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Smart Solar Drip Irrigation System for Reducing Operational Carbon Emissions and Enhancing Water-Use Efficiency under Egyptian Agricultural Conditions

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ABSTRACT

Water scarcity, irrigation energy demand, and greenhouse gas emissions are the major constraints to sustainable agricultural production in arid regions. This paper proposes an integrated Smart Solar Drip Irrigation System (SSDIS), which is comprised of photovoltaic (PV) power generation, low-pressure drip irrigation, Internet of Things (IoT)-based soil-moisture sensing, automated irrigation control, and remote monitoring. For a typical one-acre tomato field, we performed hydraulic and photovoltaic design calculations and built a laboratory-scale prototype to test the sensing and control functions. The design procedure was to estimate crop water demand, irrigation flow rate, pipe sizing, total dynamic head, pump selection, and PV array sizing, followed by Energy, Exergy, Economic, and Environmental (4E) assessment. The estimated irrigation-water requirement was 30 m³/day, which was equivalent to a design flow rate of 5 m³/h for six hours of daily pumping. Hydraulic analysis gave a total dynamic head of 60 m, and a 1.5 kW submersible pump was selected. The final installed PV array capacity was 2.2 kWp, comprising four 550 W modules. The exergy efficiency was found to be about 8.5%. The estimated annual economic saving and simple payback period were 18600 EGP/year and 4.5 years, respectively. Prototype observations suggested that soil-moisture-based control reduced unnecessary irrigation events and allowed for demand-based water application. Prototype monitoring also indicated lower water delivery under the controlled drip-irrigation configuration than under the adopted flood-irrigation baseline. Because photovoltaic pumping does not require diesel combustion during normal operation, the proposed configuration also avoids direct fuel-combustion emissions at the point of use.

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Smart Solar Irrigation; IoT-Based Irrigation; Photovoltaic Water Pumping; Water-Use Efficiency; 4E Assessment.

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1. INTRODUCTION

Agricultural irrigation is a major user of water and energy, especially in arid and semi-arid regions where crop production is largely dependent on supplementary irrigation [1]. Increasing demand for agricultural water, limited availability of freshwater and energy required for groundwater pumping are important constraints to sustainable agricultural production in Egypt. Conventional irrigation methods, especially flood irrigation, result in considerable water losses due to evaporation, surface runoff and deep percolation [2]. Additionally, conventional electricity- and diesel-powered irrigation systems increase operating costs and contribute to greenhouse gas emissions. These challenges highlight the need for irrigation systems that can improve water-use efficiency and decrease reliance on conventional energy sources [3].

The combination of photovoltaic (PV) energy and efficient irrigation technologies represents an alternative pathway to tackle the interdependence between agricultural water and energy needs[4]. Solar-powered pumping systems can reduce the dependency on fossil fuels and are especially important for regions with high availability of solar resources[5]. In contrast, drip irrigation can deliver water directly to the crop root zone with relatively low operating pressure, which reduces unnecessary water losses and improves irrigation efficiency [6]. So, the combination of photovoltaic pumping and drip irrigation is an engineering approach that is appropriate for reducing the consumption of conventional energy, as well as the demand for irrigation water[7].

Improvements in irrigation systems have been achieved in the area of digital agriculture thanks to recent advances in the application of the Internet of Things (IoT), soil-moisture sensing, embedded controllers, wireless communication, and remote monitoring [8]. Sensor-based irrigation systems can apply water based on measured soil conditions instead of preset irrigation schedules[9]. At the same time, broader research on sustainable water management has highlighted the increasing importance of artificial intelligence and IoT-enabled monitoring for prediction, operational efficiency, and data-driven decision support across water-related systems [10]. Recent studies have also demonstrated that smart irrigation management systems can combine sensor-based monitoring and intelligent control to improve water-use efficiency and foster precision and climate-resilient agriculture [11].These developments are also favorable for the broader transition to intelligent sensor-driven water management systems, for instance, in precision irrigation applications.

However, the existing literature generally addresses smart irrigation control and solar-powered irrigation from different engineering perspectives. IoT-oriented studies are mostly related to sensing, communication, soil-moisture monitoring, automated irrigation scheduling, and remote supervision. Solar-irrigation studies usually emphasize hydraulic design, photovoltaic sizing, energy performance, economic feasibility, or environmental impacts [12]. Several studies have started to integrate some of these functions; however, relatively limited attention has been paid to systems that collectively consider sensor-based closed-loop irrigation control, remote monitoring, hydraulic and mechanical design, photovoltaic system sizing, and Energy, Exergy, Economic and Environmental assessment in a single framework, especially under Egyptian agricultural conditions. This division inhibits the possibility to assess both the operational behavior and the engineering sustainability of smart solar irrigation systems within a single design framework.

Thus, this study presents an integrated smart solar drip irrigation system (SSDIS) combining photovoltaic power generation, low-pressure drip irrigation, IoT-based soil-moisture sensing, automatic irrigation control, and remote monitoring. A small-scale prototype is implemented to test the sensing and threshold-based control functionalities, and the hydraulic, pumping and photovoltaic requirements are determined for a representative agricultural-scale tomato irrigation system. The engineering design includes estimation of irrigation-water demand, determination of flow rate requirement, sizing of pipe network, calculation of total dynamic head, pump selection and photovoltaic array sizing. The resulting configuration is then evaluated by an integrated 4E framework of Energy, Exergy, Economic and Environmental analysis.

The main contribution of this study is the integration of prototype smart irrigation control with agricultural-scale hydraulic and photovoltaic system design and the multidimensional 4E assessment. The proposed method integrates the sensing and control subsystem and the solar-powered pumping system into a common engineering framework, instead of evaluating each subsystem separately. This enables the system to be evaluated from operational, hydraulic, energetic, thermodynamic, economic, and environmental perspectives.

The paper is organized as follows. Section 2 discusses the related literature on solar-powered irrigation, IoT-enabled irrigation control, and integrated sustainability assessment. Section 3 describes the system architecture of the proposed system, including mechanical, electrical, control, and remote-monitoring parts of the experimental prototype. Section 4 presents the engineering design and mathematical analysis of the representative agricultural-scale system, including crop water requirements, hydraulic network design, total dynamic head, pump selection, and photovoltaic array sizing. Section 5 presents the integrated 4E (energy, exergy, economic, and environmental) evaluation. Section 6 presents system performance in terms of energy use, carbon-emission reduction, and water-use efficiency. Finally, Sections 7 and 8 present, respectively, future research directions and key findings of the study.

2. Literature Review

Solar-powered irrigation has received considerable attention as a potential approach for reducing the dependence of agricultural pumping on fossil fuels while supporting efficient irrigation practices. An early field investigation by Burney et al[13]. evaluated photovoltaic-powered drip irrigation in rural West Africa and demonstrated that the technology could provide economic and food-security benefits under water-constrained conditions. Their work established the practical potential of combining photovoltaic pumping with drip irrigation, although intelligent sensing and automated irrigation control were not the primary focus of the study [13]. Subsequent research increasingly focused on intelligent irrigation scheduling through sensing, communication, and data-driven control. Goap et al[14]. developed an IoT-based irrigation management system that combined soil and environmental sensing with weather forecasts and machine-learning-based soil-moisture prediction. The system was implemented at pilot scale and supported closed-loop irrigation control, demonstrating the potential of integrating field sensing, cloud services, and predictive decision-making [14]. Their system achieved an irrigation water-use efficiency of 41.23 kg/m³ compared with 31.58 kg/m³ under the conventional irrigation scheme considered in their experiment, emphasizing the importance of crop- and soil-responsive irrigation scheduling[15]. IoT-enabled drip irrigation has also been experimentally investigated under controlled agricultural conditions. Kumar et al[16]. developed a sensor-based drip irrigation system in which irrigation was automatically triggered according to soil-moisture thresholds and operational data were transmitted to a cloud platform. During a 31-day experiment, the proposed system achieved approximately 35% water savings relative to the evapotranspiration-based drip irrigation treatment while reducing pump operating time from 125 to 85 min.[16]. reviewed IoT-based smart irrigation systems and highlighted the roles of soil and environmental sensors, wireless communication, remote monitoring, and automated control in improving agricultural water management. Their analysis also identified implementation challenges associated with communication infrastructure, system cost, and large-scale deployment [17].

