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Recent Advances in Solar-powered Photovoltaic Pumping Systems for Drip Irrigation

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ABSTRACT

Solar-powered photovoltaic pumping systems (SPVPSs) have emerged as a promising solution for sustainable drip irrigation in agriculture. This review article presents recent advances in SPVPSs for drip irrigation, with a focus on their design, performance and integration. The paper provides an overview of the key components and working principles of SPVPSs. Various system configurations and optimization strategies are discussed, emphasizing the importance of system sizing, energy management and water supply efficiency. The review also addresses challenges and future directions in the field. The initial investment costs, technical constraints, and the need for capacity building are identified as key challenges to widespread adoption. However, ongoing research and development efforts are focused on cost reduction, system optimization, and policy support to overcome these challenges. Technological innovations, such as advanced control algorithms and energy storage systems, are paving the way for improved system performance and reliability. The integration of SPVPSs with drip irrigation offers environmental and socio-economic benefits. These systems contribute to reduced greenhouse gas emissions and water conservation. Moreover, they enhance agricultural productivity, income generation, and food security, particularly in off-grid and rural areas. SPVPSs for drip irrigation hold great promise for sustainable agriculture and water resource management. Continued research, collaboration, and policy support are essential to further advance these systems, address challenges, and promote their widespread adoption. This review paper provides insights for researchers, policymakers, and practitioners interested in harnessing the potential of SPVPSs for sustainable drip irrigation.

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1. Introduction

Agriculture plays a vital role in meeting the growing global demand for food, which is expected to increase by 50% to 70% by 2050 (FAO, 2017; Van Dijk et al., 2021). However, this increase in food production must be balanced with sustainable practices (Shah et al., 2021) to minimize environmental impact. Efficient irrigation systems play a crucial role in achieving this balance by optimizing water use and improving crop yield (Chávez et al., 2020; Gong et al., 2020; Pereira et al., 2020; Zahoor et al., 2019). According to the United Nations' Food and Agriculture Organization (FAO), irrigation accounts for approximately 70% of global freshwater withdrawals (FAO, 2021). Therefore, adopting efficient irrigation technologies is essential for sustainable water resource management (Zhang et al., 2019).

In recent years, there has been a notable shift towards utilizing renewable energy sources to power irrigation systems (Caldera & Breyer, 2019; Ghasemi-Mobtaker et al., 2020), driven by the need to reduce dependence on fossil fuels and mitigate climate change (Achakulwisut et al., 2023; Kirsch, 2020; Panepinto et al., 2021). Among the various renewable energy options, solar power has gained significant attention (Hasan et al., 2023; Javed et al., 2020; Rabaia et al., 2021) for its abundant availability and environmental benefits. Solar energy is a clean and renewable resource that produces no greenhouse gas emissions during operation (Wang et al., 2023). This characteristic aligns with the goals of sustainable agriculture and supports the transition to low-carbon farming practices.

Moreover, solar-powered irrigation systems offer the potential for long-term cost savings (Grant et al., 2022; Guno & Agaton, 2022; Hilarydoss, 2023; Raza et al., 2022). Once installed, solar panels require minimal maintenance (Awasthi et al., 2020; Hernández-Callejo et al., 2019) and have a lifespan of 25 years or more (Mahmoudi et al., 2019; Tan et al., 2022). Additionally, solar energy is essentially free, allowing farmers to offset electricity costs and achieve energy independence.

SPVPSs have emerged as a promising solution for meeting the irrigation needs of agricultural farms. These systems harness solar energy through photovoltaic (PV) panels and convert it into electricity, which is then used to power water pumps for irrigation purposes (Ahmed et al., 2023; Al-Ali et al., 2019; Kumar et al., 2020; Lixue, 2017). PV panels, composed of semiconductor materials, generate direct current (DC) electricity when exposed to sunlight. This DC electricity is then converted into alternating current (AC) using solar pump controllers (inverters) to power the water pumping system as demonstrated in Figure 1.

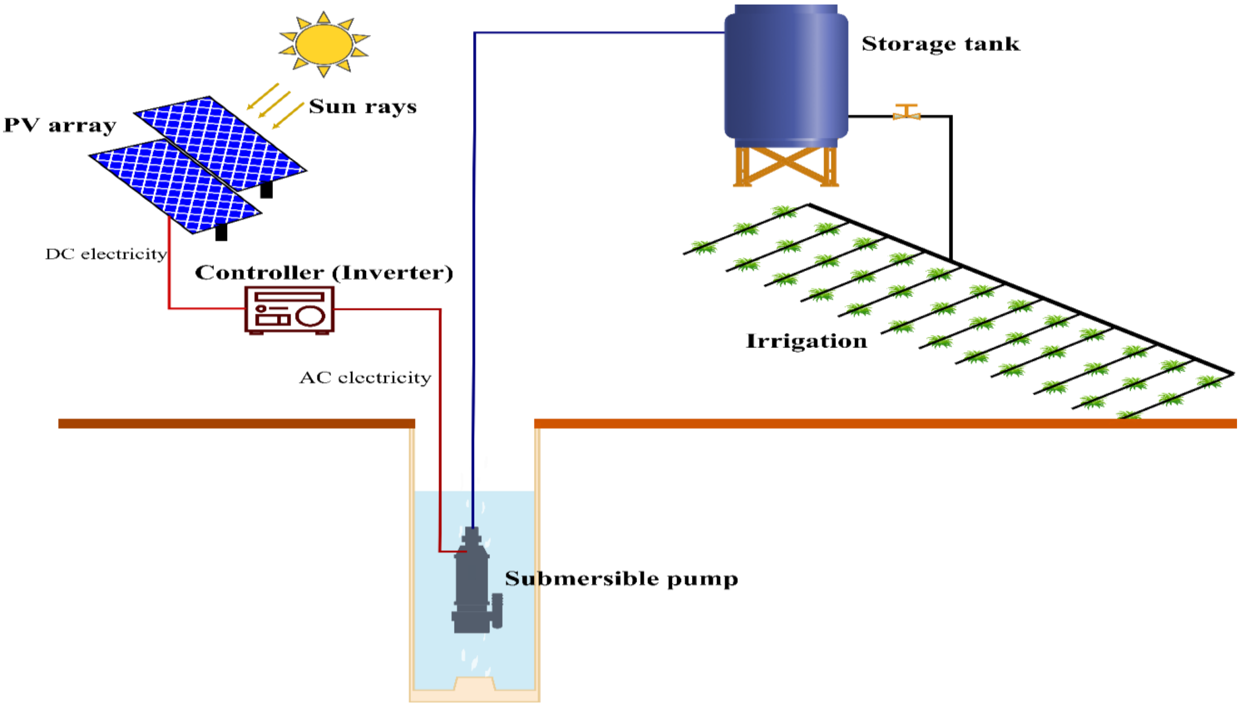


Figure 1: Solar Drip Irrigation System Using a Controller to Convert DC from PV Arrays to AC Electricity for the Pump

The primary components of a SPVPS include PV panels, an inverter, a controller, a water pump, and sometimes a storage battery to store excess energy for use during periods of low sunlight (Gevorkov et al., 2022; Muralidhar & Rajasekar, 2021; Verma et al., 2021). The PV panels capture solar radiation and generate electricity, which is then fed into the system. The controller regulates the system operation, optimizing the power flow from the panels to the pump. The water pump, driven by the electricity generated, draws water from a source such as a well or a reservoir and delivers it to the irrigation system as in Figure 1.

