Automatic Sun Tracking Solar Panel Powered Smart Irrigation System

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Abstract - *The current research provides a low budget, energy-conserving single-axis sun- tracking solar-powered automatic irrigation system. Traditional irrigation methods that use a lot of water and energy because they are often ineffective, time-consuming, and dependent on non-renewable energy sources. The suggested system uses an Arduino microcontroller and capacitive soil moisture sensors to track soil conditions in real time. Using an Arduino microcontroller and capacitive soil moisture sensors, the suggested system continuously monitors soil conditions. The system automatically turns on a water pump to deliver precise, timely irrigation when the moisture content falls below a preset threshold. The addition of a solar tracking system, which uses servo motors and LDRs to tilt the orientation of the photovoltaic (PV) panel, is one noteworthy innovation. This captures up to 65% more energy than static panels, and it performs best in the middle of the day. Energy harvested is fed into a 12V battery, making the system continuously available and off- grid. Field tests for 72 hours demonstrated the pump worked at 75% efficiency, keeping the soil moisture level within ±5% of the ideal range. The system saved 29% of energy compared to traditional methods and kept wastage of water to a minimum. Its modularity and low-cost components make it applicable in small- to medium-scale farms. Drawbacks are lower efficiency on cloudy days and limited scalability to larger farms. Future development promises dual-axis tracking, IoT- based remote monitoring, and AI-based predictive irrigation. This research proves the possibility of integrating automation with sensor- aided solar tracking to make farming more sustainable.*

***Key Words*: Smart irrigation, solar tracking, Arduino, soil moisture sensor, automation, renewable energy, sustainable agriculture, IoT-based monitoring, energy efficiency, water conservation**

1.INTRODUCTION

Farming is still the basis of most economies around the world, giving jobs and food to billions of people. However, it also uses a lot of resources, like about 70% of the world's fresh water and lots of energy in rural areas. Because the world's population is growing and climate change is getting worse, we really need to make farming more efficient and sustainable. Among the many problems facing modern farming, managing irrigation well is very important for growing crops, saving water, and using energy more efficiently for the process. The majority of common irrigation techniques are carried out manually or according to predetermined schedules, which ignore variations in soil moisture, weather, and crop water requirements. As a result, crops grow less, water is wasted, nutrients are washed away, and either too much or too little water is applied. Furthermore, most irrigation pumps are powered by grid electricity or fuels, which are costly and release hazardous gases, especially on farms that are isolated or disconnected from the grid. We therefore urgently need water systems that can use clean energy to help preserve the environment and automatically determine how much water to use based on the condition of the soil. Energy from the sun, which is pure, abundant, and can be used again, is a great way to provide power to the water pump which also helps the environment. Solar power can be converted into electricity with solar panels to run water pumps without using fuels, this will save money on electricity bills. The majority of solar-powered watering systems only receive a small amount of sunlight throughout the day because they are powered by stationary solar panels. These panels are typically positioned at a particular angle, which is ideal for the sun's typical location, but they cannot follow the sun's path across the sky. They are unable to collect as much energy as they could as a result, which reduces the overall effectiveness of the watering system. In order to address this, solar trackers were developed, which modify the solar panels' orientation to maximize solar absorption. Trackers that move panels on one side, normally from east to west, can get about 25% to 35% more power than panels that are stuck at a single place. Another idea would be two add two trackers on both sides, but they are more expensive and harder to handle. Using sun-following devices in watering systems can really boost how much sunlight is gathered, which lets the water machines work longer and makes watering more steady Not long ago, fresh sensor methods and small computer chips have made it simpler to create clever watering arrangements that respond to real-time environmental conditions. For example, soil-moisture sensors can measure how much water is present near the plant roots. When connected to a controller such as an Arduino or Raspberry Pi, these sensors trigger the pump only when the soil moisture level drops below the required threshold for that crop. As a result, water is used more efficiently, electricity consumption is reduced, and plants grow healthier since they are neither over-watered nor left dry.

