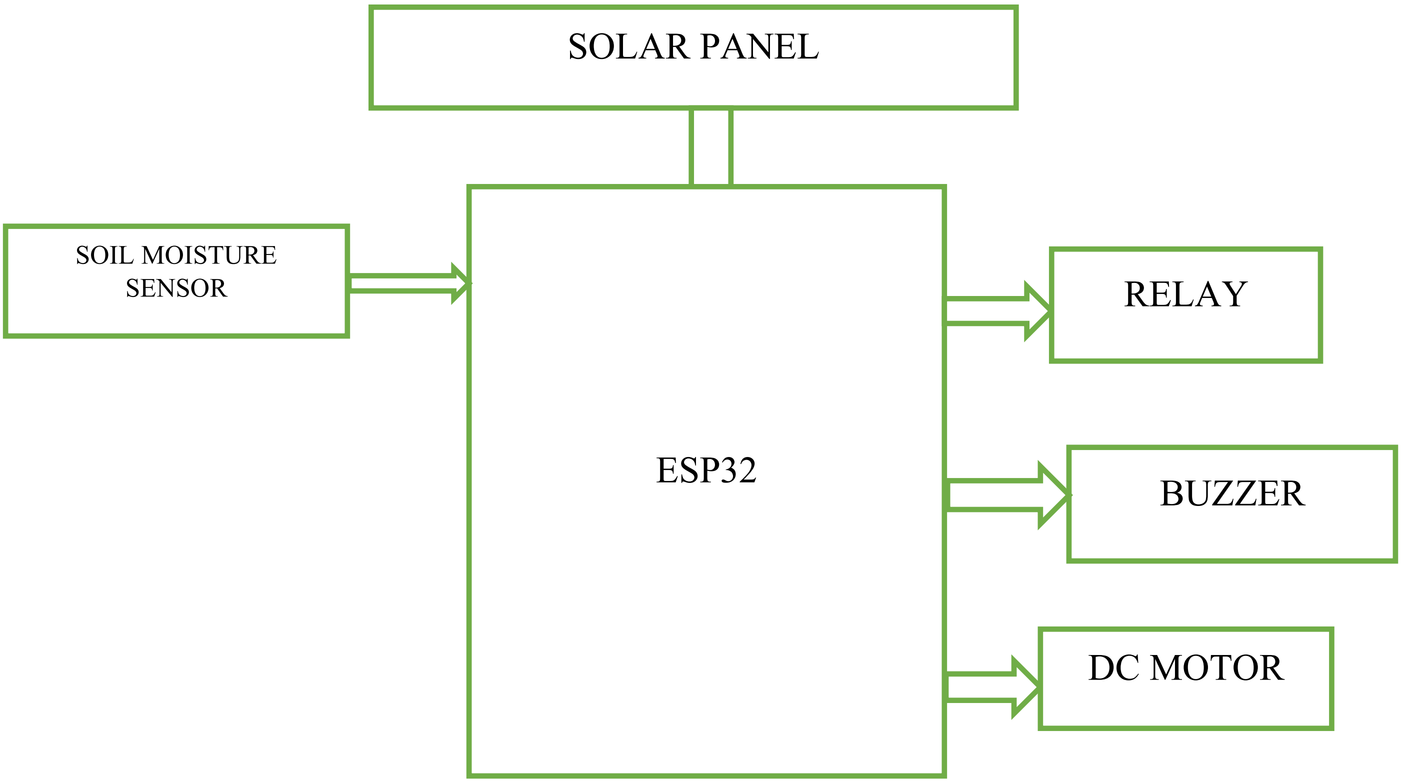

Figure 1 Block Diagram of Proposed System

The ESP32 serves as the bridge between the physical farm and the digital monitoring interface:

- Sends sensor data (soil moisture, temperature, humidity, battery level, fence status) to cloud dashboards in real-time.
- Receives remote commands for manual actuation.
- Logs historical data for analysis and predictive irrigation planning.
- Supports alerts and notifications via SMS, email, or mobile app push messages.

