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Development and Performance Assessment of a Solar-Powered Backpack Sprayer under Field Conditions

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Abstract

The demand for sustainable and energy-efficient agricultural machinery has increased significantly due to rising fuel costs, labor shortages, and environmental concerns. This study focuses on the design, development, and performance evaluation of a solar-operated backpack sprayer suitable for smallholder farming systems. The sprayer was developed at the Workshop Machinery and Maintenance Division of Bangladesh Rice Research Institute (BRRI), Gazipur, incorporating a 15 W photovoltaic panel, a 12 V rechargeable battery, and a DC motor-driven pump. The system utilizes solar energy to operate the spraying mechanism, thereby reducing reliance on fossil fuels and manual effort while promoting environmentally friendly agricultural practices. The performance of the developed sprayer was evaluated through laboratory testing and field experiments under different operating conditions. Key performance parameters, including discharge rate, application rate, and field capacity, were measured and analyzed. The results indicated that the discharge rate remained relatively stable throughout the day, ranging from 1.49 to 1.55 L min^{-1}, with an average value of 90.05 L h^{-1}. The sprayer exhibited optimal performance during midday due to higher solar irradiance and battery voltage. The application rate increased from 20.83 to 104.16 L ha^{-1} with increasing spray volume, while the field capacity decreased from 4.36 to 0.85 ha h^{-1}, indicating a trade-off between application volume and operational efficiency. The effective field capacity and field efficiency of the backpack sprayer were recorded as 0.136 ha h^{-1} and 71.39%, respectively. The study also revealed that solar irradiance and battery voltage significantly influenced system performance. Overall, the developed solar-operated sprayer demonstrated consistent performance, energy efficiency, and suitability for field conditions. The findings suggest that the system can serve as a viable, cost-effective, and sustainable alternative to conventional sprayers, particularly in rural and off-grid agricultural areas.

Keywords

Solar Sprayer, Renewable Energy, Sustainable Agriculture, Spray Uniformity

1. Introduction

Agricultural spraying is a crucial operation in modern crop production systems, enabling the effective application of pesticides, herbicides, and fertilizers required for crop protection and yield enhancement. In many developing countries, including Bangladesh, backpack sprayers are widely used due to their low cost, simplicity, and suitability for small and fragmented landholdings. However, conventional sprayers are often associated with several limitations, such as high labor requirements, operator fatigue, non-uniform spray distribution, and dependence on manual pumping or fossil fuel-based energy sources. These constraints reduce operational efficiency and can lead to improper application of agrochemicals, resulting in reduced crop productivity and increased environmental risks P [1] [2].

With the growing emphasis on sustainable agriculture and environmental conservation, there has been increasing interest in integrating renewable energy technologies into agricultural practices. Solar energy, in particular, has emerged as a viable alternative due to its abundance, eco-friendliness, and economic feasibility. Solar photovoltaic (PV) systems convert solar radiation into electrical energy, which can be used to power agricultural machinery without relying on conventional energy sources. The adoption of solar-powered technologies in agriculture offers several advantages, including reduced operational costs, elimination of fuel dependency, and decreased greenhouse gas emissions. These benefits are especially significant in rural and off-grid areas where access to electricity is limited [3] [4].

Solar-operated sprayers have been developed to overcome the limitations of traditional spraying equipment by incorporating photovoltaic panels, rechargeable batteries, and electrically driven pumps. In such systems, the solar panel generates electrical energy that is stored in a battery, which subsequently powers a DC motor-driven pump to deliver liquid through a nozzle system. This arrangement ensures relatively stable pressure and discharge rates compared to manual sprayers, leading to improved spray uniformity and coverage efficiency. Uniform application of agrochemicals is critical for effective pest and weed control, as inconsistent spraying can result in under-application or over-application, thereby increasing production costs and environmental hazards [5].

The performance of agricultural sprayers is typically evaluated using key parameters such as discharge rate, application rate, field capacity, and field efficiency. The discharge rate determines the volume of liquid delivered per unit time, while the application rate indicates the amount of liquid applied per unit area. Field capacity reflects the ability of the sprayer to cover a given area within a specific time, and field efficiency measures the effectiveness of field operations under actual working conditions. These parameters are influenced by factors such as nozzle design, operating pressure, forward speed, and power availability [6].

In solar-powered systems, performance is further influenced by environmental conditions, particularly solar irradiance and battery voltage. The availability of solar energy varies throughout the day, which affects the output of the photovoltaic panel and, consequently, the operation of the pump. Previous studies have shown that solar-operated sprayers generally perform optimally during midday when solar irradiance is at its peak, while slight variations in discharge rate and pressure may occur during morning and late afternoon due to reduced sunlight intensity [4] [7]. Therefore, understanding the relationship between solar energy availability and sprayer performance is essential for optimizing system design and ensuring consistent operation under field conditions.

In Bangladesh, agriculture plays a vital role in the national economy, and the adoption of efficient and sustainable technologies is essential for enhancing productivity and ensuring food security. Farmers frequently encounter challenges such as rising fuel costs, limited access to electricity, and labor shortages, which hinder timely agricultural operations. Solar-operated sprayers provide a practical solution to these challenges by offering a cost-effective, portable, and environmentally friendly alternative to conventional sprayers. Moreover, the use of renewable energy in agricultural machinery contributes to reducing environmental pollution and supports sustainable farming practices. Despite the potential advantages, the adoption of solar-powered sprayers remains limited due to factors such as lack of awareness, initial investment costs, and insufficient performance evaluation under local conditions. Therefore, it is necessary to design and develop solar-operated sprayers that are suitable for local farming systems and to conduct detailed performance evaluations to assess their efficiency and reliability.