Alongside intelligent control, several studies have addressed the engineering and economic design of photovoltaic irrigation systems. Grant et al.[18] proposed the Solar-Powered Drip Irrigation Optimal Performance (SDrOP) model, which integrates agronomic, hydraulic, pumping, photovoltaic, and operational components to optimize solar-powered drip irrigation systems. For the investigated case, the optimized designs reduced life-cycle cost by up to 56% relative to designs obtained using commercial software, while comparison with field data indicated that the optimized design could satisfy approximately 92% of recorded irrigation events. These findings illustrate the importance of considering interactions among water demand, hydraulic requirements, pump characteristics, and photovoltaic generation rather than sizing individual components independently.

Thermodynamic and environmental analyses have further expanded the assessment of photovoltaic water-pumping systems. Chahartaghi and Nikzad[19] investigated a photovoltaic water-pumping system designed for irrigation of a one-hectare potato field and evaluated its energy, exergy, and environmental performance under different irradiation and temperature conditions. The reported exergy efficiency varied between approximately 0.27% and 3.56%, while replacing conventional energy sources with the photovoltaic system was estimated to avoid about 4.8 t of CO_2 emissions annually [19]. reviewed precision irrigation water-saving technologies under changing climatic conditions and highlighted the roles of sensing, automation, improved irrigation scheduling, and precision water application in enhancing water-use efficiency, crop productivity, and environmental performance. Their review also emphasized the continuing need for improved integration and practical implementation of precision irrigation technologies under diverse agricultural conditions[20].

The Egyptian agricultural context has also received increasing attention. Karnib et al.[19] investigated solar-powered drip irrigation for sugarcane production in Qena, Egypt, using a water–energy–food–ecosystem nexus framework. Their scenario-based assessment reported approximately 48% lower water use and 93% lower diesel-fuel consumption compared with diesel-powered surface irrigation, together with a 16% increase in sugarcane yield. The study provides important evidence regarding the potential sustainability benefits of solar-powered drip irrigation in Egypt; however, its primary emphasis was nexus-based sustainability assessment rather than the development and experimental validation of an IoT-enabled closed-loop irrigation control architecture.

More recently, researchers have begun to integrate solar energy, IoT infrastructure, automated control, and data-driven decision-making within unified smart-irrigation platforms. developed a four-layer IoT architecture based on an ESP32 microcontroller, environmental sensors, MQTT communication, and a Random Forest model for automated irrigation decision-making. The model achieved a reported accuracy of 99.3%, while a one-month comparative evaluation showed approximately 50% reductions in both water consumption and energy use relative to the investigated baseline. Although this work demonstrates the potential of combining IoT, intelligent control, and solar energy, its main emphasis was greenhouse automation and AI-assisted irrigation rather than comprehensive agricultural-scale hydraulic design and simultaneous Energy, Exergy, Economic, and Environmental assessment[21].

Overall, the literature shows notable progress in the fields of photovoltaic water pumping, IoT-enabled irrigation, soil-moisture-based automated control, hydraulic optimization, and sustainability assessment, as shown in **Table 1.** However, these fields are often studied in isolation or with a focus on only a subset of the relevant technical and sustainability dimensions. In Egypt, integrated approaches combining design of hydraulic and mechanical systems, photovoltaic sizing, sensor-based closed-loop irrigation control, remote monitoring, and Energy, Exergy, Economic, and Environmental assessment have received little attention. The present study therefore develops an integrated Smart Solar Drip Irrigation framework and utilizes a prototype to validate the sensing, monitoring, and automated control strategy while the hydraulic and energy requirements of a representative agricultural-scale irrigation system are evaluated through engineering calculations and an integrated 4E assessment.

Table 1: Comparative Summary of Related Studies on Smart Solar Irrigation Systems

Ref	System / Method	Main Evaluation	Key Findings	Research Limitation
[13]	Solar-powered drip irrigation evaluated under field conditions	Agricultural, economic, and water-use performance	Demonstrated practical benefits of photovoltaic-powered drip irrigation for improving food security and agricultural productivity	Did not investigate IoT-based sensing, automated irrigation control, or integrated thermodynamic assessment
[14]	IoT-based smart irrigation integrating environmental sensing, weather information, machine learning, and closed-loop control	Irrigation scheduling and intelligent monitoring	Demonstrated the feasibility of sensor-driven and predictive irrigation management at pilot scale	Did not consider photovoltaic system design, hydraulic sizing, or integrated 4E assessment
[15]	Real-time soil-moisture-based irrigation control for greenhouse tomato production	Water-use efficiency and irrigation performance	Reported an irrigation water-use efficiency of 41.23 kg/m³ compared with 31.58 kg/m³ for the reference irrigation scheme	Focused on irrigation control without photovoltaic energy or comprehensive sustainability assessment

[19]	Photovoltaic water-pumping system for agricultural irrigation	Energy, exergy, and environmental performance	Reported exergy efficiencies of approximately 0.27–3.56% and estimated annual CO_2 avoidance of about 4.8 t	Did not include IoT-based monitoring or automated irrigation control
[18]	Integrated agronomic, hydraulic, pumping, and photovoltaic optimization using the SDrOP model	Hydraulic and techno-economic performance	Reduced life-cycle cost by up to 56% relative to commercial-software-based designs	Focused on system optimization without real-time sensor-based control or remote monitoring
[17]	Review of IoT-based smart irrigation systems	IoT architectures, sensing, communication, and automation	Identified the main technological benefits and implementation challenges of smart irrigation	Review study without implementation of an integrated solar-powered irrigation framework
[20]	Review of precision irrigation water-saving technologies	Water-use efficiency, crop productivity, and environmental performance	Highlighted the potential of sensing and automated irrigation scheduling to improve water-use efficiency	Review-based assessment rather than implementation of an integrated smart solar irrigation system
[22]	Solar-powered drip irrigation for sugarcane in Egypt using a WEFE-nexus framework	Water, energy, environmental, and sustainability performance	Reported approximately 48% lower water use and 93% lower diesel consumption	Focused on nexus-based sustainability assessment rather than IoT-enabled closed-loop irrigation control
[21]	ESP32-based IoT irrigation platform integrating MQTT, environmental sensing, solar energy, and Random Forest	Intelligent control, water use, and energy consumption	Reported 99.3% classification accuracy and approximately 50% reductions in water and energy consumption	Primarily focused on AI-assisted greenhouse irrigation rather than complete hydraulic, exergy, and economic system assessment

3. THE PROPOSED SYSTEM DESCRIPTION AND EXPERIMENTAL METHOD

This study proposes a Smart Solar Drip Irrigation System designed to improve irrigation efficiency and reduce water use, energy consumption, and operational carbon emissions in agriculture. The proposed framework brings together photovoltaic (PV) power generation, low-pressure drip irrigation, IoT-enabled sensing, and automated irrigation management within an integrated intelligent irrigation system. The system uses renewable solar energy and real-time soil moisture data to enable demand-based irrigation scheduling that optimizes water application according to crop water requirements and measured soil-moisture conditions. This integrated approach enhances the use of resources, improves operational efficiency, and supports environmentally sustainable farming practices. A prototype was experimentally implemented to validate the sensing and control strategy, whereas the hydraulic and energy analyses were conducted for a representative agricultural-scale irrigation system.

