Fabrication and Evaluation of a Photovoltaic System with a Single-Axis Solar Tracker for Automatic Irrigation

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Abstract

Fossil fuel limitations and environmental concerns have increased interest in renewable energy sources like solar power for agricultural applications. This study presents the development and evaluation of a photovoltaic water pumping system equipped with a single-axis solar tracker, designed to automate irrigation in gardens and fields lacking access to the electrical grid. The system integrates solar energy absorption and storage, a solar tracker, and automatic irrigation units. Solar energy captured by the panel is transferred to a battery via a charge controller, then converted through a voltage converter and motor driver to operate the water pump. Experimental results indicate that the system's energy intake peaks between 10 a.m. and 2 p.m. Under sunny conditions with an active tracker, the system stored 53.58 watts in the battery, compared to 43.4 watts with an inactive tracker, and 35.3 watts during cloudy weather. The study also found that the orientation of the solar panel relative to the sun and the use of the solar tracker significantly influenced energy collection, with statistical significance at the 5% level. Additionally, the type of soil moisture sensor impacted system performance, with a disturbance matrix demonstrating 100% irrigation accuracy. Overall, the solar tracker proved effective in sunny conditions, enhancing energy collection and system efficiency. The findings support the adoption of such systems for automatic irrigation, especially in remote or off-grid locations, contributing to sustainable agricultural practices and reducing reliance on fossil fuels. The integration of tracking technology and optimised sensor use can significantly improve the reliability and efficiency of solar-powered irrigation systems, making them a viable solution for modern agriculture.

Keywords: Arduino, Electrical motor, Soil moisture sensor, Solar energy, Water pump

Introduction

Over recent decades, the depletion of fossil fuel resources and their associated high pollutant emissions have prompted countries worldwide to explore alternative energy sources (Abdoli, Nasrabadi, Amid, & Hoveydi, 2007). Although renewable energy utilisation remains limited, ongoing investments and technological advancements are gradually increasing its adoption. Solar energy, in particular, is recognised as an environmentally sustainable alternative that can mitigate the adverse effects of fossil fuels (Moeini & Dehghan Menshadi, 2010). Iran's significant solar potential underscores the importance of implementing strategies to expand its use. Solar power can effectively supply electricity for agricultural water pumping, especially in remote areas lacking access to the electrical grid (Rahimi Khoygani, Fouladi Valizadeh, & Naserian, 2012). As a reliable and practical energy source, solar power offers a promising solution for enhancing agricultural productivity and reducing environmental impact, supporting sustainable development in regions with abundant sunlight (Kaldellis, Meidanis, & Zafirakis, 2011). Prioritising the adoption of solar energy is essential for fostering energy independence and environmental preservation.

Photovoltaic pumps operate using electricity generated directly from solar panels, converting solar energy into electrical power for pumping water. These systems offer numerous advantages, such as eliminating reliance on fossil fuels, reducing biological pollution, and providing independence from the national power grid. Additionally, photovoltaic pumps with low power consumption are more cost-effective than diesel-powered alternatives. Over the long-term, the initial investment in a photovoltaic system is approximately half the cost of diesel, wind, or electric pumps. As the adoption of photovoltaic pumps has increased, their prices have decreased significantly. Despite higher upfront costs, the lower operational expenses of solar pumps, particularly in fuel and maintenance, make them a competitive option. Over a twenty-year period, the total costs associated with solar pumps are 70 to 90% less than those of diesel pumps (Rahimi Khoygani *et al.*, 2012; Roy, Islam, Hasan, & Najmul Hoque, 2015). Furthermore, their lightweight design and modular components facilitate easy transportation and installation, enhancing their practicality for various applications. Overall, photovoltaic pumps present a sustainable, economical, and efficient solution for water pumping needs, especially in remote or off-grid locations.

The efficiency and capacity of photovoltaic systems significantly improve as the number of panels increases. Additionally, the power output of these systems depends directly on the solar radiation they receive. To maximise energy absorption, panels should be positioned perpendicular to the sun's rays. Solar trackers are essential in enhancing system performance by maintaining optimal panel orientation. Control algorithms for solar trackers are categorised into three strategies: open-loop, closed-loop, and hybrid systems combining both. Among these, closed-loop control is the most prevalent. Common control algorithms used in active solar tracking include on-off, fuzzy logic, PID, and PI controllers, which account for 57.02%, 10.53%, 6.14%, and 4.39% of applications, respectively (Fuentes-Morales *et al.*, 2020). Implementing effective control strategies ensures maximum energy capture and improves overall system efficiency.

Water scarcity is recognized as a critical global concern (Hajinajaf, Ghavami Jolandan, Masoudi, and Rohani, 2024). Iran's predominantly arid and semi-arid climate results in approximately 90% of its water resources being allocated to agriculture. This highlights the urgent need for innovative water management strategies to enhance water productivity within the sector (Saedi, Alimardani, Mousazadeh, & Salehi, 2018). Numerous studies have explored the application of photovoltaic systems for water pumping. For instance, Pande, Singh, Ansari, Vyas, and Dave (2003) tested a solar-powered drip irrigation system in an Indian pomegranate orchard, demonstrating its suitability for expanding orchards in arid regions. Similarly, Senol (2012) conducted a cost analysis in Turkey on a half-hectare apple orchard, comparing diesel and photovoltaic systems; results indicated that solar systems are significantly more economical. Gao *et al.* (2013) in northwest China found that solar pump installation and operational costs are lower than those of diesel pumps, with added ecological benefits. Roy *et al.* (2015) noted that despite the higher initial investment, solar pumps are cost-effective over time due to low maintenance requirements and extended service life. These studies collectively suggest that photovoltaic water pumping systems offer a sustainable and economically viable solution for irrigation, especially in water-scarce regions, contributing to more efficient water use and environmental conservation.

Mostofi, Shayeghi, and Kazemi Kargar (2012) conducted a study focused on minimising the final cost of a hybrid power plant independent of the main power grid. They proposed integrating small hydroelectric units, photovoltaic systems, and wind turbines with hydrogen storage, specifically for agricultural applications near dams. Their research highlighted that adding a hydroelectric component to a hybrid system—comprising wind, solar, and hydrogen—could reduce construction costs, enhance system reliability, and lower overall energy production expenses. These advantages make such hybrid configurations attractive for regional energy solutions. Alibeik (2016) designed, constructed, and evaluated a solar water pump tailored for agricultural farms.

