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Design, Fabrication and Preliminary Performance Evaluation of a Portable Geared Solar Irrigation Pump for Smallholder Farmers

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ABSTRACT

Agricultural productivity in many regions is increasingly challenged by erratic rainfall patterns, climate variability and limited access to affordable energy sources for irrigation. Although solar-powered irrigation systems have emerged as sustainable alternatives to diesel and grid powered pumps, many existing small-scale systems operate under fixed pumping conditions with limited adaptability to varying irrigation requirements. This study presents the design, fabrication and preliminary performance evaluation of a portable Geared Solar Irrigation Pump (G-SIP) developed to provide flexible water delivery for small-scale irrigation applications. The developed system integrates a 150 W photovoltaic module, 40 Ah battery storage unit, a 48V DC motor and a three-gear transmission mechanism to enable its operation under different pumping conditions. Preliminary test was conducted on the prototype to determine the effects of gear configuration on motor speed, static head and discharge rate. The results revealed that the highest static heads reached were 15.4 m, 12.0 m and 9.5 m with discharge rates of 32 L min^{-1}, 28 L min^{-1} and 21 L min^{-1}, respectively for Gear 1, Gear 2 and Gear 3. It was further observed that the battery required approximately 4.75 hours of sunlight exposure to fully charge the battery. This enabled the pump to operate for up to 10 hours using the stored energy. The developed G-SIP combines portability, use of renewable energy, local fabrication capability and adjustable pumping performance in one irrigation unit. These preliminary findings demonstrate the potential of integrating an adjustable geared transmission system with solar energy technology to enhance the adaptability of small-scale irrigation pumps while reducing dependence on conventional energy sources.

INTRODUCTION

Rainfed agriculture is the primary source of livelihood for more than 2 billion people worldwide, with the majority of farmers depending on production systems that are increasingly vulnerable to climate variability and water scarcity (Rockström et al., 2010; Burney & Naylor, 2012). These issues are particularly evident in sub-Saharan Africa where about 90% of agriculture is rainfed (Mutiro et al., 2006) and smallholder farmers provide 70-80% of its food (Ricciardi et al., 2018). The increasing frequency and severity of droughts combined with changing rainfall patterns have intensified the need for irrigation systems to sustain agricultural productivity (Loukas & Vasiliades, 2004; Edame et al., 2011). This problem is further amplified by growing global food demand which continue to increase due to the rise in the world population. As a result, the adoption of efficient irrigation technologies has become a critical pathway for improving crop yields while promoting the sustainable management of limited water resources (Burney & Naylor, 2012; Al-Saidi & Lahham, 2019).

The effectiveness of an irrigation system largely depends on the hydraulic performance of its pumping system which determines the discharge and pressure available to convey water from wells, rivers, reservoirs or storage tanks to agricultural fields (Ahmad et al., 2024; Hou et al., 2024). The type of pump selection is determined by the discharge required, the pumping head, the characteristics of the water source and the type of irrigation system to be used. Common agricultural pump types include centrifugal, submersible, turbine and propeller pumps with centrifugal pumps being particularly widespread (Scherer, 1993; Phocaides, 2007). However, despite the availability of these pump technologies, many smallholder farmers in developing countries continue to face limited access to reliable electricity, high fuel costs associated with diesel-powered pumps and the labour-intensive nature of manual irrigation methods.

Conventional pumping solutions such as diesel-powered systems and grid-connected systems have been shown to be effective where there is supporting infrastructure. However, diesel pumps require constant fuel supply, are expensive to run and emit large amounts of greenhouse gases. Grid-connected systems are also not feasible in rural areas where there is no access to electricity. These limitations have led to the increasing demand for renewable energy irrigation technologies, especially solar photovoltaic (PV) pumping systems (Abu-Aligah, 2011; Devabhaktuni et al., 2013). Currently, solar irrigation systems harvest solar energy using PV cells and use the resultant electricity to power motor-pump sets that deliver water for irrigation. The advantages of this approach are well-documented in the literature which includes environmental sustainability, low operating costs and suitability for rural areas with abundant solar radiation (Nyasapoh et al., 2022; Devabhaktuni et al., 2013). Furthermore, solar irrigation can reduce fossil fuel dependence and enhance water resource availability, contributing to sustainable agricultural development (Al-Saidi and Lahham, 2019). Solar irrigation can further lead to decreased dependency on fossil fuels and enhance water resources availability which contributes to sustainable agricultural development (Al-Saidi and Lahham, 2019).