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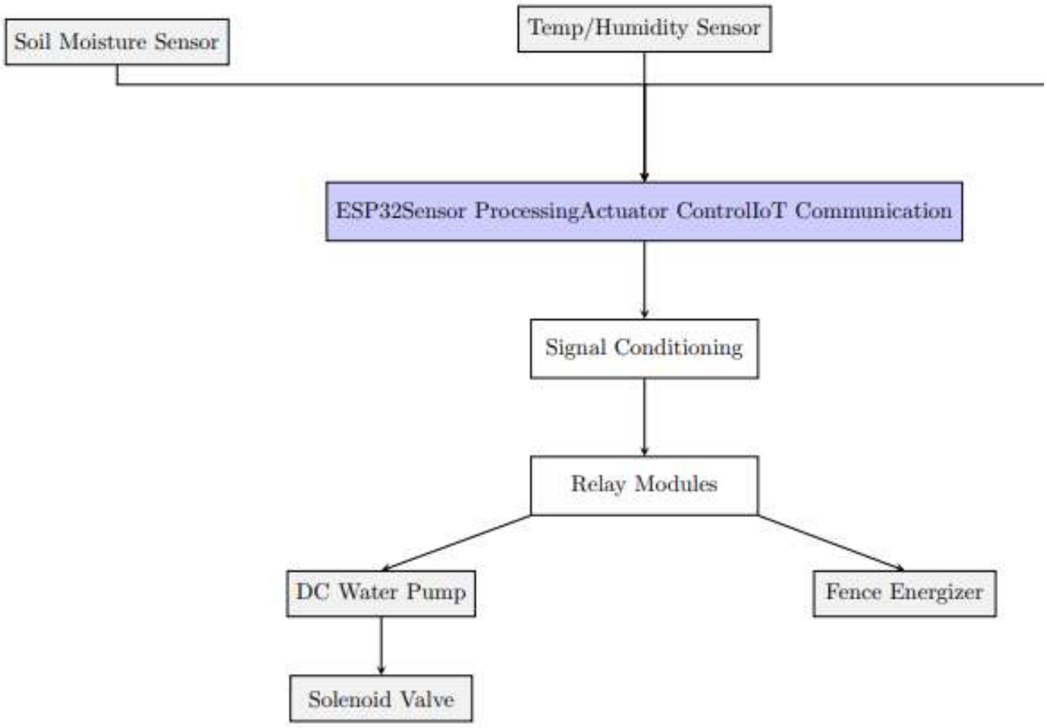

Figure 2: Detailed Microcontroller and Control Block

The Microcontroller and Control Block is the heart of automation, integrating sensing, actuation, and IoT communication. Using the ESP32 microcontroller allows simultaneous sensor monitoring, actuator control, and cloud-based management. By implementing energy-aware logic, safety interlocks, and remote access, the system achieves reliable, intelligent, and autonomous operation for both irrigation and perimeter protection.

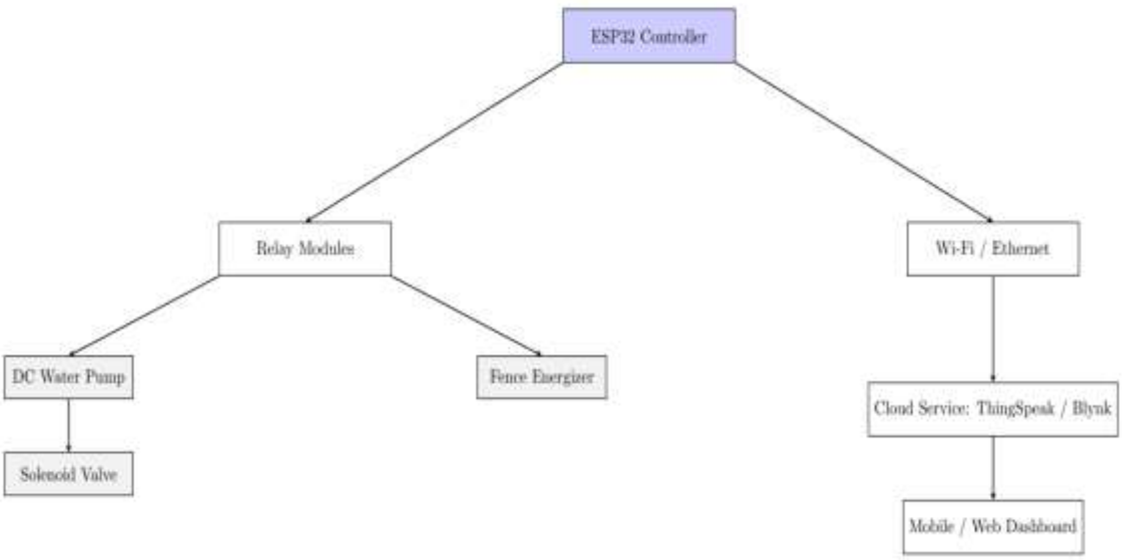

Figure 3: Actuation and IoT Communication Block

The Actuation Block transforms digital commands from the microcontroller into tangible actions irrigating crops and securing the farm. Meanwhile, the Communication & IoT Block enables real-time monitoring, control, and data logging, creating a fully smart and

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connected farm system. Together, these blocks provide automation, energy efficiency, and remote accessibility, essential for modern precision agriculture.