The system incorporated a control circuit built around an Arduino microcontroller, along with soil moisture and temperature sensors. This setup enabled automatic operation of the water pump, activating and deactivating at predetermined times aligned with irrigation schedules, thereby optimising water use efficiency during specific hours of the day and night. Shojaei and Akhavan (2019) examined the economic viability of photovoltaic-powered pumps compared to traditional electric pumps within drip irrigation systems across nine orchards. Their findings indicated that photovoltaic pumping is economically feasible without the need for an extensive distance from the electricity grid, primarily for large-scale pistachio orchards of around 60 hectares, assuming a 10% interest rate. For medium-sized walnut orchards, the investment costs were comparable to those of electric pumps, despite slight differences. The analysis also revealed that the smaller the farm and the greater its distance from the power grid, the more cost-effective photovoltaic pumping becomes. Specifically, at a distance of 0.5 km from the distribution network, photovoltaic systems proved economical for small and medium-sized pistachio and walnut orchards at both interest rates. Overall, these studies underscore the potential of hybrid renewable energy systems and solar-powered irrigation solutions to reduce costs and improve efficiency in agricultural settings, especially in remote areas where grid access is limited or costly.

Research by Barkhodari, Kalantar, and Tabibi (2019) introduced an innovative sun-tracking method utilising the solar panel itself as the tracking device. Their findings indicated that the mobile panel employing this new tracking technique generated 27.8% more power during summer and 22.6% more during winter compared to fixed panels. Additionally, this system significantly reduced construction, repair, and maintenance costs. Sharma and Sharma (2017) explored the design of a solar tracker that optimises sunlight capture by minimising the angle between the photovoltaic panel and the sun, thereby maximising energy absorption. Their system demonstrated increased energy output with minimal energy consumption for operation, and the costs associated with mechanical and electronic components remained low. Abdollahpour, Golzarian, Rohani, and Abootorabi Zarchi (2018) developed a dual-axis solar tracker employing panel shadow image processing. Experimental results showed that their system could track the sun with an accuracy of approximately ±2 degrees, maintaining the panel perpendicular to the radiation source. Bakeer, Magdy, Chub, and Bevrani (2022) proposed a novel model based on artificial neural networks with radial basis functions (ANN-RBF) to simulate the steady-state and dynamic power output of photovoltaic (PV) plants connected to the grid. Their simulation demonstrated that the ANN-RBF model more accurately captures the system's behaviour during load disturbances, making it more suitable for load frequency control (LFC) studies than traditional first-order models. Overall, these studies highlight advancements in solar tracking technology and modelling approaches that enhance energy efficiency and system performance in photovoltaic applications.

The increasing water scarcity in Iran, coupled with rising global energy prices, underscores the urgent need to conserve water and energy, particularly in agriculture. This research focuses on developing a prototype photovoltaic system designed to harness and store solar energy for automatic irrigation purposes. The system features sun-tracking capabilities to optimise solar energy absorption, thereby enhancing efficiency and capacity. The innovation lies in integrating automatic irrigation with solar tracking technology into a unified system, aiming to maximise solar energy utilisation while minimising water wastage through precision irrigation. The primary objectives are to improve energy efficiency in irrigation processes and reduce water losses, addressing critical environmental and resource management challenges. This approach offers a sustainable solution that combines renewable energy use with efficient water management, contributing to the resilience of agricultural practices amid resource constraints.

Materials and Methods

System Structure

The solar-powered water pumping system developed in this study (Fig. 1) tracks the sun continuously, ensuring optimal solar energy absorption throughout the day. The system captures sunlight, storing energy in a battery via a charge controller. This stored energy powers the pump motor to irrigate plants as needed. The design of system components was carried out using CATIA R16 software, while system performance was simulated in Proteus 8. This integrated approach enhances the efficiency and reliability of solar irrigation systems.

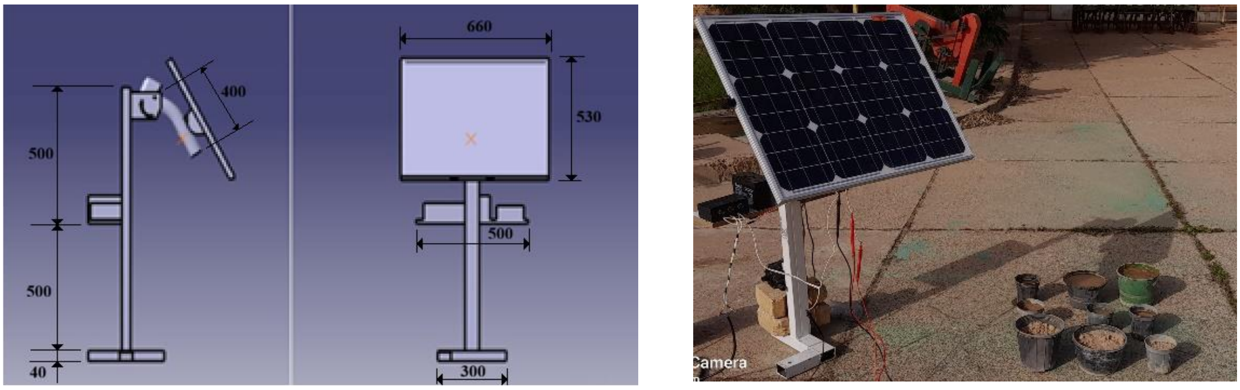


Fig. 1. Photovoltaic system dimensions (left), the built system (right)

The system depicted in Fig. 2 comprises three main components: a solar energy absorption and storage unit, a tracking system, and an automatic irrigation unit. A single microcontroller board manages both the solar tracking and irrigation functions, streamlining control and enhancing system efficiency.