Figure 1 shows the overall architecture of the proposed Smart Solar Drip Irrigation System. The system integrates photovoltaic power generation, water pumping and distribution, soil-moisture sensing, automated control, remote monitoring, and drip irrigation into a single integrated system. The experimental prototype was developed to verify the sensing, control, and monitoring functions, while hydraulic and photovoltaic requirements at an agricultural scale were evaluated through engineering design calculations.

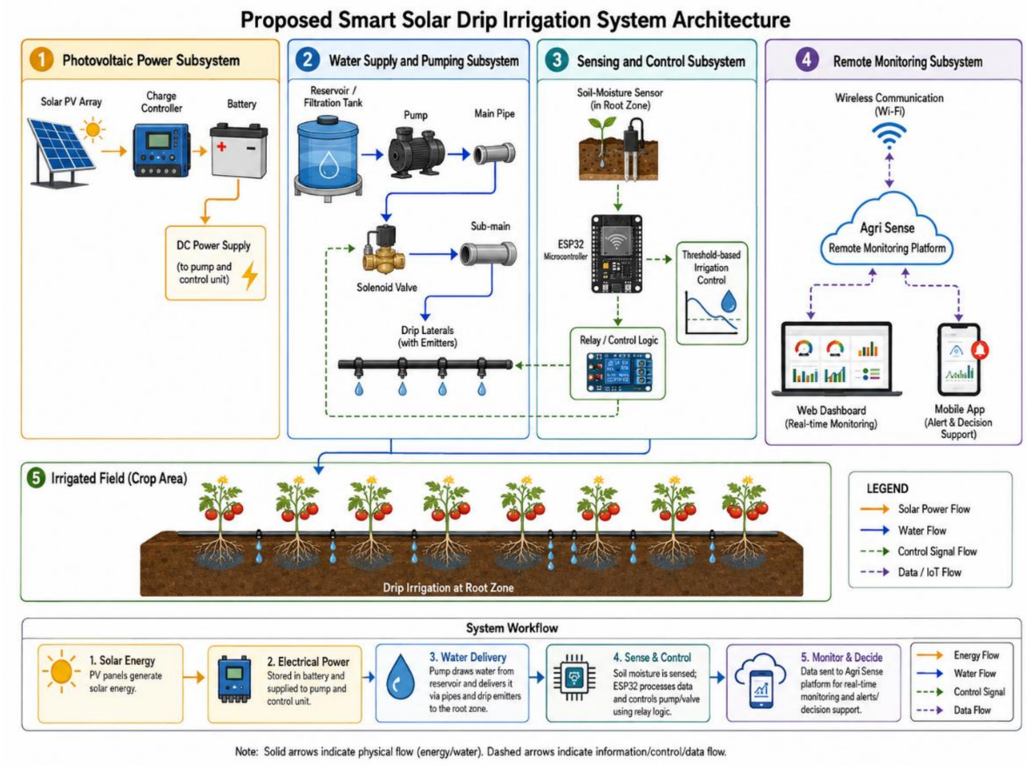


Figure 1: Overall architecture of the proposed Smart Solar Drip Irrigation System

3.1 System Description

The proposed Smart Solar Drip Irrigation System is composed of five main subsystems: photovoltaic (PV) power generation system, water pumping system, drip irrigation system, IoT-based sensing and control system, and remote monitoring system. The photovoltaic unit supplies the electrical energy required for the operation of the irrigation system; a rechargeable battery and charge controller provide energy storage and power management for the prototype under variable solar-irradiance conditions. A prototype of the proposed system was built and experimentally tested on the roof of the Faculty of Engineering, Suez Canal University at Ismailia, Egypt. The prototype is a small-scale experimental setup developed to reproduce the main sensing, control, pumping, and irrigation functions of the proposed system. The integration of renewable energy, sensor-based monitoring, and automated irrigation control enables real-time monitoring of soil conditions and demand-based irrigation scheduling, improving operational efficiency and facilitating sustainable agricultural water management. **Figure 2** illustrates the proposed system architecture, while **Figure 3** shows the experimental prototype.

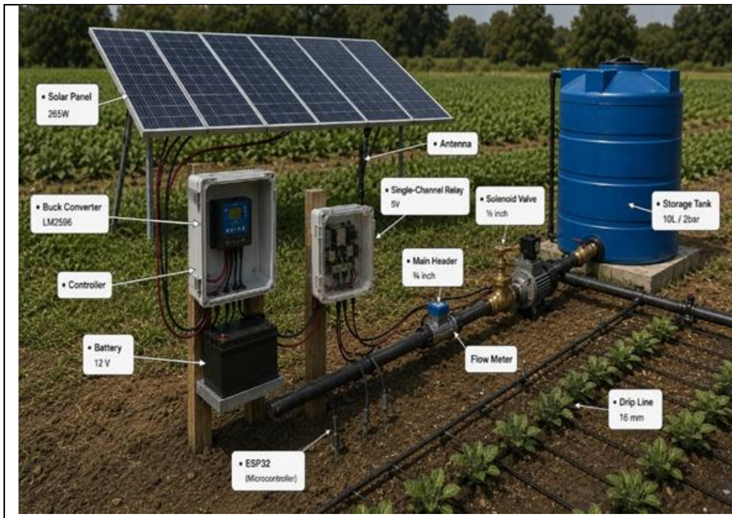


Figure 2: Proposed system layout (illustrative design).

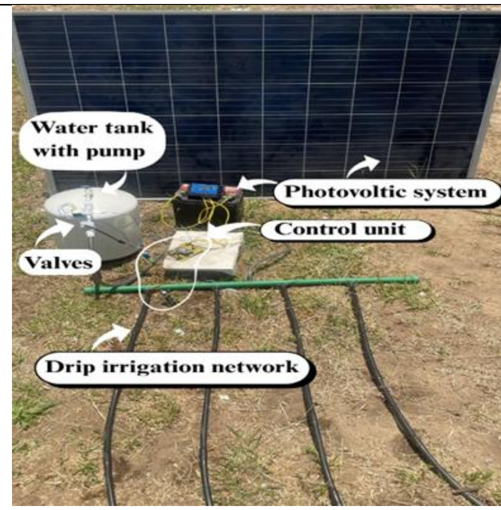


Figure 3: Overall Prototype Layout.