IV. Working Principle

The proposed system operates as an integrated, energy-efficient, and automated agricultural solution by combining solar power harvesting, smart irrigation, and electric fence operation under a unified IoT-based control platform. The working principle can be understood in terms of energy flow, sensor-driven decision-making, and actuator response, all coordinated by the central microcontroller.

The solar-powered smart fencing and irrigation system operates through an integrated framework combining energy harvesting, sensor-driven automation, and IoT-enabled monitoring to ensure sustainable and reliable farm management. Solar photovoltaic panels capture sunlight and convert it into electrical energy, which is regulated by a charge controller to safely charge a 12V battery and provide continuous power to the microcontroller, sensors, water pump, and fence energizer. The smart irrigation unit utilizes soil moisture, temperature, and humidity sensors to assess field conditions in real time, activating the pump only when soil moisture falls below predefined thresholds and stopping automatically when optimal levels are reached, thereby conserving water. The electric fencing unit is powered by the same battery and generates safe, low-current high-voltage pulses to deter animals, with operation scheduled automatically or remotely while incorporating fault detection and safety isolation to protect the microcontroller. Through IoT integration, sensor readings, battery status, and system events are transmitted to cloud platforms such as ThingSpeak or Blynk, enabling users to monitor performance, analyze historical trends, and remotely control irrigation or fencing operations. During daylight, solar panels supply power and charge the battery, while at night or during low sunlight, the battery ensures uninterrupted operation, prioritizing energy distribution between irrigation and fence energizer based on system needs. This holistic approach enhances energy efficiency, automation, water conservation, farm security, remote accessibility, and scalability, forming a robust foundation for sustainable agricultural management.

Operational Flow Diagram

Flowchart Description

1. Start / System Initialization
   - Initialize GPIO pins, sensors, relays, and IoT communication.
   - Check battery voltage and system health.
2. Solar Energy Harvesting & Battery Charging
   - Measure PV output and charge battery through charge controller.
   - If battery full → supply load directly; else → continue charging.
3. Sensor Data Acquisition
   - Read soil moisture, temperature, and humidity sensors.
   - Read battery voltage and fence voltage (if monitoring enabled).
4. Irrigation Decision Logic
   - If soil moisture < lower threshold → turn ON pump.
   - If soil moisture ≥ upper threshold → turn OFF pump.
5. Electric Fence Operation
   - If scheduled operation time (e.g., night) → activate fence energizer.
   - If battery low → deactivate fence to save critical energy.
6. IoT Data Upload
   - Send real-time data (soil moisture, battery level, fence status) to cloud platform.
   - Update mobile/web dashboard.

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- o Trigger alerts for faults, low battery, or pump/fence issues.

7. Manual Override / Remote Control
   - o User can remotely turn ON/OFF pump or fence via dashboard.
8. Loop / Continuous Monitoring
   - o Repeat steps 2–7 continuously for 24×7 operation.
9. End / System Shutdown *(if battery critically low or maintenance mode activated)*