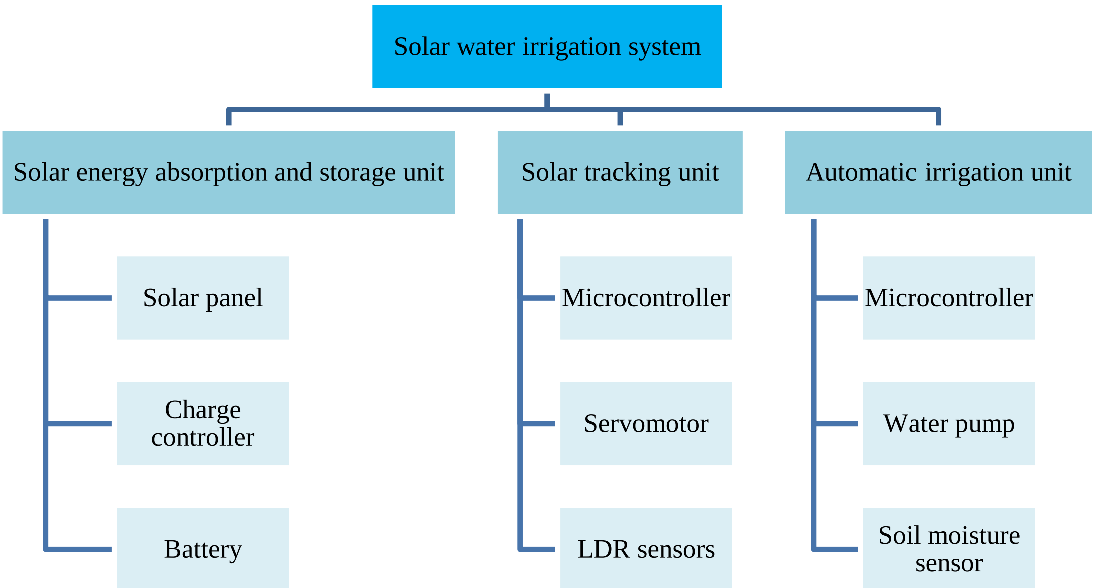


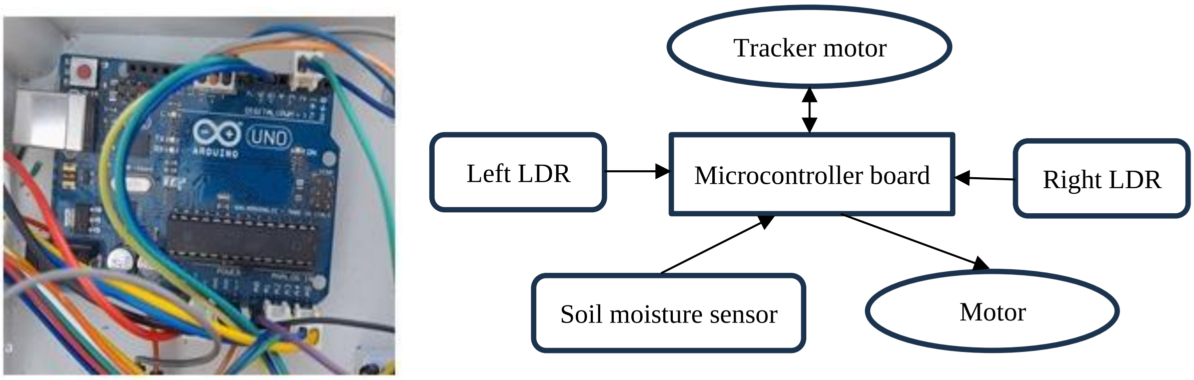
Fig. 2. The automatic solar-powered irrigation system's units and components

The System Hardware Components

The choice of components was based on a

thorough analysis of the design requirements and the specifications of the parts available in the market. Components were chosen to ensure they met the system's efficiency needs. Considering the size and weight of the solar panel, the motor was selected based on factors such as torque production, operating voltage, cost, and availability. Once the motor and panel were finalised, other necessary components, including the voltage converter, charge controller, and battery, were selected according to the output specifications of the motor and solar panel.

The Arduino UNO microcontroller manages the system's components, as shown in Fig. 3-a. It detects the sun's position during the day using data from LDR sensors. Upon detection, it activates the tracking motor, causing the solar panel to rotate and remain perpendicular to the sun's rays. Simultaneously, the microcontroller receives soil moisture data from the relevant sensor. Based on this information, it issues commands to activate or deactivate the water pump, ensuring optimal irrigation. The connections between the microcontroller and the system components are illustrated in Fig. 3-b, demonstrating how each element interacts to maintain efficient solar tracking and soil moisture management.



(a) (b)

Fig. 3. (a) The Arduino UNO board used, and (b) the inter-relationship between sensors, actuators and the Arduino board

The system utilises a YL50C-18b solar panel with dimensions of 530×664×25 mm, comprising 100 cells measuring 20×18 mm each. It weighs 4,000 grams and delivers a maximum output power of 50 watts, with a peak voltage of 22.64 volts and a current of 2.94 amps. This panel captures solar energy to power the system. A 10 STAR charge controller, manufactured in Iran, manages the battery charging process and facilitates energy transfer from the panel and battery to the electrical motors. The tracker unit features a single-axis DC electric motor, the Premium HD model, capable of rotating 85 degrees east and west (Fig. 4-a). It operates on 12 VDC and includes a rotary encoder to monitor the motor's angular position, along with three microswitches that define the limits at 85 degrees east, zero, and 85 degrees west. For automatic irrigation, a PDD-20 C motor pump from Noristo Koki Company, Japan, is employed (Fig. 4-b). The irrigation system functions based on soil moisture data collected by a sensor and processed by an Arduino board. When soil moisture drops below 20%, the pump activates to irrigate the soil. Once moisture reaches 40%, the pump turns off, ensuring optimal soil conditions. This integrated setup enhances energy efficiency and automation in solar-powered agricultural applications, combining solar energy harvesting, precise motor control, and soil moisture regulation for sustainable operation.

(a) (b)

Fig. 4. (a) Electric motor of the sun tracker, and (b) the water pump used

A YL-69 resistive soil moisture sensor was employed to measure soil moisture levels (Fig. 5-a). The sensor's analogue output increases when soil moisture is low and decreases when moisture is high. This output was connected to the Arduino's A/D port for real-time data acquisition (Masoudi, Tavakolzadeh, & Alemzadeh Ansari, 2020). Prior to use, the sensor was calibrated, resulting in the calibration equation displayed in Fig. 5-b. This setup enables accurate, immediate monitoring of soil moisture, facilitating efficient irrigation management and soil analysis in agricultural applications.