Irrigation is the practice of supplying land with water by artificial means to foster plant growth (Beier et al., 2023; Hrozencik, 2021; McDermid et al., 2023; McDermid et al., 2021). It is the artificial application of water to land to assist in the production of crops. Irrigation is necessary in areas where rainfall is insufficient or irregular to support vegetation (Irrigation, 2023). There are several methods of irrigation that differ in how water is supplied to plants (Irrigation, 2023). The methods include surface irrigation, sprinkler irrigation and drip irrigation as shown in Figure 2.

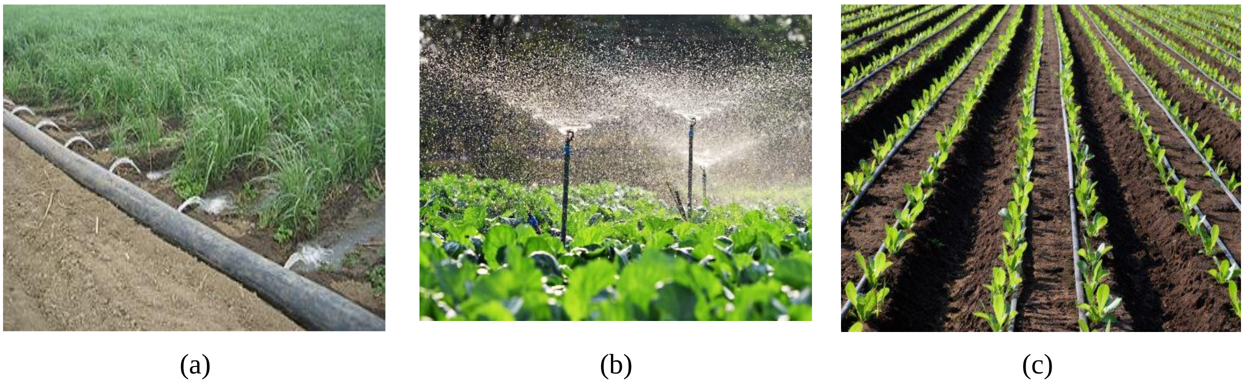

(a) (b) (c)

Figure 2: Methods of Irrigation: (a) Surface Irrigation (Surface irrigation, 2023) (b) Sprinkler Irrigation (AGRIVI, 2022) (c) Drip Irrigation (Drip irrigation, 2023)

Drip irrigation is a widely recognized and efficient method of delivering water to crops, offering numerous advantages over other irrigation techniques. It involves the slow and precise application of water directly to the root zone of plants through a network of tubes or emitters (Hornum et al., 2023; M. Liu et al., 2023; Rambabu et al., 2023; Yang et al., 2023; Yang et al., 2021). By targeting the water delivery, drip irrigation minimizes water loss due to evaporation and reduces runoff, leading to improved water-use efficiency (Grevengoed et al., 2023; Hmielowski, 2019; Wang et al., 2021; Yang et al., 2021).

Studies have reported water savings ranging from 30% to 70% when using drip irrigation systems, depending on crop type, climate conditions, and system design (Abioye et al., 2023; Hossain et al., 2017; M. Liu et al., 2023; S. Liu et al., 2023; Yang et al., 2023). This increased water-use efficiency not only conserves a valuable resource but also helps to mitigate water scarcity challenges faced by many agricultural regions. Designing an efficient SPVPS requires a comprehensive understanding of various factors such as crop water requirements, solar radiation patterns, system components, and hydraulic considerations (An et al., 2022; Department of Jobs, 2023; Ejigu, 2021; FAO, n.d.-a; Grant et al., 2022; Miran et al., 2022).

While significant research has been conducted on SPVPSs for drip irrigation, there is a need to focus on recent advancements to provide the most up-to-date insights. The review will primarily cover the developments of the past seven years, aiming to bridge the gap in the existing literature and highlight the latest findings, methodologies, and innovations.

Also, by focusing on recent developments, the review aims to address any limitations or challenges identified in earlier studies, as technological advancements and research findings continue to shape the understanding and implementation of SPVPSs for drip irrigation. By delving into the advancements made over the past seven years, this literature review provides an updated and comprehensive overview of the state-of-the-art in SPVPSs for drip irrigation. It serves as a great resource for researchers, practitioners, and decision-makers seeking the most recent information on SPVPSs.

2. Solar-Powered PV Pumping Systems (SPVPSs)

2.1 Overview of SPVPSs

SPVPSs harness the energy from the sun and convert it into electricity to drive water pumps for various applications, including drip irrigation. These systems, as in Figure 1 typically consist of PV panels, which generate electricity when exposed to sunlight, a pump to lift and transport water, and a control system to regulate the operation of the system (Ahmed et al., 2023; Kumar et al., 2020).

The PV panels, commonly composed of silicon-based solar cells, are the primary components of the system responsible for converting sunlight into electricity (Ahmed et al., 2023). When sunlight strikes the solar cells, it excites the electrons, generating a flow of DC electricity.

The generated DC electricity from the solar panels is then used to power the water pump, which lifts and transports water from a source (such as a well, reservoir, or river) to the irrigation system. The pump can be either submersible or surface-mounted, depending on the water source and specific requirements of the application (Samsa, 2022). Submersible pumps are typically used when the water source is deep as in Figure 1, while surface-mounted pumps are suitable for shallow water sources as in Figure 3.

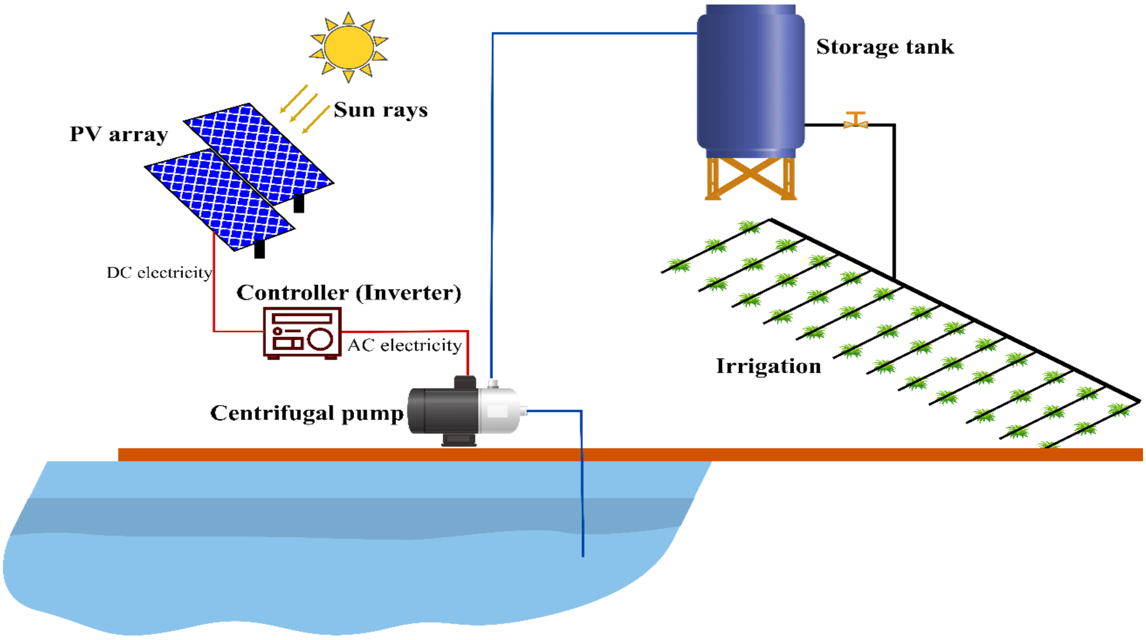


Figure 3: Surface-mounted Centrifugal Pump for Drip Irrigation

To ensure efficient and optimal operation of a SPVPS, a control system is incorporated. The control system manages the power generated by the solar panels, regulates the pump operation based on the available solar energy, and may include monitoring functionalities (Poompavai & Kowsalya, 2020). Control algorithms are employed to optimize energy utilization, manage battery storage (if present), and protect the system from potential faults or malfunctions.