3.2 Mechanical Components

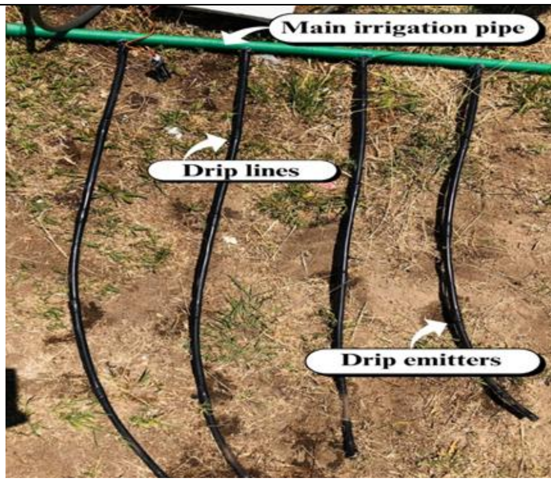
The mechanical subsystem of the experimental prototype consists of a water reservoir, a pumping unit, a distribution line, drip-irrigation laterals, emitters, manual valves, solenoid valves, and the required fittings. The prototype water-supply unit consists of a 10 L water tank equipped with a built-in pump operating at approximately 2 bar. Therefore, the prototype did not require an external pump because the built-in pump provided the pressure needed to operate the small-scale drip network. The irrigation network was configured according to low-pressure drip-irrigation principles to support efficient and controlled water delivery. It consists of a main distribution line connected to drip laterals equipped with emitters and flow-regulating valves. This configuration supports uniform water distribution and supplies water directly to the root zone, thereby reducing evaporation and deep-percolation losses and improving water-use efficiency.

3.3 Electrical Components

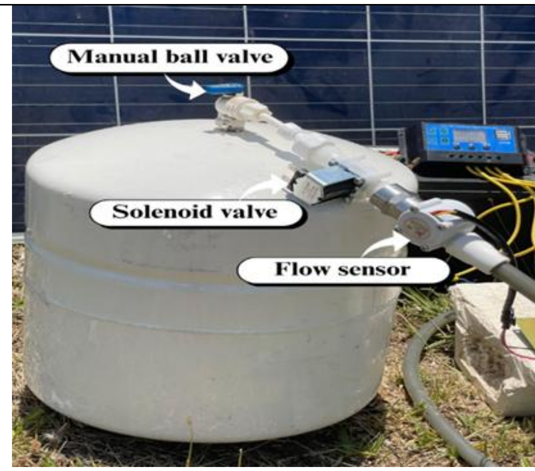
The electrical subsystem of the experimental prototype includes a photovoltaic (PV) module, a rechargeable battery, a charge controller, a relay module, sensors, and a water pump. The PV module serves as the primary energy source by converting incident solar radiation into electrical energy for system operation. Available excess PV energy can be stored in the rechargeable battery for subsequent use under reduced solar-irradiance conditions. The charge controller regulates the battery charging and discharging processes and protects the battery from overcharging and deep discharge. The ESP32 control unit interfaces with the water pump and solenoid valve through a relay module that provides the required switching function. Based on real-time sensor measurements, the controller generates commands to activate or deactivate the irrigation components. This configuration provides a compact solar-powered electrical system suitable for automated irrigation control at the prototype scale.

3.4 Control System

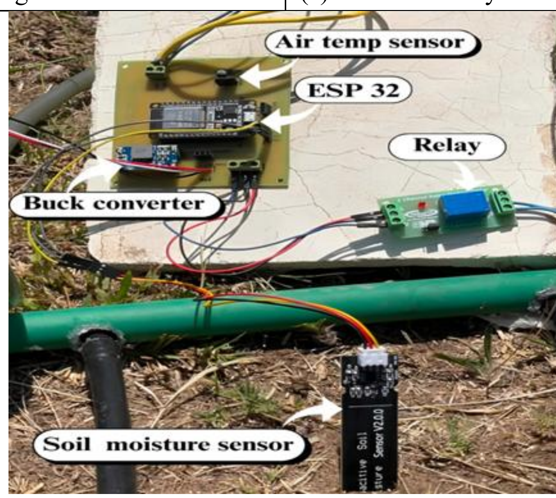
The control subsystem is based on an ESP32 microcontroller configured for soil-moisture monitoring and automatic irrigation control. A soil-moisture sensor continuously measures the moisture level in the root zone and transmits real-time data to the ESP32 for processing. The measured soil-moisture level is compared with a predefined threshold. When the moisture level falls below this threshold, the ESP32 activates the relay module to operate the water pump and open the solenoid valve, thereby initiating irrigation. Irrigation is terminated when the specified soil-moisture condition is restored, after which the controller deactivates the pump and closes the solenoid valve. This closed-loop, threshold-based control strategy enables demand-driven irrigation and reduces unnecessary irrigation and pump operation. Continuous real-time monitoring also reduces the need for manual intervention and supports the maintenance of the desired soil-moisture conditions**. Figure 4** shows the experimental setup and its main components.



(a) Drip Network Irrigation



(b) Valve Assembly.



(c) Control unit

Figure 4. Photo of the system setup with different components.

3.5 System Operation

During operation, water is pumped from the reservoir and distributed through the valve assembly to the drip-irrigation network. The irrigation process is continuously tuned based on real-time soil moisture data acquired by the sensor devices. If the sensed moisture is less than the threshold level, the ESP32 controller will activate the relay module. This will activate the water pump and open the solenoid valve to start irrigation. The drip emitters also uniformly deliver the water directly to the crop root zone, providing precise water application and minimizing evaporation and deep percolation losses. The controller automatically turns off the pump and closes the solenoid valve when the desired soil moisture level is obtained, and the cycle of irrigation is completed. This automated and demand-responsive operational approach improves the water distribution, reduces the energy consumption of pumping, and increases the overall system effectiveness and sustainability, making the proposed system highly suitable for precision irrigation in water-limited environments.

3.6 Analysis of Uncertainty

The uncertainty analysis was carried out to evaluate the precision and reliability of the measured parameters in the proposed smart solar drip irrigation system. The standard uncertainty U of the measured parameters was determined using the following relation based on the instrument accuracy(±a):

$$\text{Standard Uncertaintiy (U)} = \frac{\text{Accuracy (a)}}{\sqrt{3}}$$

The root-sum-square method was used to estimate the combined uncertainty (δ) for the derived parameters, such as irrigation efficiency, solar conversion efficiency, and battery state-of-charge estimation:

$$\delta = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 \delta_x^2 + \left(\frac{\partial F}{\partial y}\right)^2 \delta_y^2}$$

Where the measured variables x and y uncertainties are denoted by δx and δy, respectively. The partial derivatives of the targeted parameter F with respect to x and y are ∂F/∂x and ∂F/∂y. Instrumentation, accuracy, and total uncertainties for the main system components are summarized in **Table 2**. From this table, it can be seen that all values fall within the permissible range, which indicates the overall reliability of the experimental performance evaluation.

Table 2: Instrumentation accuracy and uncertainty of the measured parameters.