Despite all of the above benefits, there exist several drawbacks that make the implementation of commercial small scale solar irrigation systems challenging. First of all, most of the solar irrigation systems have hydraulic characteristics that are fixed and thus cannot be adjusted according to the needs of the farmers. As a result, both discharge and head are determined depending on the pump and the amount of solar irradiance. In addition, direct-coupled solar pumps perform inadequately under low irradiance conditions since these devices have no energy storage capability to ensure their operation in cloudy periods or during early morning and late afternoon hours. All the above factors have hindered widespread adoption of the technology among smallholders who operate under highly variable field conditions and cannot afford to oversize systems for peak demand. Beyond these technical limitations, high upfront capital costs remain a prohibitive barrier for many smallholder farmers although declining PV panel prices are gradually alleviating this constraint (Chandel et al., 2015).

The integration of energy storage and mechanical control mechanisms is a promising way to address these challenges. The use of batteries will enable solar pumps to continue to operate even when there is insufficient sunlight, while the adjustable mechanical control will increase adaptability to different conditions. Previous research has emphasized the need to integrate renewable energy solutions with agricultural technologies to increase the resilience of farming systems (Burney and Naylor, 2012; Al-Saidi and Lahham, 2019). However, the integration of energy storage and adjustable mechanical control in solar pumping systems remains limited.

To address this gap, a portable Geared Solar Irrigation Pump (G-SIP) that integrates photovoltaic energy generation, battery storage and an adjustable gear-driven pumping mechanism was developed in this study. The gear system will enable operational flexibility by allowing the mechanical transmission ratio to be varied through the selection of three different gear sizes, thereby offering different combinations of flow rate and pumping head to match site-specific requirements. In addition, portability is a further design consideration which will allow smallholder farmers who often cultivate on fragmented plots or require movement between production sites to deploy the device whenever necessary.

This study therefore aims at designing, fabricating and conducting preliminary testing of the performance of the G-SIP for small-scale agricultural applications. More specifically, the research aims at developing a solar-powered irrigation pump with a gear system, fabricating and integrating electrical and mechanical components of the system and evaluating the influence of the gear configuration on rotational speed, pumping head, discharge rate and operational performance.

MATERIALS AND METHODS

Study Area

The design, fabrication and assembly of the G-SIP was carried out at the Engineering and Mechanisation Workshop of the University for Development Studies (UDS), Nyankpala Campus, Ghana. Nyankpala is approximately 20 km southwest of Tamale, the regional capital of Northern Region of Ghana. The area is characterized by predominantly agricultural activities with many farmers relying on rainfed production systems. The location was considered suitable for the development and evaluation of a solar-powered irrigation technology due to the importance of irrigation for crop production in the region. Following fabrication and assembly, preliminary performance evaluation of the system was carried at the West African Centre for Water, Irrigation and Sustainable Agriculture (WACWISA) Green People's Irrigation Site of the UDS, Nyankpala Campus.

Design Concept of the G-SIP

The G-SIP was proposed as a renewable energy-based irrigation system designed to provide flexible water delivery for agricultural applications. The concept of the design was to integrate a photovoltaic energy source, battery energy storage, DC motor and a mechanical variable gear transmission system into a single portable pumping unit. Since the selection and operation of an irrigation pump depend mostly on the interconnection between the water demand, pumping head, discharge rate and energy availability, the matching of the irrigation pump performance parameters with those required by the irrigation is crucial for an effective irrigation (Scherer, 1993; Phocaides, 2007). Therefore, the G-SIP was developed using a variable gear system that allows adjustment of the pumping parameters under different field conditions. Unlike the conventional small-scale solar irrigation systems that operate with fixed pumping characteristics, the proposed G-SIP will use an interchangeable gear system to provide different combinations of rotational speed, torque transfer, discharge and pumping head. This feature is designed to enable operators to select suitable operating condition depending on the water source location, irrigation method and crop water requirements. The system was designed to operate primarily using solar generated electricity while allowing battery supported operation during periods of insufficient solar radiation.