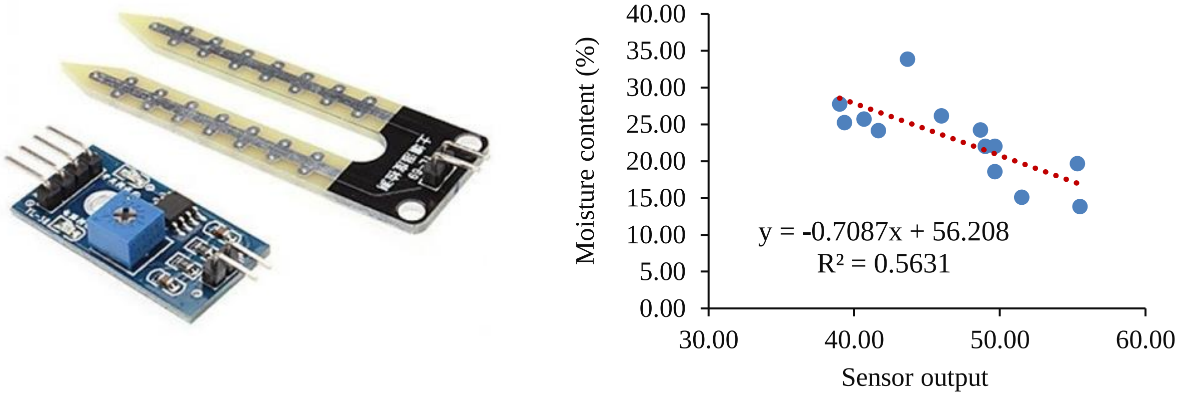


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Fig. 5. (a) YL-69 soil moisture sensor, and (b) soil moisture sensor calibration curve

The system employs an L298-based DC motor driver module to operate both the tracker and pump motors. This driver features two output channels, supporting a maximum voltage of 50 V and a current of 2 A per channel. To measure sunlight intensity, two TEMT 6000 photoresistor sensors are utilised; these sensors produce an analogue voltage proportional to light levels, which are fed into the Arduino's analogue-to-digital (A/D) pins for processing. Power management is achieved through a 150W DC-DC converter, which steps up the 12 V from the solar panel to 24 V, supplying power to the water pump and tracker motor. Additionally, a 7805 voltage regulator ensures a stable voltage supply for the Arduino and system sensors. Energy storage is handled by a 12 V, 60 Ah sealed lead-acid battery, capable of high charge capacity and reliable operation across various weather conditions. This battery supports the continuous operation of the motors by storing excess energy generated by the solar panel. The overall hardware configuration, including component connections, is illustrated in the electronic circuit diagram shown in Fig. 6. This setup ensures efficient power management, accurate sunlight measurement, and reliable motor control, forming a robust system for solar tracking and water pumping applications.

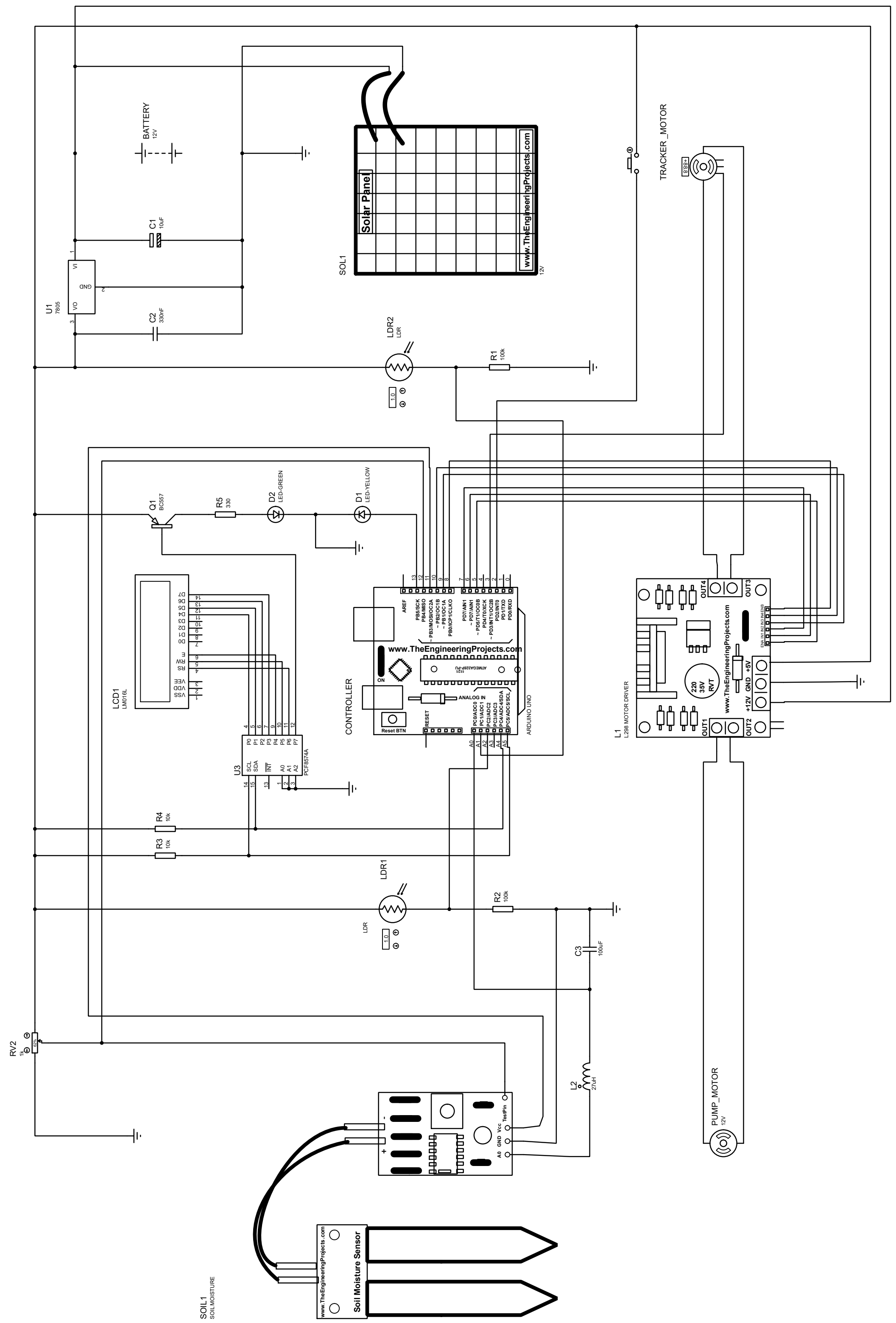


Fig. 6. Electronic circuit of the system, designed in the Proteus 8 software environment

The Control System Algorithm

The control system operates in cycles, sequentially adjusting the solar tracking and automatic irrigation units. Initially, the solar tracking unit is activated, followed by the irrigation system. The flowchart illustrating this control algorithm is shown in Fig. 7.