2.2 Battery Storage and System Optimization

Battery storage in SPVPSs allow for the storage and utilization of excess solar energy (Gevorkov et al., 2022). It enables the continuous operation of the pumping system during periods of low sunlight or during the night when solar panels are not actively generating electricity. However, the use of batteries increases the cost and complexity of the system, and can reduce the overall efficiency of the system (Sontake & Kalamkar, 2016). Hence, its use in SPVPS is not recommended (Sontake & Kalamkar, 2016).

2.3 Pump Selection and Performance

Factors such as water source characteristics, required flow rate, head requirements, and system are considered during the pump selection process (Ikrang et al., 2021). Different types of pumps are used in SPVPSs, including centrifugal pumps and submersible pumps. Centrifugal pumps are commonly used in surface-mounted applications where the water source is above ground level as in Figure 3. They are suitable for delivering water over long distances and can handle high flow rates. Submersible pumps, on the other hand, are designed to be submerged in the water source and are typically used when the water source is deep. Submersible pumps, as in Figure 1, are well-suited for applications with lower flow rate requirements (Duffy, 2018).

Pump performance parameters, such as flow rate, head, and power consumption, are evaluated to ensure optimal operation. The flow rate requirement depends on the irrigation needs and the crop characteristics, while the head requirement is determined by the elevation difference between the water source and the irrigation area. Pumps that can provide the required flow rate at the desired head while minimizing energy consumption are usually selected.

2.4 System Monitoring, Control and Remote Management

Monitoring systems are employed to gather real-time data on various parameters, such as solar energy generation, battery state of charge, pump performance, and water flow rate (Best solar monitoring systems, 2023). This data provides insights into system operation and enables proactive maintenance and troubleshooting. Monitoring is usually done through sensor networks and data logging devices that capture and transmit data to a central control unit or a cloud-based platform. Iskandar et al. (2023) used sensors in an automatic drip irrigation system. The schematic diagram and the corresponding flow chart in their work is in Figure 5.

Control systems play an important role in regulating the operation of the pumping system based on the available solar energy, water demand, and system conditions (Poompavai & Kowsalya, 2020). Automated control algorithms adjust the pump speed, optimize energy utilization, and ensure the desired water flow rate is maintained. These algorithms are based on feedback control strategies, such as proportional-integral-derivative (PID) control, or advanced predictive control methods. The control system also incorporates safety features to protect the system from overvoltage, overcurrent, or other abnormal operating conditions.

Remote management capabilities allow for the monitoring and control of the PV pumping system from a central location, providing convenience and flexibility for system operators (Njoka et al., 2023). Through remote management, system performance is monitored, and control actions are initiated, even from a distance. This is particularly useful for systems installed in remote or inaccessible locations, as it reduces the need for physical presence and on-site maintenance.

Advancements in communication technologies and Internet of Things (IoT) platforms have facilitated the development of smart and interconnected SPVPSs (Njoka et al., 2023). These systems enable real-time monitoring, remote control, and data analytics for performance optimization. IoT-based platforms provide information into energy generation, water consumption, and system efficiency, allowing for proactive maintenance, energy management, and decision-making.

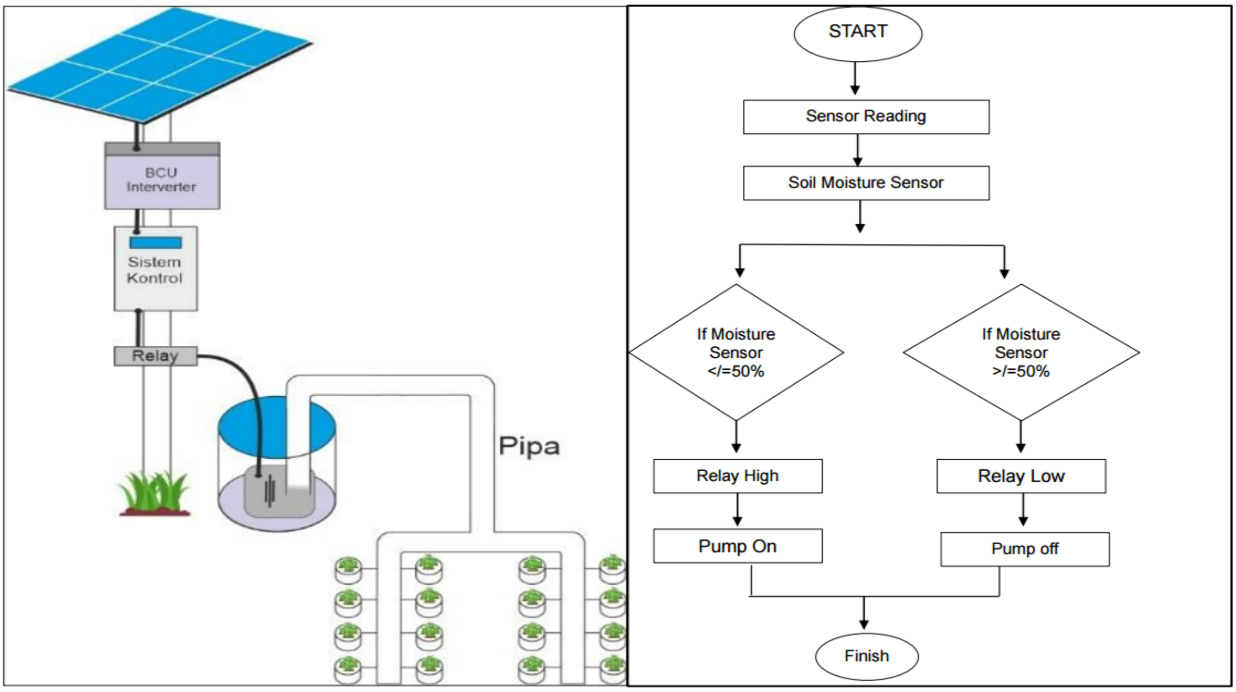


Figure 4: Schematic of an Automatic Drip Irrigation System (Iskandar et al., 2023)

The integration of artificial intelligence (AI) techniques, such as machine learning and data analytics, have further enhanced the monitoring and control capabilities of SPVPSs. AI algorithms learn from historical data and make predictions about energy generation, water demand, and system faults. This enables more accurate system control, fault detection, and predictive maintenance, leading to improved system reliability and efficiency.