No.	Parameter	Instrument	Accuracy (a)	Uncertainty (U)
1.	Soil Moisture (%)	TDR Soil Moisture Meter [20]	±3%	1.73%
2.	Water Flow Rate (L/min)	Graduated Cylinder + Stopwatch	±5%	2.89%
3.	Air Temperature (°C)	Calibrated PT100 Thermometer	±0.5°C	0.289°C
4.	Solar Irradiance (W/m²)	Pyranometer	<7 W/m²	4.04 W/m²
5.	Battery Voltage (V)	Digital Multimeter	±0.05 V	0.0289 V

3.7 Web Monitoring System

A digital monitoring platform was developed to enable real-time monitoring and remote management of the proposed smart irrigation system. The ESP32 microcontroller connects to the platform through Wi-Fi, allowing it to constantly send operational data to an easy-to-use mobile web application. The interface allows users to access real-time data on soil moisture, pump status, irrigation operations, and system alerts from their smartphones, tablets, and personal computers. This surveillance system, Agri Sense, was designed specifically to allow remote oversight and increase operational accessibility. Besides showing the sensor data and irrigation conditions, the application also allows users to monitor the overall system performance through an engaging and adaptive interface. Agri Sense combines an AI-based decision support system linked to an extensive agricultural knowledge repository that contains crop-specific data, such as growth stages, irrigation requirements, and fertilization schedules, to enhance precision agriculture. By integrating present field conditions with historical agronomic data, the smart assistant provides recommendations to facilitate irrigation planning and crop management, especially for those with limited agronomic know-how. The platform offers crop progress tracking and automated alerts for irrigation schedules, fertilizer use, and key crop development stages, enhancing operational planning and reducing routine management tasks. Agri Sense integrates real-time monitoring, smart decision support and automated farm management into one platform that improves resource efficiency, reduces manual labor and encourages more effective, sustainable and data-driven agricultural practices. The novel Agri Sense platform logo and dashboard are shown in **Figures 5 and 6**, while the report and notification pages are presented in **Figures 7 and 8**.

Figure 5: Agri Sense platform logo.

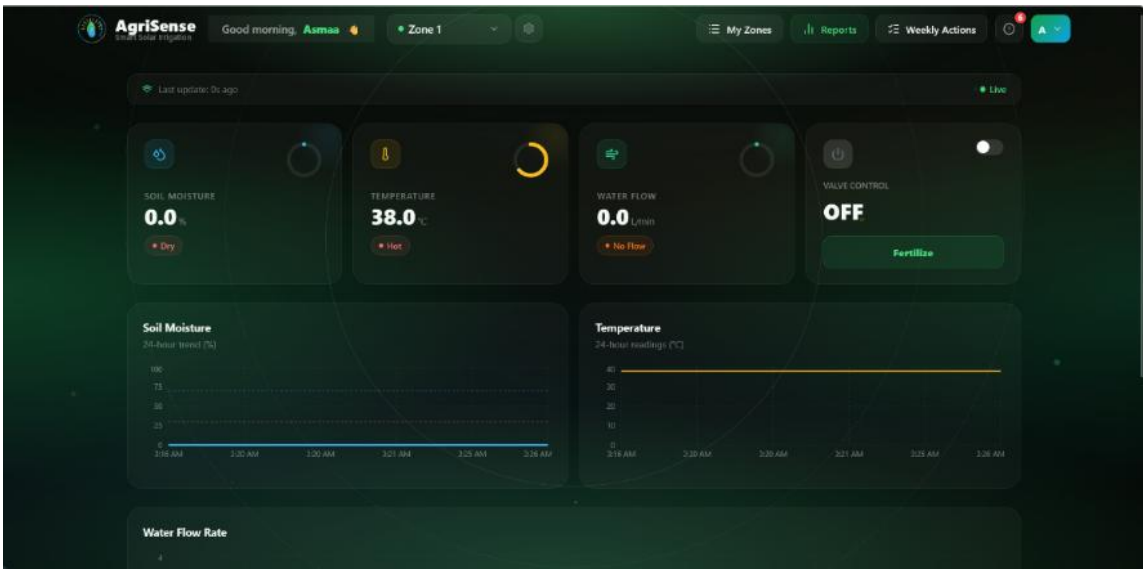


Figure 6: Agri Sense Dashboard.

Figure 7: Agri Sense Report Page.

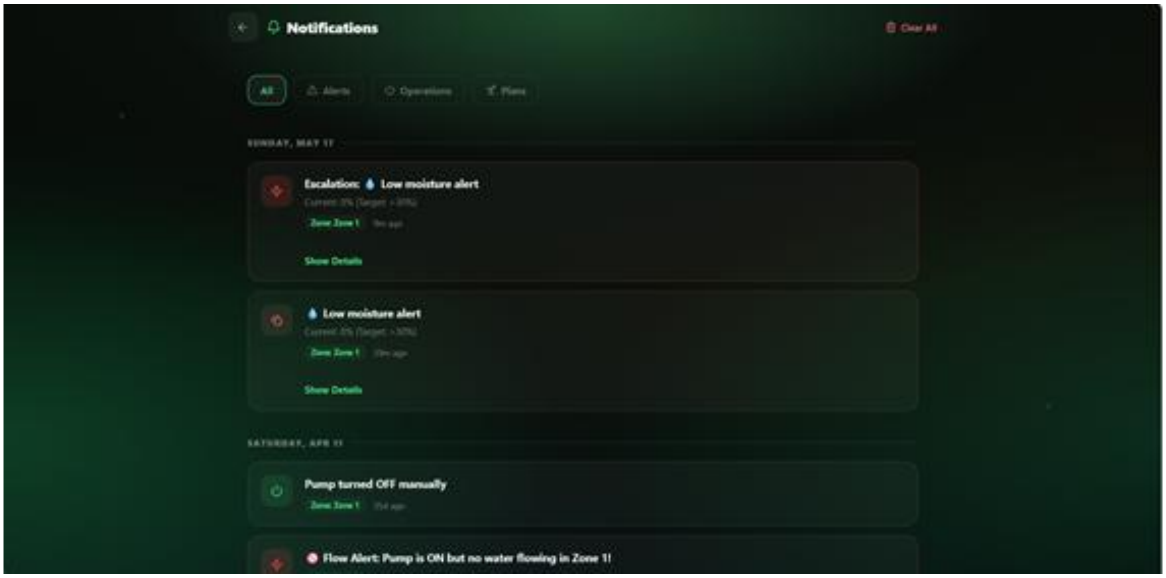


Figure 8: Agri Sense Notifications page.

4. ENGINEERING DESIGN AND MATHEMATICAL ANALYSIS

This section explains the engineering design and mathematical framework and engineering process involved in the development of the proposed Smart Solar Drip Irrigation System. The adopted strategy defines the hydraulic, mechanical, and photovoltaic design criteria to guarantee reliable irrigation efficiency with minimum water consumption, energy consumption, and running costs. Design calculations were made for a one-acre tomato farm irrigated by a photovoltaic-powered low-pressure drip irrigation system. The mathematical framework defines the main design parameters, such as agricultural water demand, irrigation flow rate, pipeline characteristics, hydraulic losses, total dynamic head (TDH), pump power, and the size of the photovoltaic (PV) array. The design approach was carried out by means of a systematic engineering process, which involved the choice of irrigation methods, the evaluation of crop water requirements, the hydraulic network configuration, the calculation of total dynamic head, the dimensioning of the pumps, and the planning of the photovoltaic system. The calculations are based on the average operational parameters of the research area, with a cultivated area of 1 acre, a constant groundwater level of 20 m and an average maximum solar exposure of 6 hours per day. The above premises form the basis for the evaluation of the technical efficiency of the suggested irrigation system.

4.1 Irrigation Method Selection

The choice of a proper irrigation technique is an important aspect in designing effective irrigation systems because of variations in water-use efficiency, energy requirements, installation costs, and operational efficiency of different methods. The present study was carried out to compare the center pivot and drip irrigation systems to select the most suitable system for the proposed solar-powered irrigation system. Center pivot irrigation is commonly used in large-scale farming but is often hampered by evaporation and wind drift losses, especially in hot and dry climates. It also typically requires higher installation costs, more pumping capacity, and increased energy consumption. On the other hand, drip irrigation delivers water directly to the crop root zone via low-flow emitters, greatly reducing evaporation, surface runoff and deep percolation losses. Thanks to its low operating pressure, accurate water distribution and high irrigation efficiency, it is especially suitable for photovoltaic pumping systems. Moreover, the lower flow-rate requirement contributes to decreasing the power requirements for pumps and the size of the photovoltaic system. Low-pressure drip irrigation was selected as the irrigation technique for the proposed Smart Solar Drip Irrigation System due to its improved water-use efficiency, lower energy requirement, and higher suitability for sustainable precision agriculture, considering the technical and operational advantages.

