Solar-Powered Smart Irrigation System

M. Sakib Rahman
Dept. of Computer Science and Engineering
University of Asia Pacific, Dhaka, Bangladesh
Email: 22201240@uap-bd.edu

Shahrier Alam Shimul
Dept. of Computer Science and Engineering
University of Asia Pacific, Dhaka, Bangladesh
Email: 22201227@uap-bd.edu

Salman Nur Ramim
Dept. of Computer Science and Engineering
University of Asia Pacific, Dhaka, Bangladesh
Email: 22201239@uap-bd.edu

Abstract

This project introduces a farming system powered by green energy cultural setup combining dual-axis sun tracking through auto watering cuts power use while saving water handling stuff with an ESP32 chip at its core, sensor unit using four light detectors to track sun movement detection yet two servo motors to keep tweaking the solar panels need to face the right way to make most electricity. Yet, ground type matters too moisture is tracked with a capacitive sensor, since it gives quick feedback when conditions shift - especially useful during sudden humidity changes Letting the system water plants on its own using a switch that runs on low-power current pump. Extra sensors - like a rain detector, DHT11 temp and humidity unit, then an ultrasonic sensor for water height with the MQ-2 gas sensor - boosts tracking of air conditions a solar panel powers a 7.4V bat tury - keeping power steady without the grid. Also links up with smart devices online using ESP32 lets you check data live from afar on a nearby network server or a Telegram Bot sending alerts. Test outcomes demonstrate around a quarter to nearly one third more electricity from sunlight using improved tech - boosted performance seen across tests Unlike static panels, while also improving how water's used less waste. This setup offers an affordable, sustainable yet practical fix that works well on small farms, growing plants on rooftops, while also working in countryside farming areas.

Keywords

Microcontroller, IoT, Solar Tracking, Smart Irrigation, Embedded Systems, Automation

1.Introduction

1.1 Background & Motivation

Farming today's hit by less water, pricier energy, yet folks still rely on old-school watering methods that waste a lot. Outdated setups guzzle way too much H2O while leaning hard on electric grids or fuel-powered pumps - neither cheap nor green. Meanwhile, standard solar panels just sit there; they don't follow the sun, so they miss out on peak light, slashing how much juice they make.

To tackle these issues, the project introduces a solar-powered smart watering setup combining two-way sun tracking with auto irrigation based on soil dampness. Using clean energy alongside sensors, it's built to boost power efficiency while cutting down excess water use. The goal is to deliver an eco-friendly tech option suited for small farms or countryside farming needs.

1.2 Problem Statement

- Frozen solar setups can't follow the sun's path - instead, they stay put while light moves across the sky
- Overall, this leads to less energy being produced.
- Hand-watering often causes uneven moisture levels plus waste of supplies
- waste - also possible harm to crops.
- Most countryside spots don't have steady power, so automatic
- Farming setups paired together are tough to set up.

1.3 Objectives

The main goals here include these points:

- Build a two-way solar tracker so it follows the sun better
- solar panels grab sunlight to make power.
- Automate watering by checking soil dampness live
- surements.
- Run the whole setup on sunlight, storing extra juice in a battery
- keep a spare ready so things run smooth.
- Incorporate IoT-based monitoring of environmental pa-
- like dampness in the ground, how warm it is, or how thick the air feels,
- rain yet gas levels.

1.4 Scope

- Good for tiny farms or growing stuff on rooftops,
- and home gardening.
- Built to work in remote areas without power or money
- where there's not much power available.
- Can grow later on, maybe adding smart watering using AI tools down the line
- tuning setups, forecast tools with clever automation
- farming systems.

1.5 Related Works

Recent research points to fast progress in farming tech using sensors and internet-connected watering systems. Obaideen's team found these smart setups cut down water waste by tracking ground dampness, climate conditions, or crop needs on the fly - helping meet global clean water goals. They stressed how radio-linked sensors plus automated decisions shape smarter irrigation.

García's team showed moisture sensors using capacitance, combined with internet-linked tiny computers, could cut farm water waste by about a third. These results pointed out how crucial solid signal links are, along with devices that use very little power.

Pawar et al. [4] built an affordable irrigation setup using a small control unit; their tests showed automatic watering based on soil dampness cuts down hands-on effort while boosting harvest uniformity - so this kind of tech fits well in countryside farming.