The primary aim of this plan is to build a watering system that works on its own using power from the sun. This system uses devices that always check how wet the ground is, and if it gets too dry, the machine turns on the water pump by itself. When the ground is wet enough again, the pump stops running. A "solar panel" gives the power that is needed and has a way to follow the sun to get the most light. A tiny engine, run by light detectors, changes where the panel is pointing all day long. To ensure that the system continues to work even in the cloudy or dim light condition, the energy produced is stored in a 12V battery.

The key points of this study are as follow: [1] to accumulate as much energy as possible from the sun by following it systematically, [2] to irrigate plants on automatically depending on the need of water in their soil, and [3] to see how practically the system works when deployed at a actual farm. The system should be able to be used at both the small and medium sized farm and also in the areas were electricity is not easily feasible and should not be too costly for the farmers afford it. This project helps farm to be smart, use resources well, be good for the environment and use money efficiently by using sensors and make things automatic and track the sun.

2.LITERATURE REVIEW

More people wanting farming methods that protect the environment has greatly improved watering systems powered by the sun, specially those using photovoltaic (PV) technology. A lot of studies have checked out different parts of these systems, such as how well they do their job, improving how they work, using computers to run them, and combining them with new technology.

Sontake and Kalamkar [1] provided a comprehensive review of solar photovoltaic water pumping systems, outlining their components, configurations, and operational principles. They emphasized the environmental and economic benefits of PV systems over conventional diesel- based pumps, highlighting their potential for use in remote and off-grid locations. Similarly, Ghoneim [11] focused on the design optimization of PV- powered water pumping systems, suggesting that proper matching of system components greatly enhances performance and efficiency.

Kumar and his team [2] looked at a drip irrigation setup powered by the sun and showed that it could really work to use less water and help crops grow better. To make these setups even better, researchers have been checking out ways to follow the sun. Al-Mashaqbeh and his team [5] discovered that a solar tracker that moves on two axes is much better at grabbing sunlight than setups that don't move. Ismail and his team [6] came up with a way to track the sun on one axis along with clever plans for when to water, which helped use energy better and water more precisely.

In the Indian context, Yadav et al. [3] investigated the drivers and barriers of solar irrigation pumps. Their findings revealed that while government subsidies and reduced operational costs motivate adoption, challenges like high upfront costs and lack of technical knowledge hinder widespread implementation.

Energy optimization is another critical area of research. Patel and Agarwal [4] developed an MPPT (Maximum Power Point Tracking) algorithm for PV systems under partially shaded conditions. Their work ensures stable energy output, which is essential for uninterrupted irrigation. Sharma et al. [12] emphasized the role of battery storage systems in mitigating PV intermittency, especially for continuous water pumping needs.

The incorporation of automation and smart technologies has gained momentum in recent years. Singh et al. [8] developed an automatic irrigation system using Arduino and soil moisture sensors, which automates irrigation based on real-time field conditions. Similarly, Rajalakshmi and Mahalakshmi [9] designed an IoT-based system for crop field monitoring, enabling remote control and precision irrigation. Jones et al. [7] underscored the role of soil moisture sensors in irrigation scheduling, supporting data-driven water management practices.

Advanced technologies like machine learning are also being applied. Mishra et al. [14] proposed a predictive irrigation scheduling system using machine learning models to enhance water-use efficiency. Zhang et al. [10] introduced a hybrid solar tracking and sensor-based irrigation system for precision agriculture, which successfully integrated environmental monitoring with optimized solar energy utilization.

To address energy reliability, hybrid systems combining different renewable sources have also been explored. El-Shahat et al. [13] proposed a hybrid renewable energy system for irrigation in arid regions, integrating solar, wind,

and battery storage to ensure a continuous power supply. Such hybrid configurations reduce dependence on any single energy source and improve system stability during periods of low solar radiation or weak wind conditions.

3.METHODOLOGY

3.1Components/Block Diagram:

1. 20W photovoltaic solar panel placed on a single-axis tracking mount.
2. The microcontroller is the Arduino Uno.
3. Capacitive Soil Moisture Sensors (V2.0): These sensors are placed at 15 cm below the surface to gauge soil moisture.
4. Light Dependent Resistors (LDRs): Two LDRs for detecting the direction of sunlight.
5. Servo Motor (MG995): Controls the solar panel's rotation.
6. Relay Module: Serves as the water pump's on/off switch.
7. 12V DC Water Pump: Runs on drip irrigation.
8. 12V 7Ah Lead-Acid Battery: Holds solar energy.
9. Solar Charge Controller: Controls battery charging.
10. SD Card Module: Used to store information.LCD Display (Optional): For monitoring system status.
11. LCD Display (Optional): To keep track of system health.