4.2 Crop Water Requirement and Flow Rate Calculation

The proposed system was designed for a one-acre tomato field with a daily irrigation water requirement of 30 m 3 /day, which was adopted. Considering one irrigation cycle per day and six peak-sun hours of pumping, the design flow rate needed was calculated at 5 m3/h. This value was used for sizing pipe networks and pump selection.

Table 3 compares the water consumption of different irrigation methods. Drip irrigation requires about 25–35 m^3/day per acre, and conventional flood irrigation requires about 200–300 m^3/day per acre. The significantly lower water requirement of drip irrigation is due mainly to the direct delivery of water to the crop root zone, which minimizes losses through evaporation, surface runoff, and deep percolation. The relatively low operating pressure and flow requirements of drip irrigation are also a beneficial match for photovoltaic-powered pumping systems and may reduce the required pumping and PV capacities[23].

Table 3: Water Consumption per Acre based on Irrigation Method [23].

Irrigation Method	Water consumption per acre (m^3)
Drip	25:35
Pivot	20:30
Sprinkler	20:30
Flood	200:300

4.3 Pipe Network Design

The irrigation pipeline system was designed for a calculated discharge of 5 m^3/h to ensure consistent distribution of water, minimize friction losses, and maintain adequate flow velocities throughout the system. The selection of pipe diameters was according to the standard irrigation design practices, considering the recommended velocities of each section of the pipeline namely main pipe, sub-main pipe, and drip laterals. The velocity of flow is maintained within the specified range of values, thus decreasing major head losses, preventing sedimentation and ensuring reliable hydraulic performance during continuous operation. Then, suitable flow velocities were determined, and the corresponding pipe diameters were chosen according to the maximum allowable flow rates. The continuity equation was then used to verify the hydraulic efficiency of the selected primary pipeline so that the working velocity meets the design parameters. The main pipe carries the discharge of the entire system and thus can be operated at the highest velocities. The sub-main and lateral pipes are recommended to operate at lower velocities to reduce the pressure losses and provide uniform water distribution to all emitters. By maintaining the flow velocity within these recommended limits the hydraulic stability is increased, the energy consumption is reduced, and the lifetime of the piping system is extended by reducing erosion and excessive pressure variations. The proposed values were established as the hydraulic design standards for the calculation of the irrigation system dimensions.

The maximum flow capacity for commercially available pipe diameters was presented in **Table 4** and was used to determine the suitable sizes of the primary pipeline. The required discharge of the system is 5 m^3/h. Therefore, a 1.5 in pipe with a maximum capacity of 8 m^3/h was selected. This capability provides a safety margin without oversizing, which would increase installation costs. The selected pipe therefore satisfies the hydraulic requirements of the intended irrigation system and has sufficient capacity for reliable operation under the given flow conditions.
The outlet diameter (Main line) = 1.5 inches.

Table 4: Flow velocity distribution in the irrigation network [23].

Pipe	Velocity (m/s)
Main pipe	1: 1.5
Sub-main	0.8: 1.2
Laterals	0.5: 1

The irrigation network pipe diameters were selected to satisfy the required flow conditions while maintaining suitable velocities and limiting hydraulic losses within the distribution system. As summarized in **Table 5**, a 1.5-inch diameter was adopted for the main pipe because it carries the total system discharge. The sub-main lines were selected within a diameter range of 1.0–1.25 inches to distribute the flow from the main line to the irrigation laterals while maintaining acceptable pressure losses. For the drip laterals, a diameter of 16 mm was used to deliver water directly to the emitters along the crop rows. This configuration provides a gradual reduction in pipe diameter from the main line to the laterals, which supports stable water distribution and efficient operation of the drip irrigation network.

Table 5: Irrigation Network Pipe Diameters [23].

Pipe	Diameter (inch)
Main pipe	1.5
Sub-main	1: 1.25
Laterals	16 mm

4.4 Total Dynamic Head Calculation

The Total Dynamic Head (TDH) represents the total energy required by the pump to deliver water from the groundwater source to the irrigation network. Several head components were considered, including static water level, drawdown head, friction losses and required irrigation pressure head. Friction losses within the piping network were calculated using Hazen - William's equation [24]:

$$\mathrm{h_f} = 10.67\left(\mathrm{LQ^{1.852}}/\mathrm{C^{1.852}d^{4.87}}\right)$$

The total dynamic head was calculated as:

$$\mathrm{TDH} = \mathrm{Static\ Head} + \mathrm{Drawdown\ Head} + \mathrm{Pressure\ Head} + \mathrm{Friction\ Losses}$$

Substituting the design values: $\mathrm{TDH} = 20 + 8 + 15 + 17 = 60\ m$, The calculated TDH value was used for pump selection and performance evaluation.

4.5 Pump Selection.

The irrigation pump was chosen according to the calculated design flow rate and total dynamic head (TDH) [25]. Using the manufacturer's performance graphs, the required operating point of 5 m³/h at the calculated TDH was determined to guarantee reliable and effective performance. Based on these design specifications, the GRUNDFOS SP7-12 stainless-steel submersible pump, with an MS402 three-phase motor, was chosen. The selected pump has nominal power of 1.5 kW and an efficiency close to 65%, satisfying the hydraulic demands of the proposed irrigation system. The design operating point falls within the manufacturer's recommended high efficiency zone, ensuring consistent water delivery, reduced energy consumption, and reliable long-term performance under the specified irrigation conditions.

4.6 Photovoltaic Array Sizing

The photovoltaic (PV) array was sized to supply the electrical power required by the selected irrigation pump while accounting for expected electrical losses and variations in temperature and solar irradiance. According to the design guidelines presented in [23], the required PV array capacity was estimated as 1.2–1.3 times the nominal pump power. For the selected 1.5 kW pump, the required PV capacity range was calculated as

$$P_{PV,min} = 1.2 \times 1.5 = 1.80\text{kW}$$
$$P_{PV,max} = 1.3 \times 1.5 = 1.95\text{kW}.$$

Using PV modules rated at 550 W each, the required number of modules was determined as

$$N_{PV} = 1950/550 = 3.55,$$

which was rounded up to four modules. Accordingly, the installed PV array capacity was $4 \times 550 = 2200$W, or 2.2 kWp. Therefore, four 550 W photovoltaic modules were selected to provide the required installed capacity for the proposed irrigation system.

As summarized in **Table 6**, the selected JKM550M-72HL4 photovoltaic module has a rated maximum power of 550 W, with a maximum power voltage of 40.90 V and a maximum power current of 13.45 A. The module provides an open-circuit voltage of 49.62 V and a short-circuit current of 14.03 A, with a reported conversion efficiency of 21.29%. It is designed for a maximum system voltage of 1500 V DC and a maximum series fuse rating of 25 A. The module also exhibits temperature coefficients of −0.35%/°C for maximum power, −0.28%/°C for open-circuit voltage, and +0.048%/°C for short-circuit current, with a nominal operating cell temperature of 45 ± 2 °C. These electrical and thermal characteristics were considered in selecting the PV modules for the proposed irrigation system and in determining the final installed array capacity of 2.2 kWp [23].