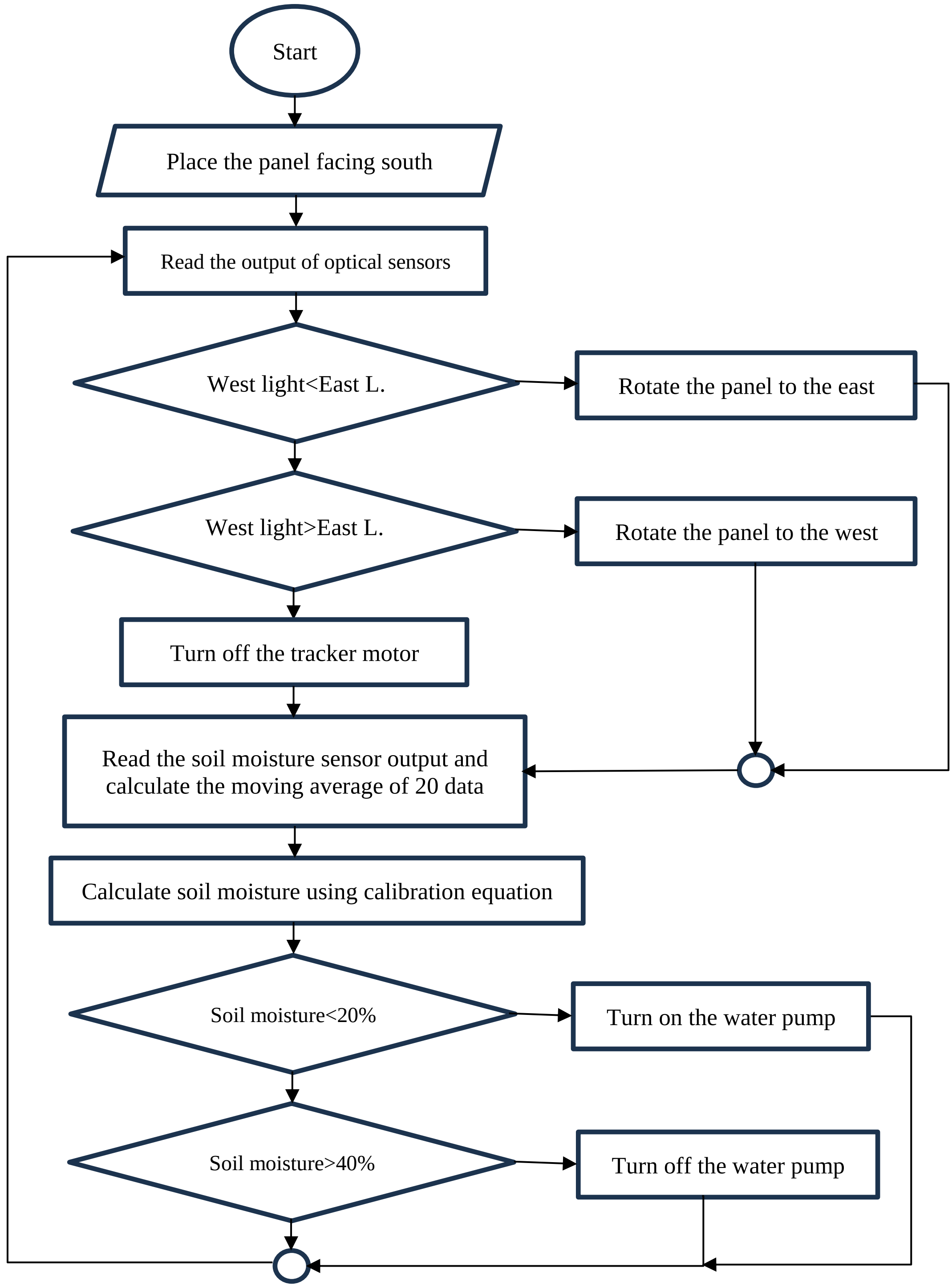


Fig. 7. Flowchart of the photovoltaic system control for automatic irrigation

System Evaluation

Field tests were carried out in Ahvaz, Iran, located at 31.32°N and 48.67°E. The tests took place outdoors with the system oriented south at a 30-degree horizontal angle. Sunlight intensity was measured using the TES_1333 light meter under various conditions, including sunny and cloudy skies, and in both direct and shaded (indirect) radiation modes. Three different tests were conducted to evaluate the system's performance comprehensively, ensuring accurate assessment across diverse environmental conditions.

Evaluation of the solar energy absorption and storage unit: To evaluate the solar panel system's performance, a voltmeter was connected in parallel and an ammeter in series with the output wires (the multimeters used were Victor VC97). The system was tested under three conditions: sunlight with an active tracker, sunlight with an inactive tracker, and no sunlight with an inactive tracker. Each condition was repeated three times, with measurements taken hourly from sunrise (7 a.m.) to sunset (6 p.m.). Instantaneous current and voltage were recorded during these periods. Additionally, to assess the total solar energy absorbed daily, the battery was initially half-discharged using two 100-watt lamps. The energy stored was calculated by measuring the battery's current and voltage at the start and end of each day. The data collected from these treatments were analysed using a completely randomised design, and differences were evaluated with Duncan's test. Data analysis was conducted using SPSS software, while graphical representations were created with Excel. This comprehensive approach provided insights into the efficiency of the solar energy absorption and storage system under varying operational conditions, ensuring reliable and repeatable results for performance assessment.

Evaluation of the solar tracker unit: Considering that the tracker's activity does not influence the amount of solar energy absorbed on non-sunny days, the experiment was conducted exclusively on sunny days. The system was positioned facing the sun with the tracker activated across three days. During each session, the solar panel's position was recorded at various times from sunrise to sunset. By comparing these positions with the optimal orientation for the test site's latitude, the tracker's accuracy was assessed. This was measured using the RMSE index derived from Equation 1 (Masoudi, 2023), providing a measure of the tracker's precision in aligning the panel with the sun throughout the day.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_a - x_d)^2}{n}} \quad (1)$$

where x_a represents the actual angle in degrees, x_d the desired angle, and n the daily data count, providing clarity on the variables involved in the measurement process. The actual angle, as measured by the rotary encoder connected to the end of the tracker's DC motor, is compared to the desired angle, which corresponds to the direction perpendicular to the sun's surface at the latitude of the test site.

Evaluation of the automatic irrigation unit: The system's accuracy and performance in automatic plant irrigation were assessed by testing the irrigation unit. Soil moisture sensors were placed in nine pots, each at three distinct moisture levels, with three repetitions and three observations per repetition. The irrigation unit's accuracy was then evaluated using a disturbance matrix, which recorded whether the water pump activated or remained inactive, providing a comprehensive performance analysis.

Solar Radiation Intensity: Solar radiation intensity (irradiance) is defined as the solar power received per unit area and determined from Equation 2 (Kalogirou, 2014):

$$G = \frac{Q}{A} \quad (2)$$

where, G = solar radiation intensity (W m^{-2}), Q = solar power received (W), and A = surface area (m^2). Also, solar radiation on Earth's surface for a tilted PV panel (Fig. 8) can be calculated from Equation 3:

$$G_T = G_b R_B + G_d\left(\frac{1+\cos\beta}{2}\right) + G_r\left(\frac{1-\cos\beta}{2}\right) \quad (3)$$

where, G_T = total radiation on tilted surface, β = tilt angle, R_b= geometric factor, G_b = beam (direct) radiation, G_d = diffuse radiation, and G_r= reflected radiation.