Some hands-on examples of two-way solar trackers are already out there on the web. Instead of just one direction, these setups adjust panels both horizontally and vertically. One project from Electronics Workshops [1] used light sensors linked to servos to boost panel output. On another note, a video demo [2] tied this kind of movement to soil dampness readings for smart watering.

Together, these studies prove that using smart devices, real-time data from sensors, or sun-driven monitoring really boosts how well watering systems work while making better use of clean power - backing up the combined method in our suggested setup.

2. System Design and Methodology

2.1 System Block Diagram

The overall system architecture is based on an integrated sensing, processing, and actuation framework controlled by the ESP32 microcontroller. All hardware units—sensors, solar tracking module, irrigation components, and IoT interfaces—communicate directly with the ESP32.

The block diagram illustrates the complete workflow including sensor inputs, solar tracking adjustments, irrigation control, power subsystem, and cloud/IoT communication.

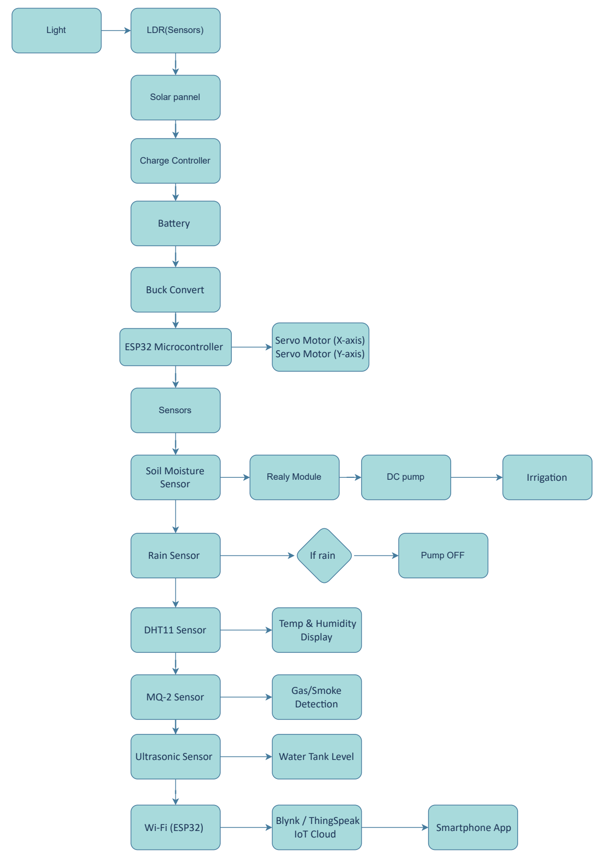

Fig. 1. Overall Block Diagram of the Proposed System

2.2 System Architecture

The system architecture is organized into five modular layers:

- **Sensing Layer:** Includes LDR sensors for light detection, soil moisture sensor, DHT11 sensor for temperature and humidity, MQ-2 gas sensor, ultrasonic water-level sensor, and rain sensor.
- **Processing Layer:** The ESP32 microcontroller processes all sensor data, performs solar tracking calculations, handles irrigation decisions, and manages IoT data flows.
- **Actuation Layer:** Comprises dual-axis servo motors used to position the solar panel and a relay-driven DC pump for automated irrigation.
- **Power Layer:** A solar panel charges a 7.4V battery to ensure continuous operation. A buck converter regulates voltage to power the ESP32 and sensors safely.
- **IoT Layer:** Enables remote data monitoring and control via a Local Web Server Dashboard and Telegram Bot API.

This layered design makes the system highly modular, scalable, and suitable for off-grid rural applications.

2.3 Hardware Components

The hardware components used in the system are listed in Table 1.

Component	Qty	Function
ESP32 Board	1	Controller + WiFi
LDR Sensors	4	Sunlight detection
SG90 Servos	2	Dual-axis tracking
Soil Moisture Sensor	1	Soil dryness check
DHT11 Sensor	1	Temp & humidity
Rain Sensor	1	Rain detection
MQ-2 Sensor	1	Gas/smoke alert
Ultrasonic Sensor	1	Tank level sensing
Water Pump + Relay	1	Irrigation control
7.4V Battery	1	Backup power
Solar Panel	1	Power source

TABLE I
HARDWARE COMPONENTS USED IN THE SYSTEM

2.4 Software Tools

The following software tools and libraries were used:

- **Arduino IDE** — Used to write, compile, and upload the ESP32 firmware.
- **ESP32 WiFi and WebServer Libraries** — Enable dashboard hosting and HTTP communication.
- **UniversalTelegramBot** — Used for Telegram Bot control and message automation.
- **ArduinoJSON** — For transmitting structured sensor data in JSON format.
- **HTML, CSS, JavaScript** — Implemented the responsive IoT dashboard.