Table 6. Solar panel Specifications [23]

Parameter	Symbol	Value
Module Type	–	JKM550M-72HL4
Maximum Power	P_{max}	550 W
Maximum Power Voltage	V_{mp}	40.90 V
Maximum Power Current	I_{mp}	13.45 A
Open-Circuit Voltage	V_{oc}	49.62 V
Short-Circuit Current	I_{sc}	14.03 A
Module Efficiency	H	21.29 %
Maximum System Voltage	–	1500 V DC
Maximum Series Fuse Rating	–	25 A
Power Tolerance	–	0 to +3 %
Temperature Coefficient of Power	γ_{Pmax}	−0.35 %/°C
Temperature Coefficient of Voltage	βV_{oc}	−0.28 %/°C
Temperature Coefficient of Current	αI_{sc}	+0.048 %/°C
Nominal Operating Cell Temperature	NOCT	45 ± 2 °C
Operating Temperature Range	–	−40 to +85 °C

4.7 Summary of Design Calculations

The engineering design process was used to establish the main specifications of the proposed Smart Solar Drip Irrigation System. The hydraulic design was based on a tomato cultivation area of 1 acre (approximately 4047 m²), with an estimated irrigation-water requirement of 30 m³/day. Assuming six peak-sun hours of pumping per day, the corresponding design flow rate was determined as 5 m³/h. The hydraulic analysis resulted in the selection of a 1.5-

inch main pipeline to maintain the flow velocity within the recommended range while limiting friction losses. A 1.5 kW submersible pump was selected to satisfy the design operating point of 5 m³/h at a total dynamic head (TDH) of 60 m. The pump was designed to be supplied by a 2.2 kWp photovoltaic array comprising four 550 W PV modules. The adopted design parameters are summarized in **Table 7** and provide the basis for the subsequent energy, exergy, economic, and environmental analyses.

Table 7. Summary of the Adopted System Design Parameters

Parameter	Value
Cultivated area	1 acre (≈4047 m²)
Crop	Tomato
Daily irrigation-water requirement	30 m³/day
Design flow rate, Q	5 m³/h
Total dynamic head, TDH	60 m
Rated pump power	1.5 kW
Installed PV array capacity	2.2 kWp
Number of PV modules	4
Rated power per PV module	550 W

5. 4 E ANALYSIS

5.1 Energy Analysis

Energy analysis evaluates the capability of the proposed smart solar irrigation system to convert solar energy into useful hydraulic energy used for irrigation. The assessment included the determination of hydraulic power requirements, pump power demand, energy consumption, solar energy generation, and overall system efficiency.
The hydraulic power required to deliver irrigation water was determined using[26] :

$$P_h = \rho \, g \, Q \, H$$

Where: P_h is the hydraulic power (W), ρ is water density (kg/m³), g is gravitational acceleration (m/s²), Q is the water flow rate (m³/s), and H is the total dynamic head (m). The pump input power was calculated as [26]:

$$P_{in} = P_h / \eta p$$

Where: η_p is the pump efficiency. The daily electrical energy consumption was evaluated using:

$$E = P \times t$$

Where**:** E is the energy consumption (kWh), P is the operating power (kW), and t is the operating duration (h). The PV to hydraulic efficiency of the solar irrigation system was determined from:

$$\eta \text{ pvh} = P_h / \text{Psolar}$$

Where: P_{solar} is the rated photovoltaic power. The results showed that the photovoltaic system generated sufficient energy to satisfy the irrigation demand while maintaining stable operation throughout the growing season.

5.2 Exergy Analysis

Exergy analysis was performed to evaluate the quality of solar energy utilization and identify the irreversible losses within the proposed photovoltaic irrigation system. Unlike conventional energy analysis, exergy analysis considers the useful work potential of the available solar energy, providing a more realistic assessment of the overall system performance. The annual average solar radiation at the project location (Ismailia, Egypt) was obtained from the NASA POWER Data Access Viewer (DAV) [27] and used as the input energy source for the exergy calculations. The obtained data was validated with the measured data for the tested experimental days. The incident solar energy on the photovoltaic array was calculated as [28]:

$$\mathrm{E\ solar} = \mathrm{G_{avg}} \times \mathrm{A_{PV}}$$

Where: E_solar is the solar energy (kWh/day), G_avg is average daily solar radiation (kWh/m²/day), and A_{PV} is total photovoltaic array area (m²).
The solar exergy was estimated using the Petela factor as :

$$\mathrm{Ex_{solar}} = 0.933 \times \mathrm{E_{solar}}$$

The useful hydraulic exergy was considered equal to the useful hydraulic energy delivered by the pumping system:

$$\mathrm{Ex_{hyd}} \approx \mathrm{E_{hyd}}.$$

The exergy efficiency of the proposed irrigation system was determined by [28]:

$$\Psi = \mathrm{Ex}_{hyd}/\mathrm{Ex_{solar}}$$

The exergy destruction within the system was calculated using:

$$\mathrm{Ex_{destroyed}} = \mathrm{Ex_{solar}} - \mathrm{Ex_{hyd}}$$

Exergy destruction represents the irreversible losses occurring throughout the energy conversion process, including photovoltaic conversion losses, electrical losses, pump inefficiencies, and hydraulic friction losses in the distribution network. The exergy assessment provides a comprehensive thermodynamic evaluation of the proposed solar-powered irrigation system and identifies opportunities for improving the overall system performance.

5.3 Economic Analysis

Economic analysis was conducted to assess the financial viability of the proposed solar-powered irrigation system compared with conventional diesel-powered irrigation systems. The evaluation considered capital investment, operation and maintenance costs, annual savings, and payback period. The simple payback period was calculated using [28]:

Payback Period = Initial Cost / Annual Savings

Where: PP is the payback period (years), Initial Cost is the total capital investment, and Annual Savings is the annual net savings achieved through replacing diesel fuel with solar energy. The economic analysis was used to estimate the potential operating cost savings and simple payback period of the proposed system.

5.4 Environmental Analysis

Environmental analysis was performed to quantify the environmental benefits associated with replacing diesel-powered irrigation with renewable solar energy. The assessment focused on greenhouse gas emission reduction and water conservation. The annual carbon dioxide emission reduction was estimated using [29]:

$$CO_2 = D \times EF$$

Where: D is the annual diesel consumption (L/year) and EF is the diesel emission factor (kg CO_2/L) [29]. In addition to emission reduction, the adoption of drip irrigation improves water-use efficiency by minimizing evaporation, runoff losses, and over-irrigation. Compared with conventional flood irrigation, drip irrigation systems can reduce irrigation water consumption by approximately 30–60%. The environmental assessment indicates the potential contribution of the proposed system to reducing operational emissions and irrigation-water demand.

6. RESULTS AND DISCUSSION

This section evaluates the performance of the proposed system in terms of energy use, operational carbon emissions, water consumption, and irrigation-control behavior. Prototype measurements are discussed together with the engineering-based results obtained for the representative agricultural-scale design.