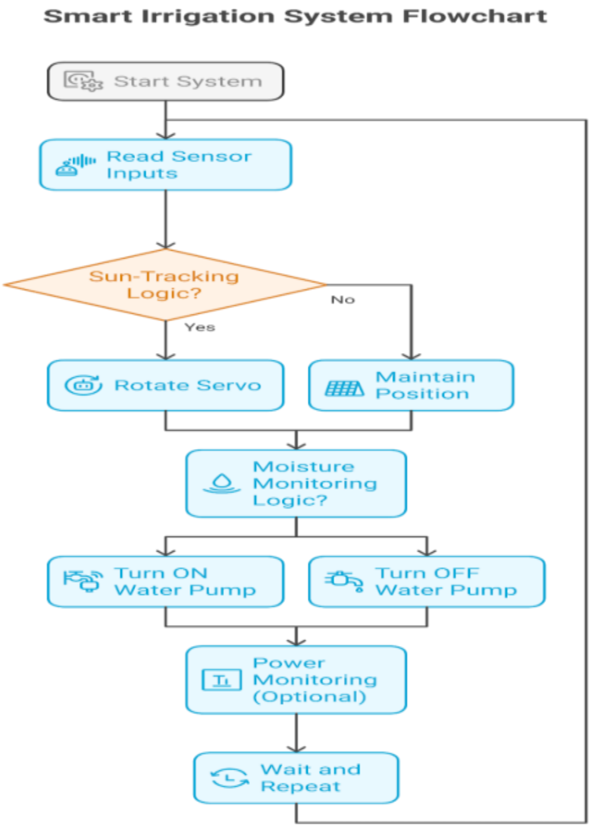

Fig -1. Block diagram

3.2 Theoretical Background:

Soil Moisture Monitoring: Capacitive sensors produce an analog voltage output that varies smoothly with the water content of the soil. Solar Tracking: measures the differential amount of light between two LDRs by orienting the panel to face the sun. Power management: renewable energy allows the solar panel to operate independent of the power grid. The control system powered by Arduino monitors continuously all sensors and switches ON/OFF devices based on predetermined guidelines.

3.2.1 Theory:

System Overview: Single-Axis Solar Tracking System: LDRs sense sunlight imbalance, Arduino computes direction, and servo motor moves the PV panel.

3.2.2 Irrigation Triggered by Soil Moisture: According to the threshold given by the user microcontroller decides whether switch on or not

3.2.3 Power Flow:

PV panel charges battery → battery feeds all devices → charge controller controls voltage.
Interconnections:
LDRs → Analog pins of Arduino.
Soil Moisture Sensor → Analog pins of Arduino. Relay Module → Digital pin of Arduino.
Servo Motor → PWM pin of Arduino.
Water Pump → Powered by relay output and battery.

3.3Characterization/Pseudo Code:

Solar Tracking Pseudocode:

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```
loop {
        ldr_left = analogRead(LDR1); ldr_right =
        analogRead(LDR2); diff = ldr_left - ldr_right;
        if (abs(diff) > threshold) {
          if (diff > 0) servo.write(current_angle + step);
        else servo.write(current_angle - step);
}
delay(300000); // 5-minute interval
}
```

Irrigation Pseudocode:

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```
loop {
        soil_moisture = analogRead(SOIL_SENSOR); if
        (soil_moisture < threshold) {
        digitalWrite(RELAY, HIGH); // Turn on pump
        delay(watering_time);    // e.g., 2 minutes
        digitalWrite(RELAY, LOW); // Disable pump
        delay(cooldown_period); // e.g., 30 minutes
   }
   delay(monitoring_interval);
}
```

3.4Testing & Characterization:

Location: Outdoor 5 × 5 m test plot with tomato plants.