2.5 Economic Viability and Sustainability

The economic viability and long-term sustainability of SPVPSs are important considerations for their widespread adoption and successful implementation. Cost analysis plays a critical role in evaluating the economic feasibility of SPVPSs (Ghosh et al., 2022; Miran et al., 2022; Sharma et al., 2020). The initial investment costs include the PV panels, pump equipment, battery storage, control systems, storage tanks, and installation expenses. Operational costs typically involve maintenance, repairs, and replacement of components over the system's lifespan.

Several factors contribute to the economic viability of SPVPSs. Advances in PV technology have led to reduced costs and increased efficiency of solar panels. This, coupled with incentives and government policies supporting renewable energy, has improved the affordability and attractiveness of SPVPSs for drip irrigation. Additionally, the long-term cost savings associated with reduced or eliminated fuel consumption and maintenance requirements of diesel pumps contribute to the economic viability of SPVPSs.

Environmental benefits, such as reduced greenhouse gas emissions and lower dependence on fossil fuels, make SPVPSs a more sustainable choice compared to conventional pumping technologies. SPVPSs also contribute to water conservation by providing precise water delivery through drip irrigation, minimizing water waste.

2.6 Water Tanks as Storage in Solar Pumping Irrigation Systems

In some SPVPS drip irrigation systems (DIS), water tanks are utilized as a means of energy storage instead of relying on traditional battery systems. In Figure 1 and Figure 3 are drip irrigation systems using storage tank. This approach offers certain advantages and considerations that contribute to the overall efficiency and effectiveness of the system.

Water tanks serve as a form of energy storage in SPVPSs by harnessing the potential energy of elevated water. During periods of ample sunlight and when the irrigation demand is low, excess solar energy is used to pump water into an elevated storage tank. This process converts electrical energy into gravitational potential energy stored in the elevated water.

2.6.1 Advantages of Water Tanks as Energy Storage

- The initial investment costs for water tanks are generally lower, and the maintenance requirements are relatively minimal compared to batteries.
- Water tanks offer a simple and robust storage solution. They have a long lifespan and do not suffer from issues such as capacity degradation or the need for regular replacement, unlike batteries.
- Apart from storing energy, the water held in tanks serves as a reserve for irrigation purposes. This enables the system to provide continuous water supply to crops, even during periods of low sunlight or when the pump is not in operation.

2.6.2 Design Considerations and Challenges

- ***Tank sizing:*** Factors such as solar panel capacity, daily water demand, and desired autonomy period are considered during the tank sizing process (Muhsen et al., 2018). Oversizing the tank can result in excessive water losses due to evaporation, while under sizing may lead to insufficient energy storage.
- ***Tank elevation:*** Higher elevations provide greater gravitational potential energy, which can enhance the system's overall efficiency.

3. Drip Irrigation Systems (DISs)

Drip irrigation is a type of micro-irrigation system that involves dripping water onto the soil at very low rates from a system of small diameter plastic pipes fitted with outlets called emitters or drippers (Drip irrigation, 2023; FAO, n.d.-b). Water is applied close to plants so that only part of the soil in which the roots grow is wetted (Drip irrigation, 2023). It is particularly suitable for water of poor quality (saline water) and when water is scarce (FAO, n.d.-b). In recent years, the demand for drip irrigation has grown rapidly and for good reason – the technology can help solve serious problems associated with water use. A typical drip irrigation system consists of a pump unit, control head, main and submain lines, laterals, and emitters or drippers (FAO, n.d.-b).

4. Design Considerations for SPVPSs

4.1 Sizing the Solar Panel Array and Pump Capacity

- The size of the solar panel array depends on factors such as solar irradiation levels, pump power requirements, and desired irrigation schedule. Accurate estimation of the solar panel capacity ensures sufficient energy generation to meet the pumping system's needs.
- The pump capacity is selected based on the water demand of the drip irrigation system. Factors such as crop water requirements, field size, and desired flow rates are considered to ensure adequate water supply for efficient irrigation.

4.2 Selecting Appropriate Pump Types and Efficiency Considerations

- The selection depends on factors such as water source depth, discharge requirements, and system efficiency.
- The pump's efficiency is considered along with the operating conditions to ensure efficient water delivery and maximize the use of solar energy.

4.3 Battery Storage Options Versus Direct Pumping

- ***Battery storage systems:*** In some cases, integrating battery storage with SPVPSs provides the advantage of energy storage for times when sunlight is insufficient. This ensures continuous water pumping even during cloudy periods or at night. The sizing and type of battery depend on the system's energy requirements and autonomy desired by the user.
- ***Direct pumping:*** Some systems can operate without battery storage, utilizing solar power only during daylight hours. The pump operates directly from solar energy, and water is pumped directly to the irrigation system without the need for storage.

5. Previous Studies on SPVPSs for Drip Irrigation Considering the Past Seven Years

A number of studies have been conducted on performance evaluation, optimization, sizing techniques, efficiency gains, economic and environmental aspects of SPVPSs. The highlights of the research investigations are summarized in Table 1.

Table 1

Summary of Previous Studies on SPVPSs for Drip Irrigation

Reference	Aim(s)	Finding(s)/Result(s)	Conclusion(s)
Grant et al. (2022)	Presented the solar-powered drip irrigation optimal performance model (SDrOP) aiming to optimize system designs and reduce life cycle costs (LCC).	• Simulated performance against operational data indicated SDrOP's capability to operate in real-world conditions, offering significant cost reduction in comparison to existing software.	• SDrOP had the potential to make solar-powered drip irrigation more accessible to smallholder farmers by significantly reducing system LCC.
Miran et al. (2022)	Optimized the design of a standalone solar PV DIS (SPVDIS) and analyze its potential for energy generation and water management.	• The designed PV system had a nominal power of 10.40 kW, and the simulation results showed that the losses caused by various factors were 14.7%, 2.9%, and 14.0% respectively. • Simulation results showed that the solar energy system was starting a little later and also could not fulfill the desired irrigation demand during certain times (morning time).	• The study demonstrated the potential of standalone PV drip irrigation systems to improve farm water management and use precious water resources wisely.
Ghosh and Biswas (2017)	Conducted an experiment to assess the feasibility of a water storage structure, drip systems, and a PV solar pump for orchard irrigation.	• Estimated cost of water storage was less than $1 per L. • Solar-powered battery pump delivered 1971.52 L of water in a 2.9-hour continuous run, capable of irrigating 0.33 ha of orchard area.	• The system had the potential to address water shortage in the western part of West Bengal, particularly during the summer season.
Mejeed et al. (2019)	Designed a solar PV pressurized drip irrigation pumping system for tomato crops in AL-Salman district, Iraq.	• Technical evaluation indicated the feasibility of the solar pumping system with a maximum flow rate of 64.45 m3/h and pump capacity of 16.79 kW. • Solar radiation data showed peak operation times of 7.2 hours/day for eight months and 5.2 hours/day for the remaining four months.	• The designed system was capable of meeting the water requirements for tomato crops, with an annual water production of 230,000 m^3. • Efficient utilization of solar energy made the system suitable for sustained irrigation.
Diarra et al. (2021)	Designed a DIS powered by PV for vegetable crops in Bellel, Guinea.	• Calculated a total water requirement of 150 m3 per day for irrigating 7 ha, with 50 m3 allocated to each crop. • The PV array comprised 5 modules in series and 3 in parallel, totaling 15 modules.	• The obtained results provided a basis for designing and implementing a DIS powered by PV energy in Bellel, Guinea.
Haupenthal et al. (2018)	Assessed the performance of a SPVDIS.	• Found that a load controller should be used for the power supply to avoid exceeding the 12 V nominal value of the water pump.	• Integrating solar PV panels with a DIS enhanced water distribution uniformity. • Advised the use of a load controller to regulate power supply and prevent exceeding the water pump's nominal voltage.
Perakis et al. (2017)	Investigated a SPVDIS in the Jordan valley by	• Found that autonomous PV-battery systems adequately cover	• Concluded that SPVDISs are preferable and economically