Computer-Aided Design and Modelling of the G-SIP

The mechanical design and assembly of the portable G-SIP were accomplished through the use of Solid Edge 2022 Computer Aided Design (CAD) software. The CAD environment was used to generate 3D models of the structural, mechanical and electrical components and to evaluate their compatibility before fabrication. The components were modelled and assembled virtually to ensure their proper positioning relative to each other as well as the integration of mechanical and electrical components of the proposed device. An exploded view of the assembled components is shown in Figure 1. The completed 3D assembly model (Figure 2) provided a visual representation of the proposed G-SIP before fabrication. This helped to analyze the overall dimensions, component arrangement and portability aspects of the pump and accessibility for assembly and maintenance. The model also helped to determine whether the integration of the solar panel support, pumping mechanism, drive system, battery compartment and casing could be integrated into a single portable unit.

A major design feature incorporated into the CAD model was the geared power transmission system which connects the DC motor to the pumping mechanism. The transmission system was designed to allow the use of three interchangeable gears, namely Gear 1 (10 cm diameter), Gear 2 (8 cm diameter) and Gear 3 (6 cm diameter) which enabled different transmission ratios to be achieved. The different gear ratios enabled the pump to be operated at different rotational speeds and torque levels thus resulting in different pumping heads and discharge rates under different operating conditions.