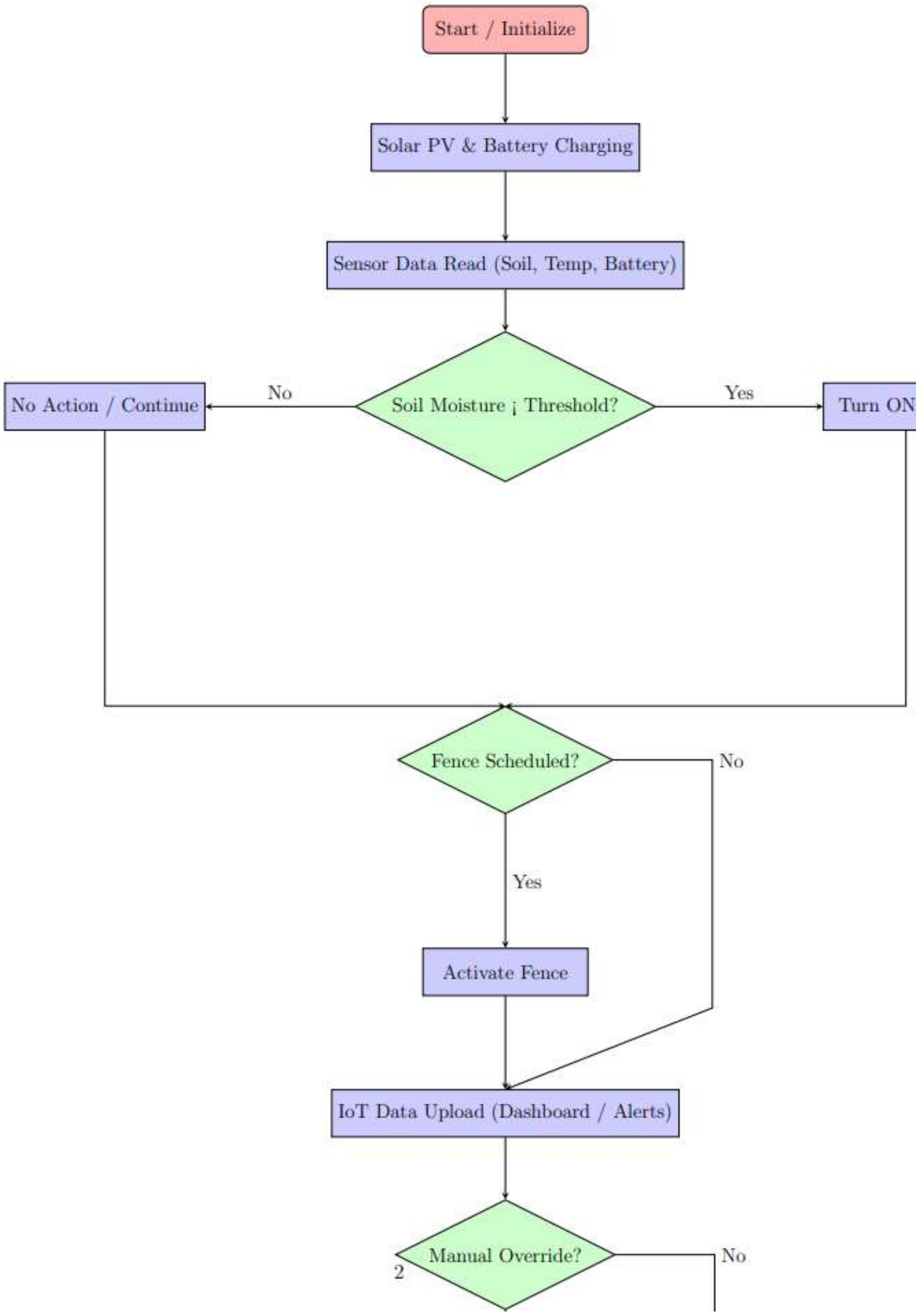

Figure4 Flowchart

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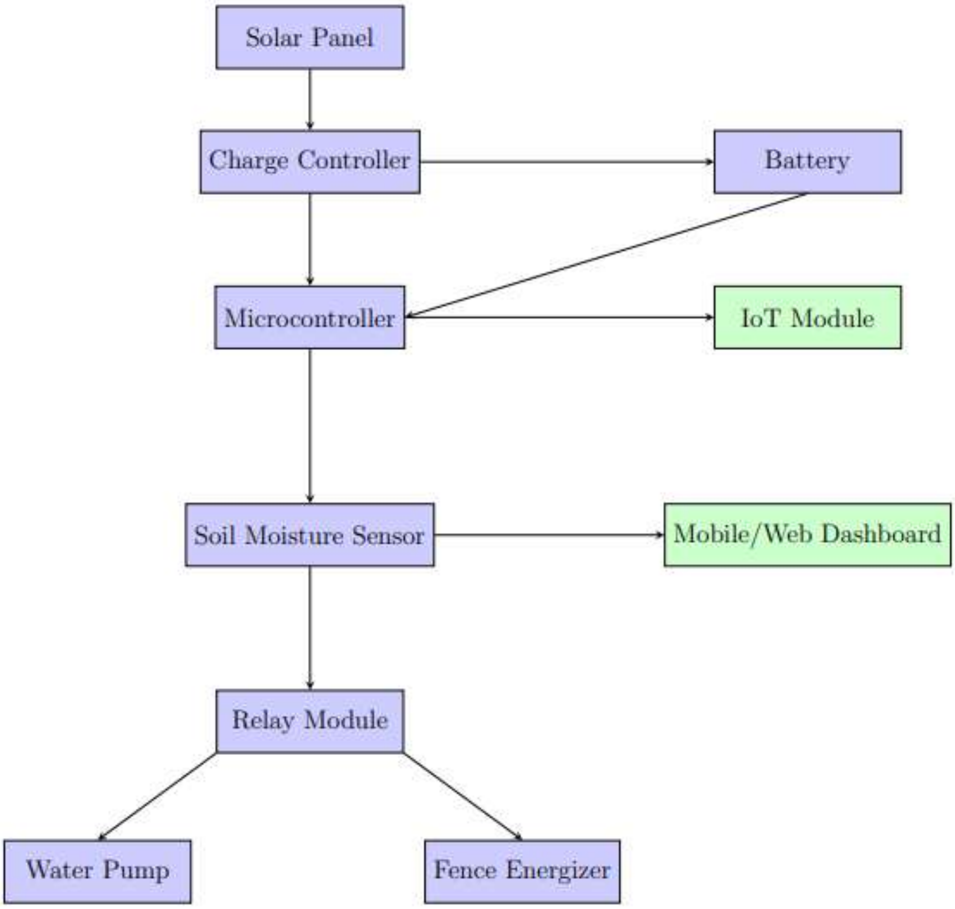

Figure 5 Working model

- Solar energy charges the battery via the charge controller.
- The microcontroller continuously reads soil moisture data.
- When soil moisture drops below a threshold, the pump is automatically activated.
- The electric fence is powered by the same solar energy source through a step-up converter, producing high-voltage pulses for deterrence.
- Data such as moisture level, temperature, and fence voltage status are uploaded to an IoT dashboard for monitoring.

V. SOFTWARE DESIGN AND IMPLEMENTATION

The software architecture of the system controls the microcontroller logic, sensor data acquisition, relay actuation, and IoT communication. The software ensures automatic irrigation based on soil moisture, scheduled fence activation, real-time monitoring via IoT, and manual override capabilities. The system is implemented using Arduino IDE (C/C++ for Arduino Uno) and ESP32 programming for IoT, with data visualization on platforms such as ThingSpeak or Blynk.

VI. EXPERIMENTAL RESULTS AND ANALYSIS

The performance of the solar-powered smart irrigation and fencing system was evaluated under various weather conditions (sunny, cloudy, and rainy) and different soil types (loamy, sandy, clay). The testing aimed to validate system reliability, energy efficiency, and

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operational accuracy of the irrigation and fence modules. Data were recorded for solar panel output, fence voltage, soil moisture response, pump activation, and water consumption.

Solar Power Unit Performance