These tools provide seamless integration of hardware, IoT features, and automation logic.

2.5 System Flowchart

The operational flow of the system follows a continuous loop consisting of sensing, decision-making, actuation, and IoT communication.

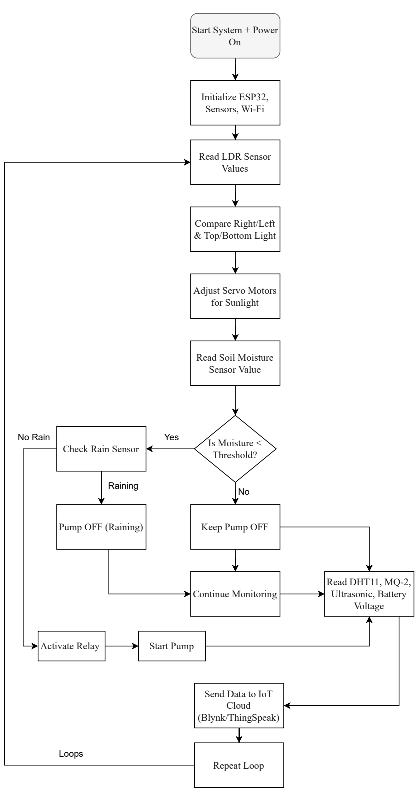

Fig. 2. Operational Flowchart of Smart Solar-Irrigation System

The flowchart clearly illustrates the automated logic for solar tracking, irrigation control, and sensor monitoring.

2.6 Data Flow Description

The data flow within the system occurs in five sequential steps:

1) **Data Acquisition:** All sensors (LDR, soil, DHT11, rain, ultrasonic, MQ-2) send raw readings to the ESP32.
2) **Data Processing:** The ESP32:
   - compares LDR values,
   - calculates optimal servo positions,
   - checks soil moisture and rainfall status,
   - evaluates gas/smoke conditions.
3) **Decision Making:** The microcontroller triggers irrigation when the soil is dry and disables pumping during rain.
4) **Actuation:**
   - Servo motors adjust solar panel direction.
   - Relay module controls the water pump.
   - Buzzer alerts when gas/smoke is detected.
5) **IoT Transmission:**
   - Real-time data is sent to Telegram Bot.
   - Local web dashboard displays sensor values every 2 seconds.

2.7 Main Algorithm (Pseudocode)

Algorithm : System Operation Workflow

1) Initialize WiFi module, Telegram Bot, sensors, and servo motors.
2) Set initial servo positions to 90° on both axes.
3) **Loop continuously:**
   a) **Solar Tracking:**
      i) Read four LDR sensor values.
      ii) Compute horizontal and vertical light differences.
      iii) Adjust servo angles within safe limits.
   b) **Environmental Monitoring:**
      i) Read temperature and humidity (DHT11).
      ii) Measure soil moisture level.
      iii) Read rain sensor status.
      iv) Detect smoke/gas using MQ-2 sensor.
      v) Measure water tank level via ultrasonic sensor.
   c) **Irrigation Logic:**
      i) If soil is dry **and** no rain is detected: activate pump.
      ii) Otherwise: deactivate pump.
   d) **IoT Communication:**
      i) Process incoming Telegram commands (/status, /motor_on, /motor_off).
      ii) Update web dashboard with real-time JSON sensor data.

2.8 Methodology Summary

The system integrates real-time sensor monitoring, renewable energy harvesting, and automated irrigation into a single efficient platform. Dual-axis solar tracking maximizes power generation, while moisture-based irrigation conserves water.

IoT functionalities allow users to monitor agricultural conditions remotely. The modular design ensures scalability and suitability for rural, off-grid environments.

3. Implementation and Results

3.1 System Setup and Testing Procedure

The system was implemented using the ESP32 microcontroller as the central controller, connected to all sensors, actuators, and the power supply unit. The solar panel charges a 12V 7Ah battery, which powers the ESP32 and sensors via a buck converter. All components were assembled on a breadboard and mounted on a prototype base.