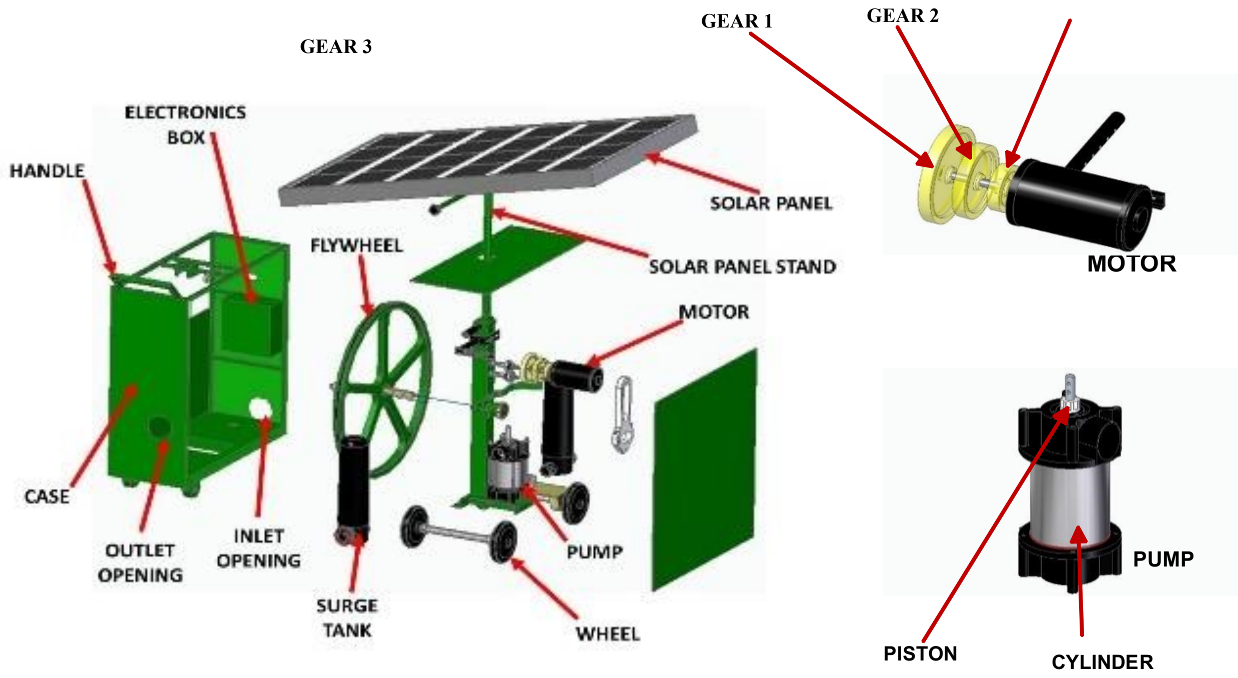

Figure 1. Exploded and Labelled CAD View of the Components of the Portable G-SIP

Figure 2. Assembled CAD Model of the Developed Portable G-SIP

Figure 3. Fabricated Prototype of the Portable G-SIP

Materials Selection and Fabrication Process

The materials used for the fabrication of the G-SIP were selected based on mechanical strength, durability, availability, resistance to corrosion and their suitability for agricultural field conditions. Mild steel was selected for the structural frame due to its strength and ease of fabrication, while 1.4 mm galvanized steel sheets were used for the pump casing to improve resistance to corrosion during field operation.

The prototype was fabricated according to the developed CAD model. A rectangular metallic frame (68.5 cm × 27 cm × 68.5 cm) was constructed and reinforced with 10 mm hollow steel sections to improve structural its rigidity. Later, front and rear wheels were fitted to enhance its portability and field mobility. The gear system was fabricated with three different sizes of gears 10 cm, 8 cm and 6 cm diameter to give different transmission ratios.

The fabrication process involved cutting, bending, drilling, welding and assembling the structural and mechanical parts. To facilitate ease of maintenance and adjustments, detachable connections were made with bolts and nuts, whereas arc welding was used to make permanent joints. After fabrication, the mechanical and electrical components were installed following the design specifications and the completed prototype was inspected to verify dimensional accuracy, proper alignment, secure mechanical and electrical connections and readiness for performance testing. The fabricated prototype of the portable G-SIP is presented in Figure 3.

Electrical System Design and Integration

The electrical subsystem of the G-SIP was designed to integrate the renewable energy source, energy storage unit, power regulation devices and drive system to ensure stable power supply for irrigation water pumping. The energy flow was configured such that electricity generated by the 150 W photovoltaic panel was fed to the charge controller for battery charging and DC power regulation. A 40 Ah battery storage system was included to ensure continuous operation of the pump during periods of reduced solar availability. A voltage converter was integrated into the electrical system to regulate the battery output and provide the required 48 V supply for the DC motor, thus ensuring efficient operation of the geared pumping mechanism. All electrical components were connected using insulated cables to ensure safe and continuous electrical transmission while a switching mechanism was incorporated to control pump operation. The complete electrical configuration and interconnection of the G-SIP is illustrated in Figure 4.