	exploring alternatives for rural agricultural areas without access to an electrical grid.	all needs, while diesel generators were not economically viable.	viable compared to grid extension or diesel generator alternatives in many cases.
Lunaria et al. (2021)	Used particle swarm optimization to determine optimal soil depth for minimizing irrigation costs. Implemented a solar-powered DIS, testing its efficiency compared to traditional methods. Utilized Internet-of-Things (IoT) technology for remote system monitoring.	• Found that the solar-powered automated DIS is comparable to traditional systems in output while using significantly less water.	• Integrating renewable energy with irrigation, particularly using particle swarm optimization, can minimize irrigation costs.
Nayyef (2021)	Conducted an experiment to study the effect of the distance between drippers and their discharge on friction losses, coefficient of variation, and emission consistency of a SPVDIS.	• Found that a distance of 60 cm between emitters resulted in the lowest percentage of friction losses, with values of 0.165 and 0.204 m for drippers with design discharges of 4 and 8 Lhr-1, respectively.	• A distance of 60 cm between emitters is optimal for minimizing friction losses in the drip irrigation system
Hadole et al. (2022)	Developed an integrated dynamic simulation model for a directly coupled SPVDIS.	• Total utilizable solar PV energy between 14 and 20 kWh/day and satisfactory emission uniformity (> 85%) for inlet pressure > 78.45 kPa. • Identified suitable operation time for the drip irrigation system (IST 9.00 h to 15.00 h) • An additional 0.19 ha of okra crop could be irrigated using the same SPVPS.	• The developed simulation model and approach were unique for real-time operation scheduling of DIS sub-main manifolds.
Suwito et al. (2022)	Utilized a binary particle swarm optimization (BPSO) method to determine irrigation in multisector setups based on solar PV power availability.	• BPSO method provided an optimal and accurate irrigation system with an average irrigation operating pressure error of 0.7 psi, water volume error of 4.01%, and uniformity coefficient of water volume of 96.55%.	• BPSO method effectively determined irrigation in multisector DISs powered by solar PV.
Boutelli et al. (2022)	Used the hybrid optimization of multiple electric renewables (HOMER) software as a simulation tool to determine the optimal configuration of a hybrid wind-solar DIS in the Ouargla region, Algeria.	• The region had significant solar energy potential, reaching 2263 kWh/m²/year, with substantial wind speeds during the spring and summer seasons. • The optimal hybrid system configuration included a 2 kW PV array, 13 kW wind turbine, and a 2 kW converter. • The configuration provided the minimum cost of energy (COE) estimated at $0.303/kWh, with a total project cost of $14,989 over 25 years.	• The Ouargla region had significant renewable energy potential, particularly in solar and wind resources. • The optimal hybrid system configuration, as determined by HOMER, offers cost-effective electricity generation for irrigation purposes.
Abo-Habaga et al. (2021)	Investigated the cost estimation of water pumping systems for irrigation, focusing on solar PV and diesel technologies using the drip irrigation.	• The system cost of solar PV panels was lower compared to diesel generator systems. • Water delivery for each kWh under the solar PV system was higher than the diesel generator systems. • Although solar PVs had a higher initial cost, they possessed a lower recurring cost compared to diesel systems over the study period.	• Encouraged farmers to consider adopting solar PV systems for operating ground wells due to their cost-effectiveness.
Rejekiningrum and Apriyana (2021)	Designed a SPVDIS, aiming to provide renewable energy solution to address water problems in agriculture.	• Significant reduction in fuel consumption, from 70 to 14 L ha−1 per season, leading to a savings of 400%. • SPVDISs contributed to a notable reduction in greenhouse gas emissions from 0.176 to 0.035 t of CO2. • Water content analysis indicated that solar water pumps with streamline drip irrigation	• SPVDISs offered an effective renewable energy solution, reducing fuel consumption and greenhouse gas emissions while improving water distribution and crop performance.

		achieved higher water content compared to traditional farmers' irrigation practices.	
Van de Zande et al. (2020)	Assessed the potential for novel, low-energy drip emitters to act as an enabling technology for SPVDISs in Sub-Saharan Africa (SSA).	• Farmers in SSA were willing to spend more time irrigating in exchange for the benefit of a reduced cost system or increased irrigated area. • Farmers cared much more about the active time they spent on irrigation tasks and less about the total time an irrigation system runs.	• Low-energy drip emitters had the potential to act as an enabling technology for solar-powered drip irrigation in Sub-Saharan Africa.
Ogunnubi et al. (2020)	Designed a SPVDIS to address the water scarcity and quality issues faced by Auchi Polytechnic in Nigeria, and the surrounding communities. The system was tested using maize, pepper, and tomatoes as test crops to determine the uniformity of water emission from the drip emitters into the field.	• The low-cost DIS developed showed a high level of efficiency and uniformity of water emission across the entire study area. • The test crops used showed uniform growth across the entire field. • The system was capable of delivering water precisely at the plant where nearly all of the water can be used for plant growth, resulting in little water being wasted in supporting surface evaporation or weed growth.	• The low-cost DIS developed was an effective solution to address the water scarcity and quality issues faced by Auchi Polytechnic and the surrounding communities. • Recommended that further studies should focus on the design, performance criteria and the long-term effects of the depth of pipe placement and depth of water application on maize growth and yield.
Iskandar et al. (2023)	Investigated the efficiency of a solar PV system in regulating irrigation water for agricultural purposes in Indonesia.	• The use of automatic drip irrigation could save costs of IDR4,346,200. • The system's performance was reliable.	• The use of automatic drip irrigation for solar power generation was more economically efficient than ordinary electricity, and it could save costs. • Further research was needed to address the challenges faced in implementing the operational control system for traditional farmers.
Salem (2019)	Designed and evaluated the performance of a water pump under a SPVDIS.	• The power generation reduced by a mean of 14.22% during noon conditions, and the PV array produced a maximum power of 10627.2 W at 12:30 pm. • The pump delivered an average discharge of 32.8m3/h from 9.45 am to 1.30 pm with a head of 1.3 bar in the mornings. • In noon conditions, the pump delivered a discharge of 41.82 m3/h at the head of 2.1 bar. • The power output from the solar array increased as solar intensity increased.	• Most productive hours of sunlight were from 9.0 am to 3.0 pm, and the month with the highest solar power output were August, July, and June. • Solar power systems produced more energy in summer than in winter. • The system was economical but the initial cost was high.
Barman et al. (2020)	Addressed the challenges in traditional irrigation methods and energy use in Indian agriculture. The study aimed to implement a solar-powered automated DIS.	• The solar-powered automated DIS proved to be eco-friendly and economically efficient, minimizing operational and maintenance costs compared to conventional methods.	• Adoption of the system would prevent over-irrigation, reduce reliance on expensive and polluting conventional energy sources, and enhance water-use efficiency.
Hameed and Jebur (2023)	Investigated the impact of emitter type and operating pressure on hydraulic properties of a SPVDIS, using various emitters.	• Increasing operating pressure enhanced emitter discharge rate and emission consistency while reducing variance ratio and coefficient of manufacturing variation for the emitters used.	• Operational pressures significantly influenced discharge rate, emission consistency, and variation parameters. • Turbo emitters exhibited the highest discharge rate, while the other emitters used showed increased emission consistency.
Sadek et al. (2019)	Compared traditional energy sources with solar generators for powering drip irrigation pumping systems in terms of energy consumption and cost effectiveness.	• Higher irrigation water delivery in spring time than winter. • Dippers flow rate increased with increasing pressure. • Emission uniformity of the DIS was classified as good. • Solar radiation intensity measurements increased since sunrise, peaking at midday and gradually decreasing until sunset. • Pump discharge depended on the intensity of solar radiation.	• The system was very suitable for remote areas in the desert and luxurious areas. • The pumping system demonstrated reliability with efficient performance. • Solar pumping systems showed promise as a reliable and cost-effective alternative for powering drip irrigation units, especially considering Egypt's increasing energy demands.