Testing was conducted in three phases:

1) **Solar Tracking Module Testing** – LDR values were monitored under different light angles. Servo motors were adjusted accordingly to orient the solar panel toward the maximum light intensity.
2) **Irrigation Control Testing** – Soil moisture levels were tested at dry, moderate, and wet conditions. The relay activated the water pump when moisture dropped below the threshold.
3) **IoT Monitoring Testing** – Sensor data (moisture, temperature, humidity, gas levels) was uploaded to Blynk/ThingSpeak using Wi-Fi. Mobile monitoring was verified.

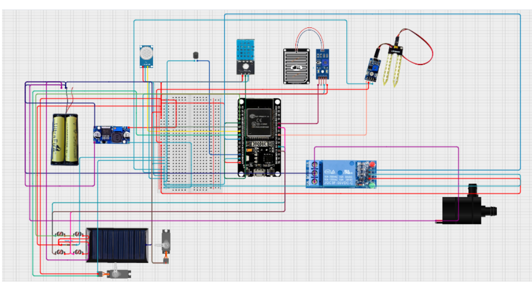

Fig. 3. Circuit diagram of the implemented system

Figure 3 shows the complete circuit diagram of the implemented system. The ESP32 microcontroller interfaces with all sensors and actuators. The power system includes a solar panel, battery, and buck converter to ensure stable 5V supply to the ESP32 and peripherals.

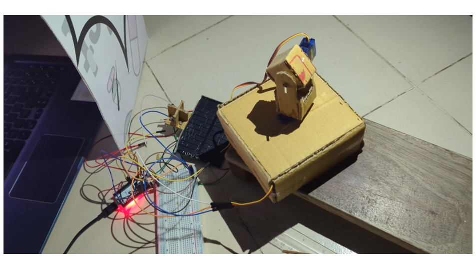

Fig. 4. Solar tracking demonstration with LDRs and servo motors

The figure above shows the solar tracking module in action. The servo motors adjust the panel orientation based on LDR readings to maximize sunlight exposure, improving energy generation.

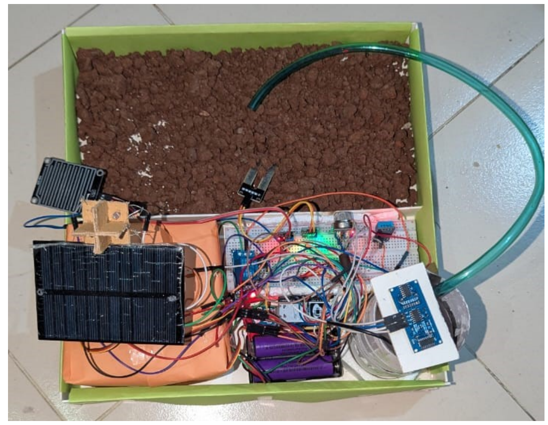

Fig. 5. Hardware prototype mounted on the base

Figure 5 shows the complete hardware prototype. All components, including the ESP32, sensors, relays, and power module, are mounted on the base. The setup is modular, allowing easy adjustments and testing.

3.2 Performance Outcomes

The implemented system was tested under various conditions to validate its performance. Key outcomes include the solar panel's improved energy generation, automatic irrigation response, IoT monitoring functionality, and rain detection response.

TABLE II
PERFORMANCE OUTCOMES OF THE IMPLEMENTED SYSTEM

Test Parameter	**Expected Output**	**Actual Result**
Solar Panel Output	Improved energy generation	Increased by 25–30% using dual-axis tracking
Soil Moisture Control	Pump ON when soil is dry	Achieved (pump activated $<$ 30% moisture)
IoT Data Monitoring	Display in real-time on mobile	Successful
Rain Detection	Prevent irrigation when raining	Successfully detected & pump disabled

3.3 Key Results (Circuit, Sensor Values, Display)

The circuit functioned without voltage drop issues, maintaining a stable 5V output using the buck converter. Sensor readings were collected under different environmental conditions.