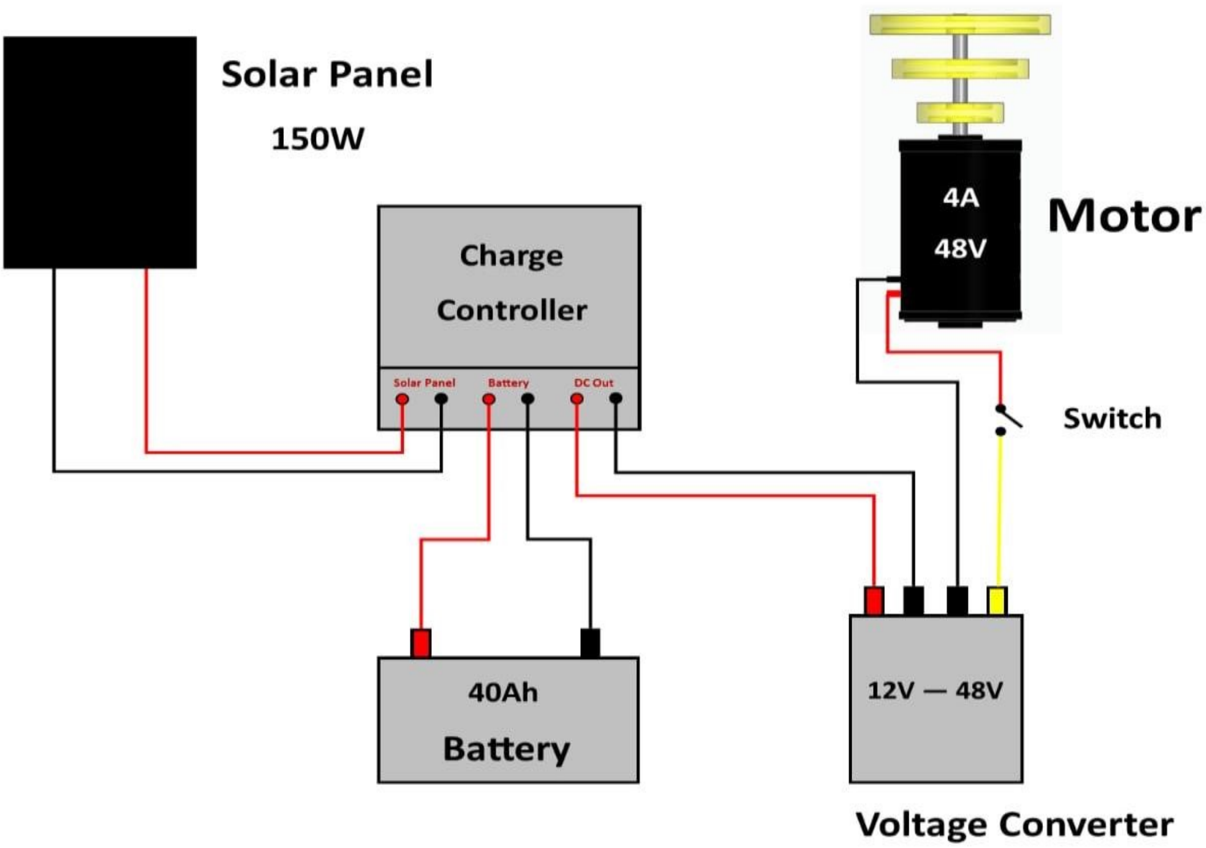

Figure 4. Electrical Integration Diagram of the Portable G-SIP System

Preliminary Performance Evaluation of the G-SIP

Preliminary performance evaluation of the developed G-SIP was conducted to determine the influence of gear configuration on the performance of the pump. The parameters evaluated were rotational speed of the motor, discharge rate and static head. These parameters are important indicators for assessing irrigation pump suitability because pump performance is determined by its ability to deliver required flow rates at specified lifting conditions (Scherer, 1993; Phocaides, 2007). The rotational speed of the motor was measured using a PCE-151 digital tachometer (PCE Instruments, Meschede, Germany). Pump discharge was determined using the volumetric method by collecting water in a graduated bucket and recording the collection time with a stopwatch (Osome et al., 2023). The static head was determined by measuring the maximum vertical elevation reached by water discharge through a 32 mm PVC delivery pipe. This approach follows irrigation pump evaluation procedures where pump head is expressed as the vertical height of water column or hydraulic head required to lift water. Similar approaches have been used in studies of irrigation pump performance where operating head, discharge and hydraulic performance are determined under field conditions (Vedant and Vekariya, 2018). Each of the three gear configurations was tested independently to evaluate its influence on the operating characteristics of the pump. In addition, the charging time required for the battery and the duration of pump operation using stored battery energy were recorded.

RESULTS AND DISCUSSION

Overview of Prototype Development and Preliminary Performance Evaluation

The design, fabrication and integration processes described in the previous section resulted in the successful development of a portable G-SIP. The developed prototype consisted of a photovoltaic power generation system, battery storage unit, electrical control components, DC motor, geared transmission mechanism, pumping chamber and a portable supporting frame. The integration of these components produced a compact irrigation system which can operate independently of any conventional electricity sources. One of the design features of the developed system was the incorporation of an adjustable gear transmission mechanism which allowed different pumping characteristics to be achieved under varying irrigation conditions. After fabrication of the prototype, it was tested to examine its performance under different settings of the gears. The parameters that were measured include motor speed, static head and discharge rate. These parameters are significant in terms of measuring the performance of the irrigation pumps since they demonstrate the relation between the water delivery and the need for lifting (Scherer, 1993; Phocaides, 2007). The performance of the solar-battery power system was also evaluated to estimate the time for charging and operation. The results of the performance test are described below.