Akram et al. (2018)	Addressed the increasing global demand for water and energy by replacing conventional energy sources with renewable energy and conventional irrigation with high-efficiency systems.	• The system proved cost-effective with minimal operational and maintenance costs.	• SPVDIS offered substantial water and fertilizer savings, making it a cost-effective and sustainable solution for citrus, olive, and grape cultivation.

Overall, previous works on solar water pumping have demonstrated that it is a reliable and sustainable option for irrigation and domestic water supply, especially in areas with high solar radiation and low access to grid electricity. However, the initial cost of installation remains a barrier to adoption, and further research is needed to optimize the design and operation of solar water pumping systems.

6. Key Findings from the Reviewed Studies

6.1 Benefits of SPVPSs for Drip Irrigation

6.1.1 Reduced Reliance on Fossil Fuels and Electricity Grid

- ***Energy independence*** (Abo-Habaga et al., 2021; Akram et al., 2018; Barman et al., 2020): SPVPSs eliminate the dependence on fossil fuels, such as diesel or gasoline, for drip irrigation. This reduces operating costs and eliminates greenhouse gas emissions associated with conventional fuel-based pumps.
- ***Grid independence*** (Boutelli et al., 2022; Perakis et al., 2017; Sadek et al., 2019): By utilizing solar energy, farmers can reduce or eliminate their reliance on the electricity grid, mitigating the risks of power outages or rising energy prices. This promotes self-sufficiency and resilience in agricultural operations.

6.1.2 Cost Savings and Long-term Financial Viability

- ***Lower operational costs*** (Abo-Habaga et al., 2021; Akram et al., 2018; Barman et al., 2020; Grant et al., 2022; Iskandar et al., 2023; Miran et al., 2022; Ogunnubi et al., 2020; Perakis et al., 2017; Sadek et al., 2019): Once the initial investment in the system is made, the operational costs are significantly reduced. Farmers can save on fuel or electricity expenses, leading to long-term financial benefits.
- ***Return on investment*** (Abo-Habaga et al., 2021; Iskandar et al., 2023; Rejekiningrum & Apriyana, 2021): SPVPSs for drip irrigation offer a positive return on investment over time. The savings in energy costs, coupled with potential government incentives or subsidies, make these systems financially viable for farmers, contributing to their economic sustainability.

6.1.3 Increased Accessibility to Water Resources in Remote Areas

- ***Off-grid irrigation*** (Perakis et al., 2017): The systems provide a feasible solution for irrigation in remote areas without access to electricity grids. These systems can bring reliable water supply to agricultural lands in rural and off-grid locations, empowering farmers and promoting agricultural development.
- ***Water availability*** (Ghosh & Biswas, 2017; Mejeed et al., 2019; Miran et al., 2022; Van de Zande et al., 2020): By harnessing solar energy, farmers can tap into water resources such as wells or rivers located in remote areas, where traditional energy sources are limited. This enhances water availability for irrigation and enables cultivation in previously underserved regions.

6.1.4 Improved Energy Efficiency and Carbon Footprint Reduction

- ***Sustainable agricultural practices*** (Mejeed et al., 2019): SPVPSDISs align with sustainable agriculture principles by reducing reliance on non-renewable energy sources and minimizing carbon emissions. These systems contribute to the

conservation of natural resources and promote environmentally friendly farming practices.
- ***Climate change mitigation*** (Iskandar et al., 2023; Rejekiningrum & Apriyana, 2021): By utilizing clean solar energy, these systems help mitigate climate change by reducing greenhouse gas emissions.

6.1.5 Resilience to Power Outages and Grid Failures

- ***Reliable operation*** (Abo-Habaga et al., 2021; Haupenthal et al., 2018; Lunaria et al., 2021; Mejeed et al., 2019; Perakis et al., 2017; Rejekiningrum & Apriyana, 2021; Suwito et al., 2022; Van de Zande et al., 2020): SPVPSDISs operate independently of the electricity grid. This ensures continuous water supply for irrigation, even during power outages or grid failures. Farmers can maintain their irrigation schedule and protect their crops from water stress, enhancing agricultural productivity and resilience.
- ***Disaster resilience*** (Diarra et al., 2021): In regions prone to natural disasters or unstable power supply, SPVPSDISs provide a reliable and resilient solution for irrigation. They reduce vulnerability to disruptions and enable farmers to sustain their agricultural activities during challenging times.

6.2 Challenges and Considerations in Integrating Solar-Powered Pumping Systems with Drip Irrigation

6.2.1 Variable Solar Resource Availability

- ***Weather dependency*** (Haupenthal et al., 2018; Iskandar et al., 2023; Mejeed et al., 2019; Salem, 2019): SPVPSDISs rely on sunlight for energy generation. The variability of solar radiation due to weather conditions, including cloud cover and seasonal changes, can impact the system's performance and water delivery. Adequate system design and sizing, coupled with accurate solar resource assessment, are essential to address these challenges.
- ***Energy storage requirements*** (Perakis et al., 2017): In regions with limited sunlight hours or intermittent cloud cover, energy storage systems, such as batteries, may be necessary to ensure continuous operation.

6.2.2 System Maintenance and Reliability

- ***Technical expertise*** (Van de Zande et al., 2020): Effective system maintenance and troubleshooting require technical expertise. Ensuring access to skilled personnel or providing training programs can overcome challenges related to system maintenance and improve long-term reliability.