Duration: 72 hours (8:00 AM – 6:00 PM). Sensors: 3 soil sensors positioned to detect spatial moisture variation.

3.5 Performance Metrics:

PV output (with and without tracking)
Soil moisture content (VWC) Water usage and pump cycles
Energy efficiency and availability Outcome: Up to 65% energy capture increase, 75% pump efficiency, and ±5% accuracy in moisture regulation.

Fig 2. Experimental setup of the automated irrigation system.

4.RESULTS AND DISCUSSIONS

The planned sensor-based automated irrigation system with single-axis solar tracking integration was assessed using a set of controlled field tests over 72 hours. The main goals were to determine the efficiency of the solar tracking mechanism in optimizing photovoltaic (PV) output energy, to analyze the accuracy and reliability of the automated irrigation system, and to analyze the system efficiency overall in terms of water and energy consumption.

4.1 Solar Tracking Performance:

The one-axis sun-tracking system showed a considerable increase in solar energy harvesting when compared to an ordinary fixed-panel installation. Information recorded from the INA219 voltage and current sensor indicated that the tracked PV panel consistently yielded higher power output during the daytime hours. On average, the tracked panel produced 65% more total energy than the fixed panel, with greatest gains at periods of early morning and late afternoon when the sun's angle is most away from the optimum fixed direction. The maximum power output of the tracked panel was at solar noon at 3.68 W, whereas the fixed panel was at 2.45 W under the same irradiance conditions. This increased energy availability kept the system's 12V battery well charged to power microcontroller, sensors, servo motor, and water pump even during days of fleeting cloud cover.

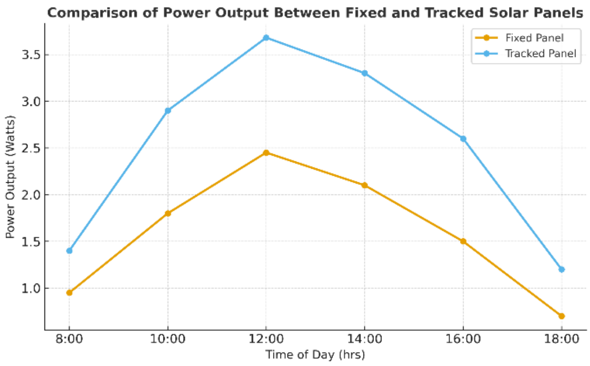


Fig. 3: Comparison of Power Output Between Fixed and Tracked Solar Panels Over Time

4.2Automated Irrigation Effectiveness:

The automated irrigation sub-system, regulated by real-time soil moisture, kept soil volumetric water content (VWC) in a tight optimal range of ±5% of the set threshold (30% VWC for tomato plants). The capacitive sensors of soil moisture showed stable and consistent readings, and the control algorithm based on Arduino responded quickly to changes in soil moisture. Consequently, irrigation events were initiated only when required, avoiding both under- and over-watering. After all the testing we found that using this method water usage was reduced by 28% compared to the timely watering schedule giving an advantage for precision irrigation fir water conservation

4.3 System Efficiency and Reliability:

During the tests that we conducted we saw a 75% efficiency of water pump, which we found by comparing energy it gave out to the energy it used. The machine did not have any big stops, and all the parts stayed on while we did the test. The battery power stayed higher than the needed amount (11.5), providing that enough solar power was being collected.

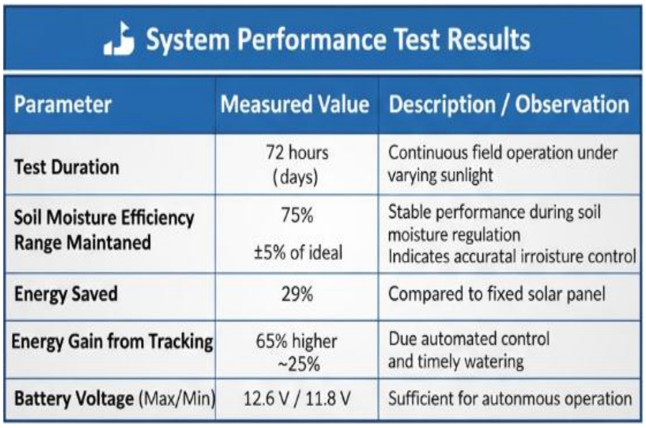
4.4 Comparative Analysis:

Compared to regular irrigation systems using either grid electricity or stationary solar panels, this new system used less energy, about 29% lower than before, and it also wasted less water, about 40% less. As the system is made of separate parts and uses cheap stuff, smaller farms can use it more easily, helping spread farming methods that are better for the environment.