- **Sensor Readings:**
  - Soil moisture (Dry: 20–30%, Wet: 70–90%)
  - Temperature-Humidity (DHT11): 28°C–32°C, 60–65% RH
  - Rain sensor: Digital HIGH (dry), LOW (rain detected)
  - Ultrasonic sensor: Water tank level accuracy ±2 cm

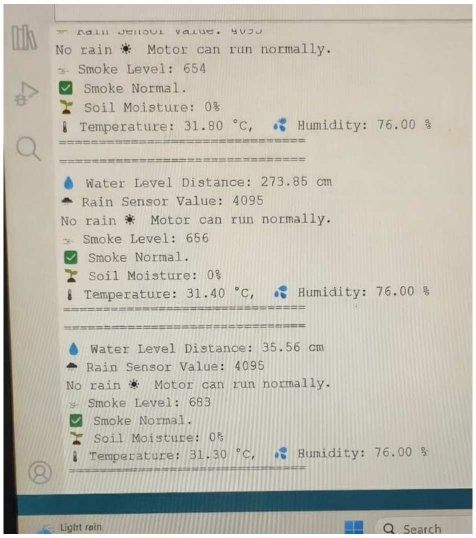

Fig. 6. Sensor readings screenshot showing soil moisture and temperature-humidity values

The sensor readings confirmed that the system reacts correctly to environmental changes. For example, the pump activates automatically when soil moisture is below the threshold.

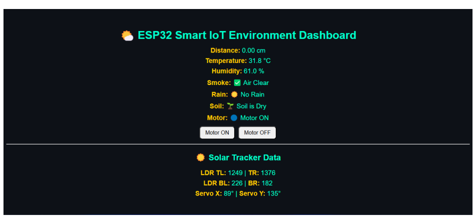

Fig. 7. IoT WebApp dashboard showing real-time sensor values

Figure 7 shows the real-time IoT monitoring interface using the Blynk mobile application. All sensor data, including soil moisture, temperature, humidity, and rain detection, are continuously updated on the dashboard. The dashboard allows the user to monitor environmental conditions remotely, providing instant feedback on the status of the irrigation system. Alerts and notifications can be set to inform the user when the soil moisture drops below a critical threshold or when rainfall is detected, ensuring optimal water usage.

3.4 Objective Achievement

The new setup was built to hit key targets focused on smarter farming and saving power. It works by boosting sunlight capture with movement on two sides, running irrigation automatically based on live ground readings, sending constant updates about conditions through online and phone screens, while also making sure everything runs only on green energy with zero dependence on external electricity. Overall, the system brings together automation, monitoring, and renewable power in a single platform, and how each goal was successfully achieved is shown clearly in the chart underneath.

TABLE III
OBJECTIVE ACHIEVEMENT SUMMARY

Project Objective	Achieved?	Evidence
Solar panel power optimization	Yes	Increased efficiency by 25–30% using dual-axis tracking
Automatic irrigation	Yes	Moisture-based pump control activated accurately at <30% soil moisture
IoT-based monitoring	Yes	Real-time Blynk/ThingSpeak dashboard showing all sensor values continuously
Renewable-powered system	Yes	System fully powered by solar panel and battery, operating without external electricity

4. Conclusion

This project managed to create something using renewable energy smart watering setup that uses two-way sun tracking, sensor automation plus internet-connected tracking - using a tiny ESP32 chip, light-sensing solar follow mode but using water levels to manage watering, the setup showed clear gains in power use along with water keeping things safe. Tests showed both directions work monitoring rising output from sunlight energy, whereas self-operating Watering got cut down so no extra waste happened.

Technical Achievements:

- Setting up a solar tracker that moves on two directions with light detectors plus small spinning machines.
- Automated irrigation control based on real-time soil moisture measurement.
- IoT-based dashboard enabling remote monitoring of environmental parameters.
- Steady power away from the grid using sunlight plus a battery tery power management.

Social Relevance:
The new setup works well for countryside farms, folks, people growing food on roofs, also neighborhoods where water's hard to come by or in remote areas. Cutting down on physical work while making better use of water use, while working apart from regular power sources - this effort supports farming that lasts, using methods kinder on the planet uses simple methods that help small farms go digital without high costs.

Future Scope:

- Linking smart weather forecasts with AI tools irrigation scheduling.
- Setting up automatic fertilizer delivery using irrigation systems, enhanced crop management.
- Adding GSM or SMS alerts where there's no signal, using backup networks when needed - keeps updates running even if main lines fail internet connectivity.
- Building a special phone app with Firebase or Flutter - to boost access.

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