Performance Characteristics and Influence of Gear Design on Hydraulic Performance

The performance characteristics of the developed G-SIP under the three gear configurations are shown in Table 1. From the results, it is evident that changes in the gear diameter influenced the rotational speed, static head and discharge of the pumping system. As the gear diameter decreased from 10 to 6 cm, the motor rotational speed increased from 614.00 to 762.92 rpm. Gear 3 which had the smallest diameter (6 cm) recorded the highest rotational speed (762.92 rpm) but produced the lowest static head (9.5 m) and discharge (21 L min^{-1}). On the other hand, Gear 1 with the largest diameter (10 cm) operated at the lowest rotational speed (614 rpm) but recorded the highest static head (15.4 m) and discharge (32 L min^{-1}).

The observed differences suggest that the performance of the pump depended not only on the rotational speed but also on the mechanical advantage offered by the gear transmission system. This is so because, the larger gear diameter is likely to have provided a greater mechanical advantage by transmitting higher torque to the pumping mechanism, which made it easier to overcome the hydraulic resistance associated with lifting water. The ability of an irrigation pump to deliver water depends on the relationship between flow rate, pumping head and the mechanical characteristics of the driving system (Moreno et al., 2009).

The flywheel and reciprocating pumping mechanism also facilitated the conversion of motor rotation into pumping action, while the variable gear system controlled the mechanical advantage supplied to the pump by adjusting the speed and torque transmitted by the motor to the pumping mechanism. This combination enabled the G-SIP to achieve different hydraulic conditions without replacing the complete pumping unit. The incorporation of an interchangeable gear system allows greater operational flexibility compared with the conventional solar irrigation pumps which are designed to operate within a fixed performance range determined by the selected motor–pump combination and available solar energy (Abu-Aligah, 2011). By selecting an appropriate gear configuration, the G-SIP can be adapted to different water source depths, field conditions, and irrigation requirements.

Table 1 Performance Characteristics of the G-SIP under Different Gear Configurations

Gears	Diameter (cm)	Motor Speed (rpm)	Static Head (m)	Discharge (L min^{-1})
Gear 1	10	614.00	15.4	32
Gear 2	8	657.33	12.0	28
Gear 3	6	762.92	9.5	21

Solar Energy and Battery System Performance

The solar energy and battery storage system was also evaluated to determine its ability to provide continuous power supply for the operation of the developed G-SIP. The results showed that it took about 4.75 hours of sunshine to fully charge the battery. This enabled the battery to run the pump for a maximum duration of 10 hours. The results show that the integration of battery storage improved the continuity of the pump operation by supplying the electrical energy when the solar radiation was insufficient.

The incorporation of battery storage addresses one of the main drawbacks of direct coupled photovoltaic pumping system that the system operates based on the availability of solar radiations. It has been reported that photovoltaic irrigation systems along with the energy storage systems offer better performance in terms of reliability because they can supply water in the times of low solar radiation (Abu-Aligah, 2011; Devabhaktuni et al., 2013). In that way, the developed G-SIP can overcome one of the major disadvantages of direct coupled photovoltaic irrigation system as its operation is not dependent on solar radiation only. This feature is especially applicable in agricultural settings where irrigation scheduling may be driven by crop water requirement rather than by solar availability alone. The integration of photovoltaic as energy source and the battery as an energy storage system will also result in decreasing the use of conventional irrigation systems which operate on fossil fuel. This is because, renewable energy-based pumping technologies have been recognized as sustainable solutions for agricultural water management due to their ability to minimize costs of operations as well as environmental impacts associated with conventional fuel-powered systems (Devabhaktuni et al., 2013; Al-Saidi and Lahham, 2019). Based on the observed charging time and operating duration, the integrated photovoltaic–battery system demonstrates its potential to provide a reliable energy supply for small-scale irrigation while maintaining the environmental benefits associated with solar-powered technologies.