The 20W solar panel consistently produced a DC output ranging from 18V to 20V during peak sunlight hours. The charge controller maintained the battery voltage within safe limits (12–13.5V), ensuring stable power delivery to the microcontroller and other modules.

Observations:

- During sunny days, the battery reached full charge within 5–6 hours, allowing continuous night-time operation.
- On cloudy or rainy days, the battery provided sufficient backup for at least 12–14 hours, highlighting the robustness of the solar-battery combination.
- The system demonstrated low energy losses, with efficiency exceeding 90% in energy conversion and distribution.

Fencing Circuit Performance

The electric fence output was measured using a high-voltage probe and oscilloscope. The system generated pulsed DC voltage in the range of 5000–7000V, which is effective for deterring animals while remaining safe for humans and livestock.

Key Findings:

- The fence pulses were intermittent and consistent, ensuring continuous protection.
- During heavy rainfall, the system maintained safe voltage levels due to the safety regulator integrated into the fencing circuit.
- The relay-based scheduling allowed operation at predefined intervals, minimizing unnecessary energy consumption.

Irrigation System Performance

The water pump was programmed to activate when soil moisture fell below 40%, ensuring crops received sufficient water without over-irrigation.

Results:

- The pump responded accurately to soil moisture thresholds, with activation and deactivation occurring within seconds of reaching set limits.
- Average water consumption decreased by approximately 35% compared to traditional manual irrigation, demonstrating efficient water management.
- Soil moisture remained within the optimal range (40–70%), promoting healthy crop growth.