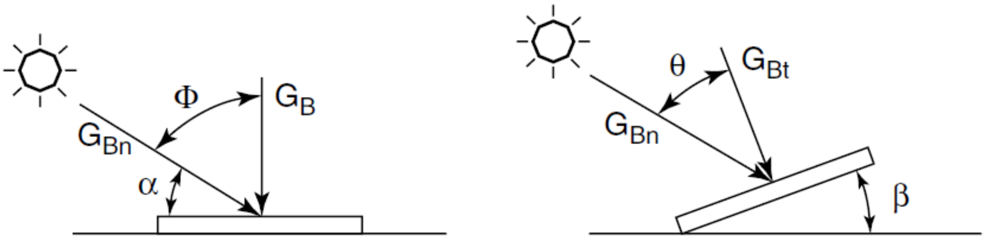


Fig. 8. Solar radiation on horizontal and tilted surfaces (Kalogirou, 2014)

The maximum absorption in a solar panel occurs when sunlight strikes the panel directly at a 90° angle, the panel is tilted at the optimal angle, and the sky conditions are clear. Fig. 9 shows the variation of solar radiation intensity under different conditions throughout the day. Therefore, a sun-tracking unit was incorporated into the system to ensure maximum solar energy capture (Kalogirou, 2014).

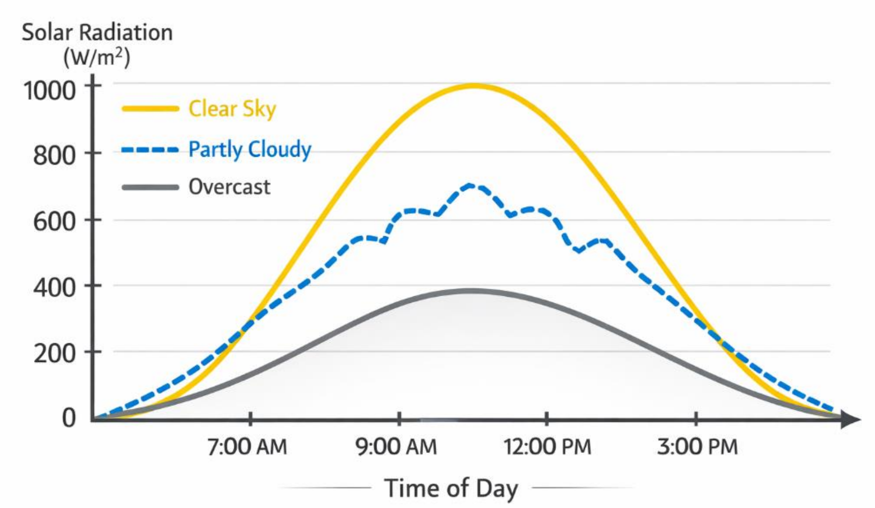


Fig. 9. A typical daily solar radiation intensity for different conditions

Photovoltaic panel power can be calculated from solar radiation intensity or electrical output using Equations 4 and 5 (Chandel, Nagaraju Naik, & Chandel, 2017; Kalogirou, 2014):

$$P_{PV} = G_T \times A \times \eta \quad (4)$$

$$P_{PV} = V \times I \quad (5)$$

where, P_{PV} = output power (W), G_T = solar irradiance on panel (W m^{-2}), A = panel area (m²), η = panel efficiency; and V = voltage (V), I = current (A).

Uncertainty Analysis of the System

Uncertainty analysis is essential for evaluating the reliability and accuracy of an automatic solar irrigation system. The system integrates photovoltaic energy generation, soil moisture sensing, water pumping, and automated control mechanisms. Measurement inaccuracies and environmental variations contribute to overall system uncertainty (Allen, Pereira, Raes, & Smith, 1998).

Uncertainties in the photovoltaic subsystem arise from solar radiation measurement accuracy (±2–5%), temperature effects on panel efficiency (±3–8%), dust accumulation, shading losses, and battery efficiency variations. Uncertainty sources in the irrigation unit include soil moisture sensor accuracy (±2–5%), flow meter accuracy (±1–3%), pump efficiency variations, and frictional pressure losses in pipelines. So, the total uncertainty of the system can be estimated from Equation 6 using the Root Sum Square (RSS) method for independent error sources (Duffie & Beckman, 2013; Taylor, 1997):

$$U_{total} = \sqrt{U_1^2 + U_2^2 + U_3^2 + \cdots + U_n^2} \quad (6)$$

where, U_{total} is the total system uncertainty, and U_n is the individual component uncertainty. Assuming solar radiation sensor uncertainty of ±3%, flow meter uncertainty of ±2%, and soil moisture sensor uncertainty of ±4%, the combined uncertainty from Equation 6 is:

$U_{total} = \sqrt{(3\%)^2 + (2\%)^2 + (4\%)^2} = \sqrt{9 + 4 + 16} = \sqrt{29} \approx 5.4\%$

Thus, the total experimental uncertainty of the system is approximately ±5–6%.

Additional uncertainties arise from seasonal solar variations, sudden cloud cover, ambient temperature fluctuations, and soil variability across the irrigation field. These factors introduce variability that cannot be fully eliminated but can be minimised through calibration and data averaging.