Practical Application and Sustainability of the G-SIP

The obtained performance results of the developed G-SIP indicate that this pump could be used for irrigation purposes on a smaller scale. The maximum discharge of 32 L min^{-1} and static head of 15.4 m achieved while applying the 10 cm gear configuration indicate that the pump could provide enough water to support a range of small-scale irrigation applications, including vegetable production. The pump is also mobile due to the supporting structure with wheels. This is particularly useful for smallholder farmers farming on fragmented plots of land or who require seasonal movement of their irrigation equipment. Generally, smallholder irrigation has been recognized as an important approach for improving agricultural productivity, reducing vulnerability to rainfall variability and supporting rural livelihoods particularly in regions where access to conventional irrigation infrastructure is limited (Burney and Naylor, 2012). The portability and independent energy supply of the G-SIP therefore provide a flexible irrigation option for such farming systems.

The use of solar energy further enhances the sustainability of the developed pump. Unlike diesel-powered irrigation pumps which require continuous fuel consumption and generate greenhouse gas emissions during operation, the G-

SIP utilizes renewable solar energy as its primary power source. According to Devabhaktuni et al. (2013) and Al-Saidi and Lahham (2019), technologies for solar-powered irrigation have been recognized as sustainable ways to manage water in agriculture as they facilitate energy access while decreasing operating costs and negative environmental impact. Furthermore, the use of locally available materials and fabrication techniques provides opportunities for easier maintenance, repair and adaptation under local conditions. This will enhance accessibility of renewable energy irrigation technologies for small-scale farmers. Overall, the developed G-SIP integrates portability, renewable energy utilization, and adjustable pumping performance into a single irrigation system. The findings therefore suggest that the technology has the potential to improve water access for small-scale crop production and contribute to sustainable agricultural mechanization and climate-resilient irrigation systems.

CONCLUSION AND FUTURE WORK

Conclusion

The design, fabrication and performance evaluation of a portable G-SIP were successfully achieved. The developed system integrates photovoltaic energy generation, battery storage, electrical control components and a mechanically adjustable geared pumping mechanism into a single portable irrigation unit for small-scale agricultural applications. The incorporation of an adjustable gear transmission system provided flexibility in modifying the pump performance according to different irrigation conditions. The performance evaluation showed that the gear system had some impact on the rotational speed, static head and discharge rate of the pump. The 10 cm gear configuration (Gear 1) achieved the highest hydraulic performance with static head and discharge of 15.4 m and 32 L min^{-1}, respectively while Gear 2 and Gear 3 recorded lower heads and discharge values. These results further show that the adjustable gear drive mechanism was effective in altering the mechanical performance of the motor to enhance operational versatility of the devised system. The integration of photovoltaic energy generation with battery storage ensured that there was continuity in the operation of the pump. The solar-battery system achieved full charging within 4.75 hours of sunshine exposure and the pump was able to continue running for up to 10 hours using stored energy. These findings suggest the potential application of G-SIP in facilitating irrigation activities in locations where conventional sources of electrical energy are not readily available. The portability, use of renewable energy source and the local manufacturing capability make the G-SIP a suitable choice for irrigation activities. Also, the combination of solar energy technology and adjustable mechanical drive system makes the devised pump an adaptive solution to improve access to sustainable irrigation technologies.

Future Work

While the developed G-SIP showed good performance, additional research is required in order to prove its technical viability, economic feasibility and scalability. Field tests need to be conducted under varying weather conditions and agricultural practices for the determination of durability, maintenance and long-term operational performance. Further investigations should also quantify hydraulic and energy performance by measuring electrical input power, hydraulic output power and the efficiency of the whole system under various gear and operating head configurations. Economic assessment should include fabrication costs, operational benefits, payback period and economic gains for the farmer. As it stands, the current design operates using manually operated gears; thus, future development could involve the use of automatic control that will allow adjustment of the operation to meet the requirements of the irrigation needs, water level, soil moisture and solar radiation. Integration of IoT-based monitoring and control systems could also make it possible to assess the pump efficiency, energy availability and field conditions in real-time. Monitoring based on sensors for soil moisture, solar radiation, battery power status and water distribution could help in intelligent irrigation scheduling. Improvement in design could involve the increase of energy storage capability, decrease of weight and optimization of the pumping unit for efficiency and ease of deployment in larger areas under cultivation. These improvements will support the further development of G-SIP and its potential commercialization as a portable solar irrigation system.

CONFLICT OF INTEREST

The authors have declared no conflict of interest regarding the publication of the paper.

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