6.1 Energy Consumption Analysis

Energy consumption is an important operational factor influencing pump operation, thus minimizing the sustainability and economics of agricultural irrigation systems. The majority of conventional irrigation systems are operated by diesel engines or grid electricity for pumping water, which leads to high operating costs and greenhouse gas emissions. However, pump operation, which is minimized by the proposed Smart Solar Drip Irrigation System, integrates photovoltaic power generation with low-pressure drip irrigation, thus decreasing reliance on conventional energy sources. The system consumes about 9 kWh/day, i.e., 1,620 kWh for the estimated operating period of 180 days, considering the design conditions adopted. This represents an estimated reduction of approximately 93.5% compared with the adopted conventional diesel-powered irrigation baseline of approximately 25,000 kWh over the same reference period. This reduction is mostly associated with the lower hydraulic and water delivery requirements of drip irrigation, which operates at relatively low pressures and delivers the water directly to the crop root zone, thus decreasing unnecessary pumping demand and water losses. Furthermore, the photovoltaic array supplies the electrical energy required for pump operation, thus minimizing the dependence on fossil fuels and grid electricity during normal operation of the system.

6.2 Operational Carbon Emissions and Environmental Performance

The ecological advantages of the proposed irrigation system were further explored by comparing the carbon emissions of the proposed system with those of a conventional flood irrigation system. Flood irrigation generally requires a greater volume of water and more energy for pumping due to its relatively low application efficiency and high water losses due to surface runoff, evaporation, and deep percolation. The Smart Solar Drip Irrigation System, in contrast, has accurate water delivery and solar-powered pumping, which lowers energy consumption and greenhouse gas emissions. The analysis indicates that the proposed system can significantly reduce carbon emissions by reducing the amount of extracted water and the associated energy requirements. Drip irrigation increases water-use efficiency by delivering water directly into the crop root zone, while the photovoltaic system eliminates the need for electricity from fossil-fuel sources during normal operation. Thus, the combined effect of efficient irrigation and renewable energy leads to a considerable improvement in the ecological sustainability of the irrigation system.

6.3 Water use efficiency and temporal dynamics of the system

The efficiency of water use of the proposed Smart Solar Drip Irrigation System was compared with traditional flood irrigation over time. Daily, monthly, and seasonal evaluations were made to investigate irrigation, soil moisture, and water use. The proposed system is sensor-driven and utilizes drip irrigation to apply water according to the needs of the crop, as opposed to flood irrigation, which applies large volumes of water at short intervals. This method helps reduce water waste from runoff, evaporation, and deep percolation, while ensuring the soil has enough moisture for agricultural development. Consequently, the system enhances irrigation efficiency and reduces supplemental water use during the growing season. The experimental results show that the intelligent irrigation system has a controlled output of about 2.2 L/min (prototype). The flood irrigation requires flow rates of up to 6.0 L/min during watering times. Reduced discharge rate and real-time monitoring of soil moisture allow for constant adjustment of irrigation scheduling based on field conditions. Therefore, the proposed system keeps the soil moisture relatively stable while greatly reducing the irrigation water amount.

Figures 9 and 10 present the daily water-use records for the proposed drip-irrigation system and the conventional flood-irrigation system, respectively. The monitored daily values show a lower water requirement for the drip-irrigation configuration under the investigated conditions. The lower discharge and controlled irrigation operation of the proposed system reduces unnecessary water application compared with the higher water delivery associated with flood irrigation.

Figure 9: Daily water consumption under the proposed smart drip irrigation system

Figure 10: Daily water consumption under conventional flood irrigation

The monthly water-use records **in Figures 11 and 12** present the monthly water-use records for the proposed drip-irrigation and conventional flood-irrigation systems, respectively. The results indicate that the lower daily water demand of the smart drip system leads to reduced cumulative water consumption over the monitoring period. The use of controlled water delivery and sensor-based irrigation scheduling, therefore, provides a potential advantage in reducing unnecessary water irrigation use over longer operating periods.

Figure 11: Monthly water consumption under the proposed smart drip irrigation system

Figure 12: Monthly water consumption under conventional flood irrigation

Figures 13 and 14 summarize the seasonal water consumption of the proposed smart drip-irrigation system and the conventional flood-irrigation system, respectively. The seasonal comparison indicates that the reduction in water use observed at the daily and monthly scales is maintained throughout the irrigation period considered. These results demonstrate the potential of combining drip irrigation with soil-moisture-based control to reduce cumulative irrigation-water demand under the investigated conditions.

Figure 13: Seasonal water consumption under the proposed smart drip irrigation system

Figure 14: Seasonal water consumption under conventional flood irrigation

7.FUTURE RESEARCH DIRECTIONS

The future work should focus on validation of the proposed system through long-term field experiments under different crop types, soil properties, climatic conditions, and irrigation seasons. Such field-scale validation is required to evaluate the stability of the sensing and control strategy, the seasonal variability in water and energy demand, and the long-term reliability of the photovoltaic and pumping components. The proposed design should also be investigated for scalability to larger cultivated areas and different irrigation layouts, considering pressure distribution, emitter uniformity, pumping requirements, and photovoltaic-system sizing.

Incorporating weather forecasts, estimates of evapotranspiration, and soil-moisture measurements for predictive irrigation scheduling could lead to additional improvements. This could be achieved by incorporating weather forecasts, estimates of evapotranspiration, and soil-moisture measurements for predictive irrigation scheduling instead of relying on threshold-based methods. This could help the controller to forecast the crop water demand and cut down unnecessary irrigation events in fast-changing environmental conditions. Future studies can also explore adaptive control strategies that can adjust the irrigation thresholds according to the crop growth stage, soil properties, and seasonal water demand.

Cloud-based monitoring and digital-twin technologies are another promising area of research. The digital representation of the irrigation system can be used to support real-time performance monitoring, fault detection, predictive maintenance and early identification of abnormal hydraulic or electrical operating conditions. Moreover, the integration of historical operational data with sensor measurements could enhance system diagnostics and allow for more informed irrigation management decisions.

The energy-management subsystem needs to be studied in more detail, including the effects of solar-resource variability, battery-storage capacity, inverter or variable-frequency-drive operation, and pump efficiency when operating at partial loads. This analysis would provide a more realistic valuation of system performance under variable field conditions and could enable better coordination between photovoltaic generation and irrigation demand.

Future work should include full life cycle, techno-economic and environmental assessments. These analyses should include operational performance as well as component manufacturing, installation, maintenance, replacement and end-of-life impacts. Long-term field measurements of cumulative water consumption, actual pumping energy, crop yield, maintenance requirements and operating expenses would provide a more solid basis for evaluating the economic feasibility, water-saving potential and overall environmental sustainability of the proposed system.

8.CONCLUSION

The results of this work demonstrate that the proposed design can offer a trade-off between irrigation demand, hydraulic performance, renewable energy supply, and automated water management. The hydraulic calculations defined an operating point achievable with the selected pumping and photovoltaic configuration, and the 4E analysis showed a positive thermodynamic and economic performance according to the design assumptions adopted. At the same time, prototype experiments demonstrated the potential for soil-moisture-based control to operate irrigation based on actual moisture levels rather than fixed schedules, reducing unnecessary water application and pump use. Crucially, the results indicate that a singular focus on a control perspective for smart irrigation or an energy perspective for solar irrigation paints an incomplete picture of system performance. Combining hydraulic behavior, energy consumption, exergy efficiency, economic viability, environmental impact, and real-time irrigation control provides a more complete platform to assess solar-powered irrigation systems. The obtained water-use and economic indicators indicate the potential applicability of this integrated approach to water-scarce agricultural environments. However, the current results need to be interpreted considering the conditions and assumptions applied in this study, and long-term field-scale experiments are needed to validate the seasonal performance, scalability, and environmental benefits for different crops, soils, and climates.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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