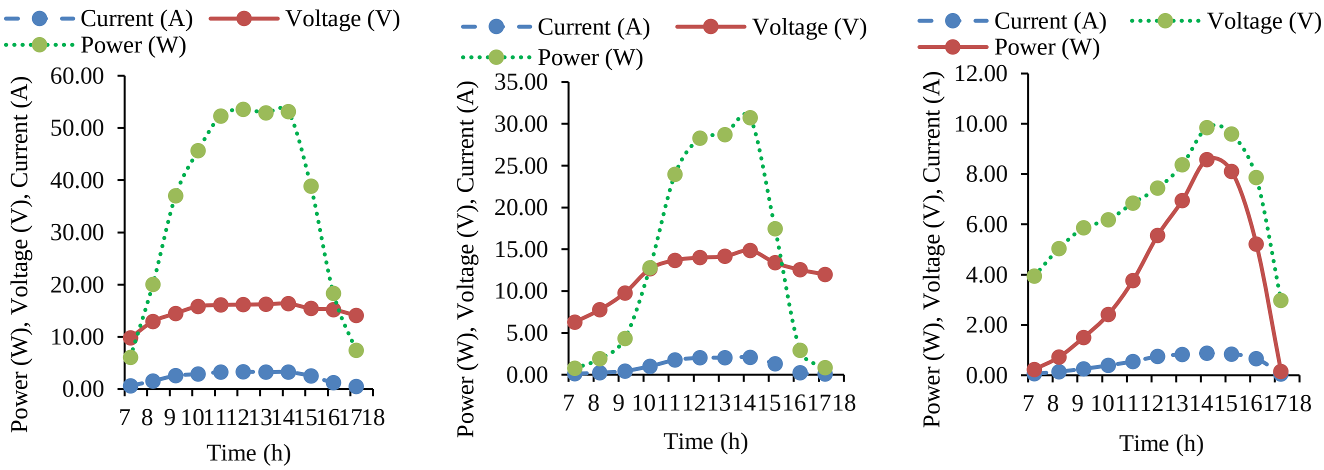
Results and Discussion

On a sunny day, the direct and indirect solar radiation intensities measured were 728.56 W m^{-2} and 52.23 W m^{-2} , respectively. During a cloudy day, these values decreased to 514.70 W m^{-2} and 5.27 W m^{-2}. The results of all three tests are detailed below.

The Results for the Solar Energy Absorption and Storage Unit

The analysis of the current, voltage, and instantaneous power generated by the solar panel under various conditions is illustrated in Fig. 10. The initial hypothesis suggested that the system would capture more solar energy on sunny days with an active tracker compared to both sunny and cloudy days with an inactive tracker. The data indicates that, on sunny days with the active tracker, the power output fluctuated throughout the day. Peak power levels, approaching the nominal 50 W specified by the manufacturer, were observed around midday. However, during the early morning and late afternoon hours, the power output declined due to reduced sunlight intensity. The average instantaneous power during sunny days with the active tracker was approximately 35.02 W. The highest energy collection occurred between 11:30 and 14:30. Interestingly, despite the panel's catalogue listing a voltage of 22.64 V, the maximum voltage recorded in the outdoor setting was approximately 16.60 V. Conversely, the current measured was about 31.3 A, which closely resembled the current observed on sunny days with the inactive tracker, at around 2.94 A. These findings highlight the variability in power output influenced by sunlight conditions and tracking system operation, emphasising the importance of optimal positioning and tracking for maximising solar energy absorption in outdoor environments.

The analysis compares the instantaneous power received by a solar panel under different conditions, focusing on sunny days with and without an active tracker. When the tracker is active, the panel receives more energy throughout the day, thanks to its ability to rotate and follow the sun, maximising exposure. In contrast, during days with the inactive tracker, the panel receives limited sunlight from sunrise until about 10 a.m., with peak energy levels occurring between 11:30 a.m. and 2:30 p.m., similar to the active mode. The average power during sunny conditions with the inactive tracker was 13.98 W, notably lower than with the active tracker, demonstrating the positive impact of tracking on power output. On cloudy days, the power levels drop significantly in both modes, with the inactive tracker receiving an average of only 3.93 W. This sharp decline highlights the reduced efficiency of the panel in overcast conditions, regardless of tracking. Overall, the data indicate that active tracking enhances energy collection during sunny periods, while cloudy conditions substantially diminish power output, emphasising the importance of tracking systems for optimising solar energy harvesting in clear weather.



(a) Sunny day with active tracker (b) Sunny day with inactive tracker (c) Cloudy day with inactive tracker

Fig. 10. Current, voltage, and instantaneous power received from the solar panel under different conditions

The analysis of variance (Table 1) indicates a significant difference in power values across different system modes, with a p-value below 0.05, confirming statistical significance at the 5% level. This suggests that system mode impacts power output significantly.

Table 1- Analysis of variance of the power values received by the system

SV	SS	DF	MS	F
Between groups	492.771	2	246.385	*8.732
Inside groups	169.293	6	28.215	
Total	662.064	8		

* Significant at the 5% level

The analysis reveals variations in total power output across different operational modes, with the highest power observed under sunny conditions using a tracker, and the lowest during cloudy conditions without a tracker. These findings indicate that sunlight and tracking systems significantly enhance energy absorption (Fig. 11). The observed power differences align with the initial research hypothesis, confirming its validity. Additionally, when compared to previous studies by Shahriari and Khoshbakht (2014), the results demonstrate strong consistency, supporting the reliability of the current findings and emphasising the positive impact of tracking systems and sunlight on system performance.

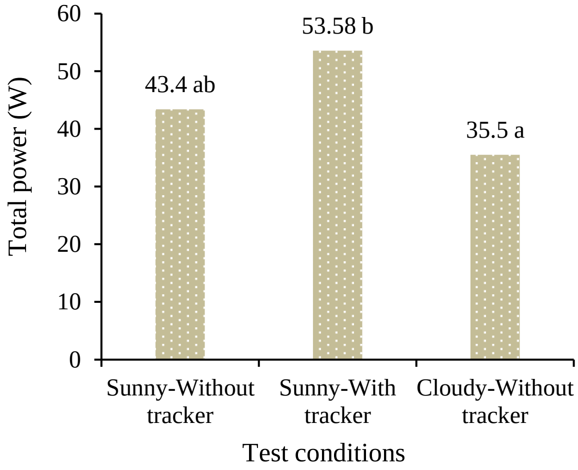


Fig. 11. Total power received by the system under different conditions

Results of the Solar Tracker Unit Evaluation

Fig. 12 illustrates the comparison between the desired panel orientation angles at various times of the day and the actual angles achieved during operation. It demonstrates that the tracker control system effectively adjusted the panel's position from sunrise to sunset, aligning it with optimal angles. A minor discrepancy exists between the actual and target angles, with an average RMSE of 16.60 degrees across all evaluated positions. This variation can be attributed to several factors, primarily the precision and sensitivity of the optical sensors. Higher sensor accuracy results in the actual panel angles closely matching the desired positions. Additionally, the mechanical components of the tracking system, such as the motor and gearbox, influence the accuracy. Mechanical imperfections or delays can contribute to the observed differences. To enhance the system's performance, improvements in the quality of the mechanical parts and sensors are recommended. Upgrading these components can reduce the RMSE value, thereby minimising the deviation between actual and desired angles. Overall, optimising both sensor sensitivity and mechanical reliability is essential for achieving more precise panel positioning, which can lead to increased efficiency in solar energy collection throughout the day. According to Sadeghi, Parenti, Memme, Fossa, and Morchio (2025) single-axis trackers achieve 20–35% higher energy yield than fixed-tilt PV systems, and dual-axis trackers offer energy gains ranging from 30% to 45% depending on geographic and climatic conditions. While, some studies have shown that the application of solar-tracker is not necessary for PV panels in regions where the average maximal power achieved from 11 AM to 02 PM every day, where the panel using the sun tracking shows a low average gain in power generated relative to the fixed panel (Vieira, Guerra, Vale, & Araújo, 2016; Wibowo, Bow, & Sitompul, 2021).