6.3 Technological Innovations and Future Prospects

6.3.1 Integration with Smart Irrigation Technologies

- ***Sensor-based irrigation*** (Barman et al., 2020): The integration of SPVPSDISs with sensor technologies enables precise irrigation scheduling based on soil moisture, weather conditions, and crop water requirements. Sensor networks provide real-time data, allowing for dynamic irrigation control and water conservation.
- ***Remote monitoring and control*** (Barman et al., 2020): IoT solutions allow remote monitoring and control of SPVPSDISs. Farmers can access system data, receive alerts, and adjust irrigation settings through mobile applications or web-based interfaces, enhancing system efficiency and convenience.

6.3.2 Performance Evaluation and Optimization

- ***System efficiency analysis*** (Hameed & Jebur, 2023; Haupenthal et al., 2018; Lunaria et al., 2021; Mejeed et al., 2019; Nayyef, 2021): Performance evaluation of

SPVPSDISs involves assessing the overall efficiency of the system, including the energy conversion efficiency of solar panels, pump efficiency, and overall system performance. Parameters such as water delivery rate, power consumption, and water utilization efficiency are analyzed to determine the system's effectiveness.

- ***Energy balance analysis*** (Hadole et al., 2022): Evaluating the energy balance of the system helps determine the energy input from solar panels and the energy output in terms of water delivered. This analysis considers factors such as solar radiation, energy losses, and system efficiency to quantify the system's energy utilization and identify areas for optimization.

6.3.3 Optimization Strategies for Improved System Performance

- ***Sizing and design optimization*** (Boutelli et al., 2022; Grant et al., 2022; Miran et al., 2022): Optimization techniques, such as mathematical modeling, simulation, or heuristic algorithms, are employed to determine the optimal sizing of components, including solar panels, batteries, storage tanks, and pumps, based on specific irrigation requirements. In Figure 4 is the SDrOP model architecture implemented in MALAB to optimize SPVPSs design.

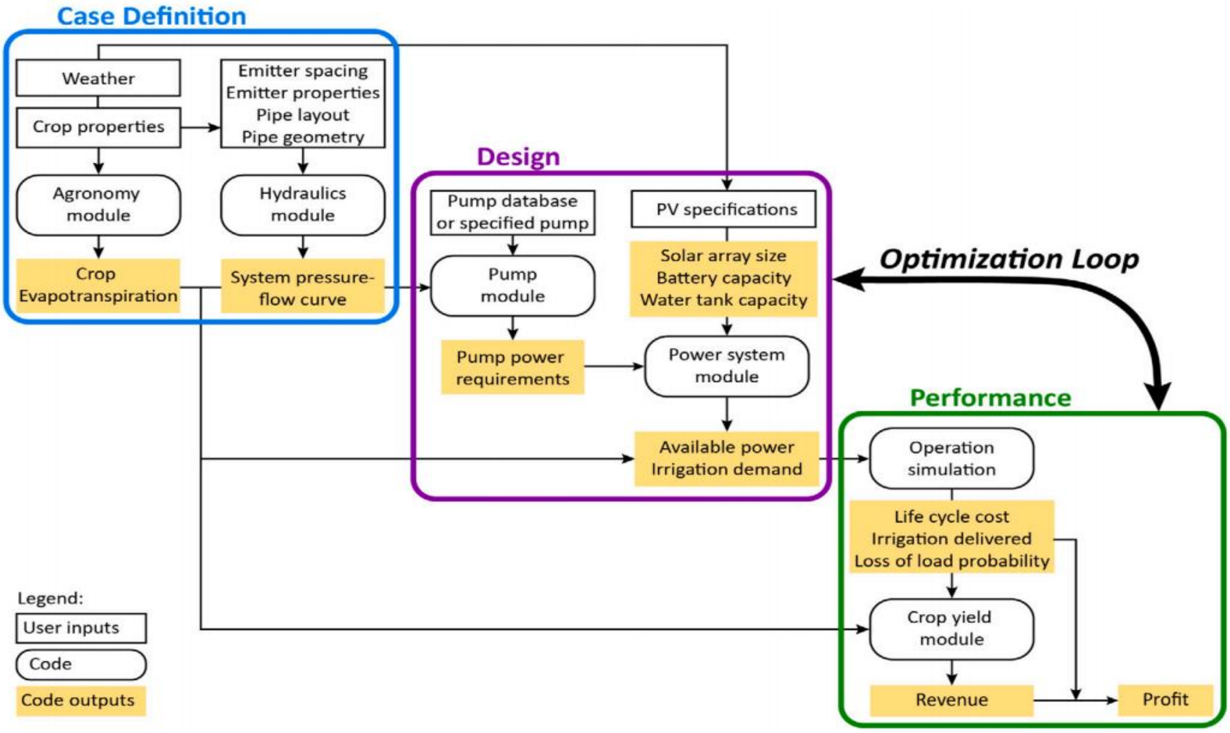


Figure 5: SDrOP System Architecture (Grant et al., 2022)

- ***Control and operation optimization*** (Suwito et al., 2022): Advanced control strategies, such as MPPT algorithms, are utilized to optimize the operation of solar panels and maximize energy extraction from the solar resource. Additionally, intelligent control systems can dynamically adjust pump speed, optimize water delivery, and minimize energy losses, resulting in improved system performance. Suwito et al. (2022) in their work on performance enhancement of a SPVPSDIS, the authors used MPPT to optimize the PV power. The functional diagram of their proposed system is in Figure 6.

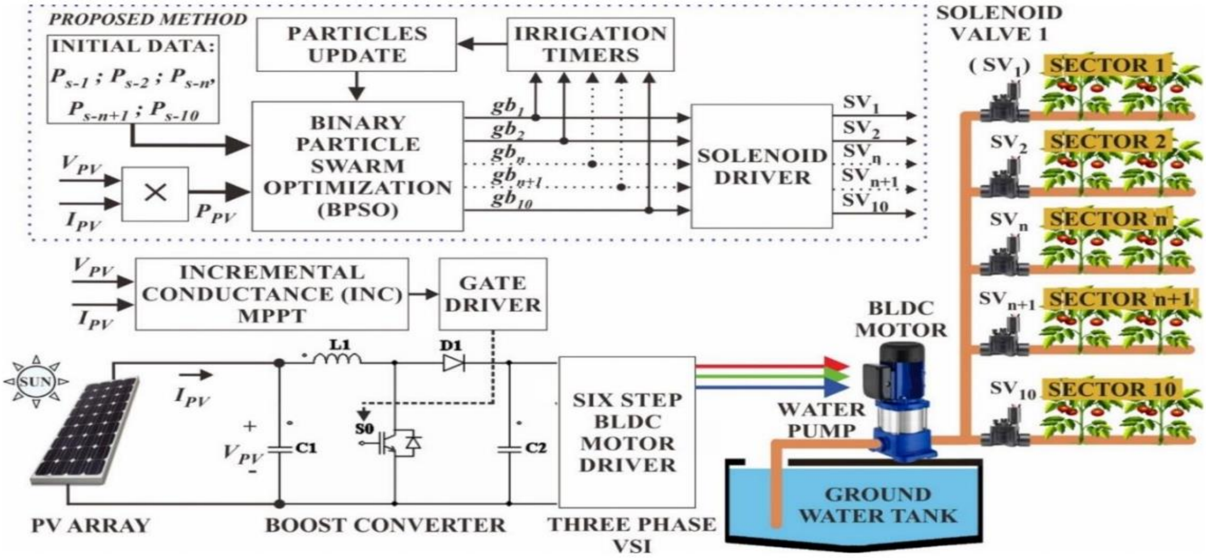


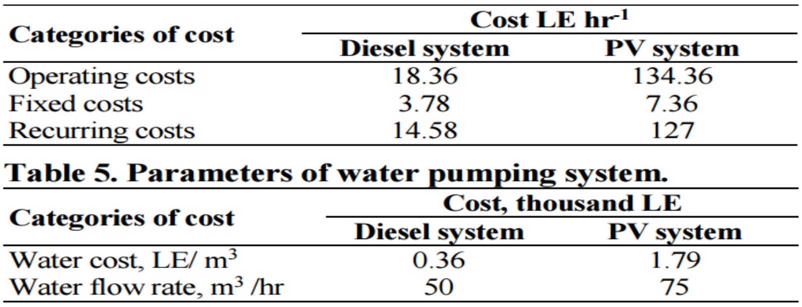
Figure 6: Functional Diagram of a SPVPVDIS Performance Enhancement (Suwito et al., 2022)