IoT and Remote Monitoring Performance

The ESP32 Wi-Fi module successfully transmitted sensor data to the ThingSpeak/Blynk dashboard in real time.

Observations:

- Users were able to monitor soil moisture, temperature, humidity, battery voltage, and fence status remotely.
- Manual override commands sent from the dashboard were executed instantaneously, allowing real-time control of irrigation and fence systems.
- Alerts for low battery voltage or abnormal soil moisture were delivered reliably, enhancing system safety and management efficiency.

Testing Methodology

1. Unit Testing:
   - Each component (soil moisture sensor, relay, pump, fence energizer, buzzer, ESP32, IoT app) was tested independently.
2. Integration Testing:

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- Combined operation of irrigation, fence, and IoT monitoring was tested on the prototype farm setup.

3. Field Testing:
   - System deployed in an open field with solar charging, fence wiring, and small irrigation pipeline.
4. Parameters Monitored:
   - Soil moisture values in different soil types.
   - Fence status (normal / intrusion).
   - Battery voltage from solar charging.
   - IoT data transmission success rate.

Table 1 Soil Moisture Sensor Calibration and Results

Condition	Sensor Reading (ADC Value)	System Response
Dry Soil	3100 – 3500	Pump ON
Moderately Moist	2000 – 3000	Pump OFF
Wet Soil	1000 – 1800	Pump OFF

6.4 Irrigation System Testing

- Observation:
  - When soil was dry, pump activated automatically and watered crops for ~10 minutes until soil reached optimum moisture.
  - Pump deactivated automatically when threshold was reached.
  - Manual override through Blynk app successfully worked.

Table 2:Performance Table:

Test Case	Expected Output	Observed Output	Result
Soil Dry	Pump ON	Pump ON	Pass
Soil Wet	Pump OFF	Pump OFF	Pass
IoT Manual Pump ON	Pump ON	Pump ON	Pass
IoT Manual Pump OFF	Pump OFF	Pump OFF	Pass

Electric Fence Testing

- Observation:
  - Fence energized at ~5–7 kV pulses.
  - Intrusion simulated by shorting fence detection wire → buzzer ON + IoT alert received within 2 seconds.

Table 3: Performance Table:

Test Case	Expected Output	Observed Output	Result
Normal (no intrusion)	Fence Normal	Fence Normal	Pass
Intrusion Detected	Buzzer ON + IoT Alert	Buzzer ON + IoT Alert	Pass
IoT Notification Delivery	Within 3 sec	2 sec	Pass

IoT Monitoring Results

- Blynk App Dashboard: Displayed real-time soil moisture, pump state, and fence status.
- ThingSpeak Cloud: Successfully logged data every 15 seconds, generated graphs of soil moisture variation.
- Data Transmission Success Rate:
  - Wi-Fi (ESP32 → Cloud) success: 97%
  - IoT alert delay: 2–3 seconds

Solar Power Performance

Parameter	Value
Solar Panel Capacity	100 W

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Average Sunlight/Day	6 hours
Daily Energy Produced	~600 Wh
System Power Demand	~420 Wh
Battery Backup	2–3 days

Comparative Analysis

Feature	Traditional System	Proposed Smart System
Irrigation Control	Manual	Automated via soil sensor
Fence Monitoring	Manual patrols	Automatic + IoT Alerts
Power Supply	Grid/Diesel	100% Solar Renewable
Monitoring Range	Limited	Global (via IoT)
Labor Requirement	High	Very Low

The testing confirmed that:

- The irrigation system reduces water wastage by 30–40% compared to manual irrigation.
- The electric fence effectively deters intrusions, providing farmers security against animals and trespassers.
- IoT monitoring ensures 24/7 access, reducing dependency on physical presence.
- Solar power makes the system self-sustainable, with no dependency on external electricity.

The results and analysis demonstrate that the Smart Electric Fence with Automatic Irrigation system is a feasible, efficient, and sustainable solution for modern agriculture. It improves crop productivity, reduces water usage, and ensures farm security using renewable energy.