Results of the Evaluation of the Automatic Irrigation Unit

The soil moisture sensor was tested across three soil moisture levels: dry, semi-moist, and fully moist. In each case, three repetitions with three observations per repetition were conducted. During testing, the pump motor was activated in all three dry soil pots across all repetitions, indicating the system's response to low moisture levels. Conversely, in semi-moist and fully moist soils, the pump motor was not activated, demonstrating appropriate system behaviour under adequate moisture conditions. After constructing the disturbance matrix based on the data in Table 2, the system achieved an accuracy of 100% in irrigation performance. This indicates that the automatic irrigation system effectively maintains optimal soil moisture levels, ensuring proper plant hydration without unnecessary water use, thus confirming its reliability and precision in different soil moisture scenarios.

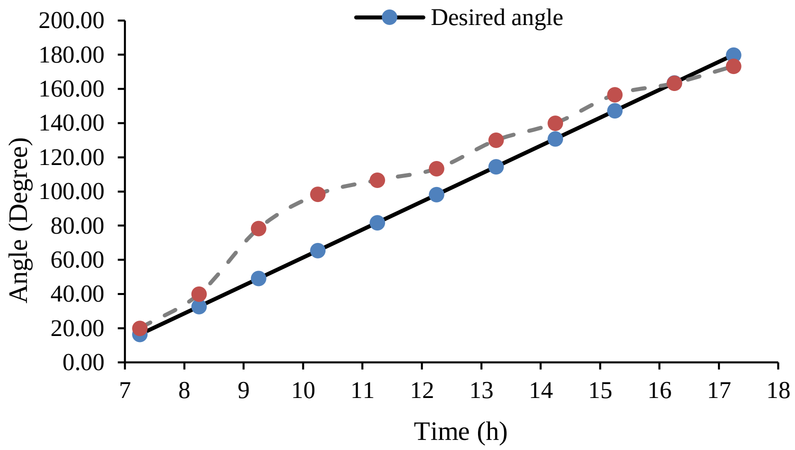


Fig. 12. Time response of the solar tracker unit at different hours of the day

Table 2- Irrigation unit performance in different soil moisture conditions

Soil type	Repetition	Active	Inactive	Accuracy (%)
Dry	9	9	0	100
Semi-moist	9	0	9	100
Moist	9	0	9	100

Conclusion

The necessity of this research is clear for several reasons, primarily the urgent need to conserve water due to increasing droughts, as well as the growing demand for clean energy in response to the environmental damage caused by fossil fuels. In this context, this research focuses on the design and construction of an automatic irrigation system powered by solar energy. To further optimise energy efficiency, a solar tracker unit was integrated into the system to enhance solar energy absorption. The photovoltaic system optimally captures solar energy between 11:30 and 14:30 under sunny conditions, regardless of whether a solar tracker is used. The analysis also revealed that adjusting the panel angle positively impacts system performance, with movable panels generating more energy than fixed ones. This underscores the benefit of incorporating solar trackers, which enhance energy collection efficiency. Additionally, the irrigation unit demonstrated perfect accuracy at 100%, indicating its effectiveness in automatically watering plants. However, soil moisture sensors' probe surfaces are prone to corrosion over time, which can impair functionality. To mitigate this issue, it is advisable to upgrade to higher-quality soil moisture sensors, ensuring long-term reliability and consistent system performance. Also, the total experimental uncertainty of the system is approximately ±5–6%. Overall, the system's design and components contribute significantly to its efficiency and operational effectiveness, making it a viable solution for sustainable energy and irrigation management.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

H. Masoudi: Supervision, Conceptualisation, Methodology, Technical advice, Data pre- and post-processing, Statistical analysis, Software services, Review and editing services

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ساخت و ارزیابی سامانه فتوولتائیک آبیاری خودکارمجهز به ردیاب خورشیدی تک‌محوره

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چکیده

با توجه به محدودیت‌ها و مشکلات زیست‌محیطی ناشی از سوخت‌های فسیلی، انرژی خورشیدی منبعی مطمئن و کاربردی برای آبیاری مزارع و باغ‌هایی است که به شبکه برق دسترسی ندارند. در این مطالعه، یک سیستم پمپاژ آب فتوولتائیک با استفاده از انرژی خورشیدی مجهز به ردیاب خورشیدی تک‌محوره به‌منظور آبیاری خودکار باغ‌ها و مزارع ساخته و ارزیابی شد. سیستم ساخته‌شده دارای واحدهای جذب و ذخیره انرژی خورشیدی، ردیاب خورشیدی و آبیاری خودکار است. انرژی دریافتی توسط پنل خورشیدی از طریق یک کنترل‌کننده شارژ به باتری منتقل شده و از طریق یک مبدل ولتاژ و یک درایور موتور برای فعال کردن پمپ آب استفاده می‌شود. مطابق نتایج آزمایش‌ها، سیستم بیشترین انرژی را بین ساعات ۱۰ صبح تا ۲ بعد از ظهر دریافت کرد. در شرایط آفتابی با ردیاب فعال، ۵۳/۵۸ وات در باتری ذخیره شد، در حالی‌که در شرایط آفتابی بدون ردیاب ۴۳/۴ وات و در شرایط ابری ۳۵/۳ وات در باتری ذخیره شد. همچنین، تأثیر ردیاب خورشیدی و زاویه پنل نسبت به خورشید بر دریافت انرژی در سطح ۵٪ معنی‌دار بود. ضمن این‌که، نوع حسگر رطوبت خاک تأثیر قابل‌توجهی بر عملکرد سیستم داشت که با تشکیل ماتریس اختلال، دقت آبیاری ۱۰۰٪ حاصل شد. در مجموع، ردیاب خورشیدی طراحی و استفاده شده در این پژوهش، در شرایط آفتابی عملکرد خوبی داشت و استفاده از آن در سامانه‌های فتوولتائیک برای آبیاری خودکار توصیه می‌شود.

واژه‌های کلیدی: آردوینو، انرژی خورشیدی، پمپ آب، حسگر رطوبت خاک، موتور الکتریکی

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