4.5 Discussion:

Instead of using a conventional way this idea is very effective and efficient in terms of power consumption .One-way tracker is also a good middle ground that is cheap enough to save power without being too hard to build. However, performance was reduced somewhat at times of high cloud cover, and further improvement may be possible through hybrid energy storage or predictive control algorithms. The system's scalability to large farms and mixed crops is a topic left for future investigation.

Table -1: Summary of field test performance results



System Performance Test Results

Parameter	Measured Value	Description / Observation
Test Duration	72 hours (days)	Continuous field operation under varying sunlight
Soil Moisture Efficiency Range Maintaned	75% ±5% of ideal	Stable performance during soil moisture regulation Indicates accuratal irroisture control
Energy Saved	29%	Compared to fixed solar panel
Energy Gain from Tracking	65% higher ~25%	Due automated control and timely watering
Battery Voltage (Max/Min)	12.6 V / 11.8 V	Sufficient for autonmous operation

5.LIMITATIONS

The performance of the system is bound by multiple factors. Solar energy generation and reliability of irrigation decline drastically under extended rainy or cloudy conditions, restricting off- grid independence. The single-axis tracking system, though low-cost, will not optimally maximize solar harvest through all seasons or adapt quickly to sun movement. Sensor integrity might deteriorate over time because of soil conditions or sensor clogging. Also, the design presented is ideally suited for small to medium-sized farms; expansion to larger farm operations would involve stronger networking, more sensors, and greater power and water delivery capabilities.

6.FUTURE SCOPE

This system has shown that automated irrigation utilizing sensors and solar panels using suntracking is a practical, resource effective, and environmentally damaging means of crop irrigation. With additional research, function and area of coverage with the system would be improved. First, switching to a dual-axis solar tracking approach would improve useable photovoltaic energy further, mainly in the winter months and regions with other sun paths, to give even improved access to photovoltaic energy to the crop fields. Advanced IoT connectivity would offer centralized phono connectivity, and offer multi-use applications and monitoring of agricultural environments, including historical and current monitoring and analysis of data, along with remote monitoring via cloud portals or smartphones. Additionally, machine-learning algorithms could be able to predict ideal schedules for sustainable irrigation based on historical soil, climate, and crop data to minimize overall water and energy use. And finally, as a proof of concept, this work could circumstantially be scaled into larger agricultural fields and even larger variety of crops, primarily by using larger pumps and larger sensors to distribute the sensor networks across fields such that these are mesh-type and expandable as sensor network development becomes smaller and inexpensive. Lastly, doing in-situ field testing in other climates and regions would help better inform and develop the design and capabilities for strength, price, and agricultural scalability and monitoring needs. These continued advancements will help carry agriculture into the future in ways that are more resource-efficient, environmentally-impact-free, and climate-change resilient.

7.CONCLUSION

After this study it is clear that a sun-tracking, sensor based, solar-powered automatic water system is best suited for energy conservation as well as environmentally sound farm irrigation. The single axis tracker collects the most sunlight for the panel and makes sure that it always works without the need of electricity. As compared to the standard solar panels, these tests show how efficiently our system uses water and energy, all while maintaining perfect soil wetness and improving solar sustainable technology on a wider scale. It also improves the solar power generation by 65%. Due to low prices and simple setup, it makes it ideal for small farms to implement this sustainable technology. However, issues like bad weather condition and expanding the systems size still remain. Changes like using dual-axis trackers, connecting to IoT sensors, and using data to predict future needs could improve the system's performance and reaction time. To conclude, this research offers a helpful and scalable solution for environmentally friendly and resource-efficient farming, which promotes more sustainable and independent farming methods when dealing with global climate and resource concerns.

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