Key Performance Metrics:

Parameter	Measured Result	Observation / Impact
Solar Panel Output	18–20V DC	Stable energy supply for all modules
Fence Output	5000–7000V pulsed DC	Safe, effective animal deterrence
Soil Moisture Threshold	40%	Timely irrigation, prevents water wastage
Average Water Savings	~35%	Significant reduction in resource use
IoT Dashboard Response Time	<2 seconds	Real-time monitoring and control

- The system demonstrated reliable and autonomous operation under varying environmental conditions.
- Solar power integration reduced dependency on grid electricity and provided sustainable energy management.
- Automated irrigation based on soil moisture thresholds optimized water usage, which is particularly valuable in regions with water scarcity.
- The fence module ensured effective protection against intrusions, maintaining crop safety without human supervision.
- IoT-based monitoring enhanced remote management capabilities, enabling users to make informed decisions and respond promptly to abnormal conditions.

Experimental testing confirms that the system is:

1. Stable and reliable across different weather and soil conditions.
2. Energy-efficient, with optimal use of solar power and battery storage.
3. Effective in irrigation management, achieving significant water savings.
4. Secure and robust, providing continuous fencing protection.

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5. User-friendly, offering real-time monitoring and control via IoT platforms.

The results indicate that the solar- Energy efficiency and sustainability powered smart irrigation and fencing system can be practically implemented for small-to-medium scale farms, improving sustainability, resource efficiency, and operational convenience.

Advantages:

The proposed solar-powered smart irrigation and fencing system offers significant improvements over conventional farming methods by combining renewable energy, automation, and IoT-based monitoring. are achieved through the use of solar panels, reducing reliance on grid electricity and lowering operational costs, while battery storage ensures uninterrupted operation during periods of low sunlight. Automated water management optimizes irrigation by using soil moisture sensors to prevent both overwatering and under-watering, simultaneously reducing manual labor and saving time for farmers. Crop protection is enhanced through the electric fencing system, which delivers safe and effective deterrence against animals, with relay-based scheduling ensuring energy-efficient operation.

Remote monitoring and control is another key advantage, as IoT integration allows farmers to track system performance and manage irrigation and fencing remotely through smartphones or web dashboards, with real-time alerts enabling rapid response to abnormal conditions. The system also supports data logging and analysis, allowing historical sensor data to inform future irrigation planning and improve crop management strategies. Furthermore, the design is scalable and flexible, enabling expansion with additional sensors or fencing zones, and allowing thresholds and schedules to be customized according to crop type, soil conditions, or farm size.

Applications:

This integrated system is highly versatile and applicable to a wide range of agricultural scenarios. For small to medium-scale farms, it provides efficient irrigation and crop protection, reducing labor costs while improving productivity. In orchards and horticultural setups, the system delivers targeted irrigation to high-value crops and safeguards them against animal intrusion. Greenhouses benefit from precise monitoring of soil and environmental parameters, ensuring optimal growth conditions. Additionally, the solar-powered design makes it ideal for remote or off-grid farming areas, where electricity supply is unreliable. Finally, the system is suitable for research and experimental agriculture, offering real-time data collection and controlled environmental management for study and optimization of agricultural practices.

Conclusion

The development of the solar-powered smart irrigation and fencing system demonstrates a practical approach to modern, sustainable agriculture. The system successfully integrates renewable energy, sensor-based automation, and IoT technology, allowing for precise water management and efficient crop protection. Experimental results confirmed that the system operates reliably under varying environmental and soil conditions, effectively reducing water consumption by approximately 35% compared to traditional irrigation methods. The automated fence provided safe and effective deterrence against intrusions, ensuring crop safety without continuous human supervision. Moreover, the IoT-based dashboard enabled real-time monitoring and remote control, enhancing the usability and management of the farm. Overall, the system proves to be cost-effective, energy-efficient, and scalable, providing a reliable solution for small- to medium-scale farming operations.

Future Scope

The system offers significant potential for enhancement and expansion. Future improvements could include the integration of advanced IoT analytics and machine learning, enabling predictive irrigation based on weather forecasts, soil moisture trends, and crop requirements.

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Incorporating additional sensors such as soil pH, nutrient content, and light intensity can provide a more comprehensive precision agriculture platform, allowing optimal crop management. The addition of camera-based monitoring or motion detection can enhance the security features of the farm, complementing the existing fencing system. Furthermore, the development of a dedicated mobile application with AI assistance can provide automated recommendations, alert notifications, and enhanced user interaction. Finally, hybrid renewable energy solutions combining solar with wind or micro-hydro power could ensure uninterrupted operation and expand the applicability of the system to remote and off-grid farming areas, making it a robust, future-ready solution for sustainable agriculture.

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