6.3.4 Monitoring and Data-Driven Optimization

- ***Real-time monitoring*** (Barman et al., 2020): Continuous monitoring of system parameters, such as solar radiation, energy production, and water flow rate allows for real-time assessment of system performance. Data logging and remote monitoring systems enable farmers to identify potential issues, optimize operation, and make informed decisions for system maintenance and performance enhancement.

6.3.5 Socio-Economic Implications and Benefits

- ***Energy cost savings*** (Ghosh & Biswas, 2017; Miran et al., 2022; Perakis et al., 2017; Sadek et al., 2019): SPVPSDISs offer significant energy cost savings compared to conventional pumps powered by grid electricity or diesel. These cost savings can contribute to improved profitability for farmers, particularly in remote or off-grid areas where access to electricity is limited or expensive. For example, in their work (Abo-Habaga et al., 2021), as in Figure 7, the authors found out that SPVPSs had a lower recurring cost compared to a diesel system, even though the initial cost of the SPVPS was higher.



Categories of cost	Cost LE hr^{-1}	
	Diesel system	PV system
Operating costs	18.36	134.36
Fixed costs	3.78	7.36
Recurring costs	14.58	127

Table 5. Parameters of water pumping system.

Categories of cost	Cost, thousand LE	
	Diesel system	PV system
Water cost, LE/ m^3	0.36	1.79
Water flow rate, m^3 /hr	50	75

Figure 7: Cost Comparison of SPVPS and a Diesel System (Abo-Habaga et al., 2021)

- ***Increased agricultural productivity*** (Rejekiningrum & Apriyana, 2021): The reliable and efficient water supply provided by SPVPSDISs enhances agricultural productivity, crop yield, and income generation for farmers. Access to sustainable irrigation enables farmers to cultivate high-value crops, extend growing seasons, and improve food security in rural communities.

- ***Rural electrification and livelihood improvement*** (Perakis et al., 2017; Van de Zande et al., 2020): SPVPSDISs promote rural electrification by providing clean energy access beyond irrigation needs. The surplus solar energy generated can be utilized for powering household appliances, charging batteries, or supporting other productive activities, contributing to rural development and livelihood improvement.

7. Challenges and Future Directions

7.1 Challenges in the Implementation of SPVPSDISs

- ***Initial investment and affordability:*** The upfront cost of installing SPVPSDISs is a significant barrier for small-scale farmers. Limited access to financing options and the high initial investment required for solar panels, pumps, tanks, and infrastructure can hinder widespread adoption, particularly in low-income regions.
- ***Technical constraints and system reliability:*** SPVPSDISs are dependent on weather conditions and solar radiation availability. Variability in solar energy generation, seasonal fluctuations, and system maintenance can affect the reliability and consistent operation of these systems.
- ***Lack of technical expertise and training:*** Limited technical knowledge and skills in designing, installing, and maintaining SPVPSDISs can be a challenge for farmers and technicians. Access to training programs, capacity building initiatives, and knowledge transfer platforms are essential for overcoming this challenge and promoting successful system implementation.

7.2 Future Directions and Areas for Improvement

- ***Cost reduction and affordability:*** Continued advancements in solar panel technology, battery storage systems, and system components are expected to drive down costs and improve affordability. Research and development efforts should focus on developing low-cost solutions, innovative financing models, and subsidy programs to make SPVPSDISs more accessible to a wider range of farmers.
- ***System optimization and performance enhancement:*** Ongoing research aims to improve system efficiency, enhance energy management strategies, and optimize system performance. This includes the development of intelligent control algorithms, energy storage technologies, and improved system designs to maximize energy utilization, water delivery efficiency, and overall system reliability.
- ***Policy support and enabling frameworks:*** Governments and policymakers play a crucial role in promoting the adoption of SPVPS for drip irrigation. Supportive policies, incentives, and regulations can facilitate the deployment of these systems, including net metering policies, feed-in tariffs, tax incentives, and favorable financing mechanisms, creating an enabling environment for their widespread implementation.

8. Conclusions

The research conducted on recent advances in SPVPSs for drip irrigation highlights the significance of this technology in addressing the challenges of sustainable agriculture, water resource management, and energy sustainability. The findings underscore the potential of SPVPSs to revolutionize drip irrigation practices, particularly in regions with limited access to electricity or unreliable water supply. By harnessing solar energy to power irrigation systems, farmers can enhance agricultural productivity, conserve water resources, and improve livelihoods.

However, the implementation of SPVPSs is not without challenges. The initial investment costs, technical constraints, and the need for capacity building pose hurdles to widespread adoption. It is crucial for policymakers, researchers, and stakeholders to address these challenges through innovative financing models, technological advancements, and knowledge-sharing platforms. Continued research and development efforts are necessary to drive down costs, improve system efficiency, and optimize performance to make solar-powered pumping systems more accessible and reliable.

Looking to the future, there are promising prospects for the further advancement and widespread adoption of SPVPSDISs. Advancements in technology, such as improved solar panels, energy storage systems, and intelligent control algorithms, hold the potential to enhance system performance and energy management. Policy support, including favorable regulations, incentives, and financing mechanisms, will play a vital role in creating an enabling environment for the deployment of SPVPSDISs.

The environmental and socio-economic implications of SPVPSDISs are significant. These systems contribute to reduced greenhouse gas emissions, water conservation, and preservation of ecosystems. Moreover, they offer energy cost savings, increased agricultural productivity, and rural electrification, thus improving livelihoods and fostering sustainable development in rural communities. It is important for policymakers to recognize these benefits and integrate SPVPSs into their strategies for agricultural development, water management, and rural electrification.

In conclusion, recent advances in SPVPSDISs present a promising solution to the challenges faced in agriculture, water resource management, and energy sustainability. Through addressing the challenges, embracing technological innovations, and implementing supportive policies, the way can be paved for the wider adoption and sustainable implementation of these systems. Continued research, collaboration, and knowledge exchange are essential to unlock the full potential of SPVPSDISs and contribute to a more sustainable and resilient agricultural sector.

Authors Contribution

Abdul-Rahim Bawa: study design & concept, data analysis & interpretation, drafting
Albert Kojo Sunnu: literature search, data collection, drafting
Emmanuel Akono Sarsah: visualization, proofread, writing review

Conflict of Interests/Disclosures

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