In this study, a solar-operated backpack sprayer was designed and developed at the Workshop Machinery and Maintenance Division of Bangladesh Rice Research Institute (BRRI), Gazipur. The system utilizes a photovoltaic panel to generate electrical energy, which is stored in a 12 V battery and used to power a DC motor-driven pump for spraying liquid through a nozzle system. The present study focuses on evaluating the operational performance of the developed sprayer under laboratory and field conditions, considering key performance parameters such as discharge rate, application rate, and field capacity, as well as analyzing the influence of solar energy availability, including battery voltage and solar irradiance, on its performance. Furthermore, the study aims to design and develop a suitable solar-operated backpack sprayer for smallholder farmers and to assess its overall effectiveness as a sustainable alternative to conventional spraying methods while providing recommendations for improving its design and field performance.

2. Material and Methods

The solar operated sprayer was fabricated in the Workshop Machinery and Maintenance Division, Bangladesh Rice Research Institute (BRRI), Gazipur. The solar operated sprayer uses solar energy as source of power, in the form of a solar cell. This cell charges a 12 V DC battery which turn operates a DC motor. This motor activates a pump which further pumps pesticide, stored in the form of a solution liquid, through a nozzle, thereby, creating a spray. It consists of a adjustable pipe to adjust the angle of solar panel (15 W), height adjustable pipe to adjust the height of panel, a liquid tank with a cap to hold the solution enclosing the tank (16 L) and to which height adjustable pipes are fixed, a 12 V battery fixed to the frame at the bottom of the tank, a 12 V DC motor pump, for spraying the pesticide. The spray consists of sufficiently long hose pipe, a spray nozzle (0.75 mm), a valve for starting and stopping the spray and also to control the flow rate of spray. The spray unit is also provided with belt and a set of clamps to fasten the entire unit to the back of the operator and also a cushion pad, glued on the tank, to provide cushioning effect when the entire unit is resting on the back of the operator. A schematic diagram of the total system developed for the experimental work is shown in Figure 1.

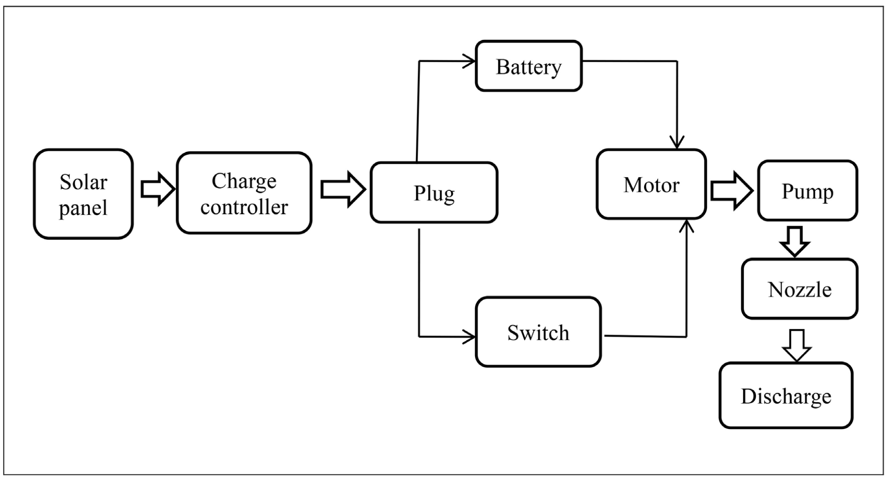

Figure 1. Working procedure of solar powered operated sprayer.

2.1. Design Consideration

Design and development of solar-powered operated sprayer involves several key considerations to ensure it meets the intended objectives. The solar sprayer was developed according to the following considerations:

- Ensuring size and weight of the panels should be lightweight and compact enough to be integrated into the sprayer without compromising mobility.

- To choose solar panels with high efficiency to maximize energy conversion.
- Optimize the solar panel and battery combination to minimize charging time while maximizing operating time.
- Using a pump can deliver the required pressure and flow rate for effective spraying.
- The pump should be compatible with the power output of the solar panel and battery system.
- To choose nozzles that provide the desired spray pattern, whether it be fine mist or broader coverage.
- The tank should be durable and lightweight materials that are resistant to chemicals.
- Design for easy maintenance, with accessible components for cleaning and repairs.
- It should be used eco-friendly materials where possible to reduce the environmental impact.
- The battery life under different operating conditions to ensure it meets the required duration.

2.2. Functional Elements of a Solar Operated Sprayer

The solar-powered operated sprayer is composed of several key functional elements, each carefully designed to work together efficiently, ensuring reliable and effective spraying.

Solar Panel: The solar panel generates electricity by converting sunlight into electrical energy. This energy powers the pump and charges the battery. The solar panel is the core of the system, providing a renewable and sustainable energy source, reducing the need for external power or fuel.

Pump: The pump drives the flow of liquid (pesticides, fertilizers, or water) from the tank through the system to the nozzles. The pump ensures that the liquid is delivered at the necessary pressure for effective spraying, which is crucial for uniform coverage.

Battery: The battery stores electrical energy generated by the solar panel and supplies it to the pump and other components as needed. The battery allows the sprayer to operate during times when sunlight is insufficient, ensuring continuous operation throughout the day.

Tank: The tank holds the liquid to be sprayed, such as pesticides, herbicides, or water.

Nozzle: The nozzle disperses the liquid into a fine spray, ensuring even distribution across the target area. The nozzle's size and design influence the spray pattern and coverage area, making it essential for precise and effective spraying.

Connecting Wire: The connecting wire carries electrical current from the solar panel to the battery and from the battery to the pump. Proper wiring ensures efficient energy transfer between components, minimizing energy loss and ensuring reliable operation.

2.3. Development and Fabrication of Sprayer

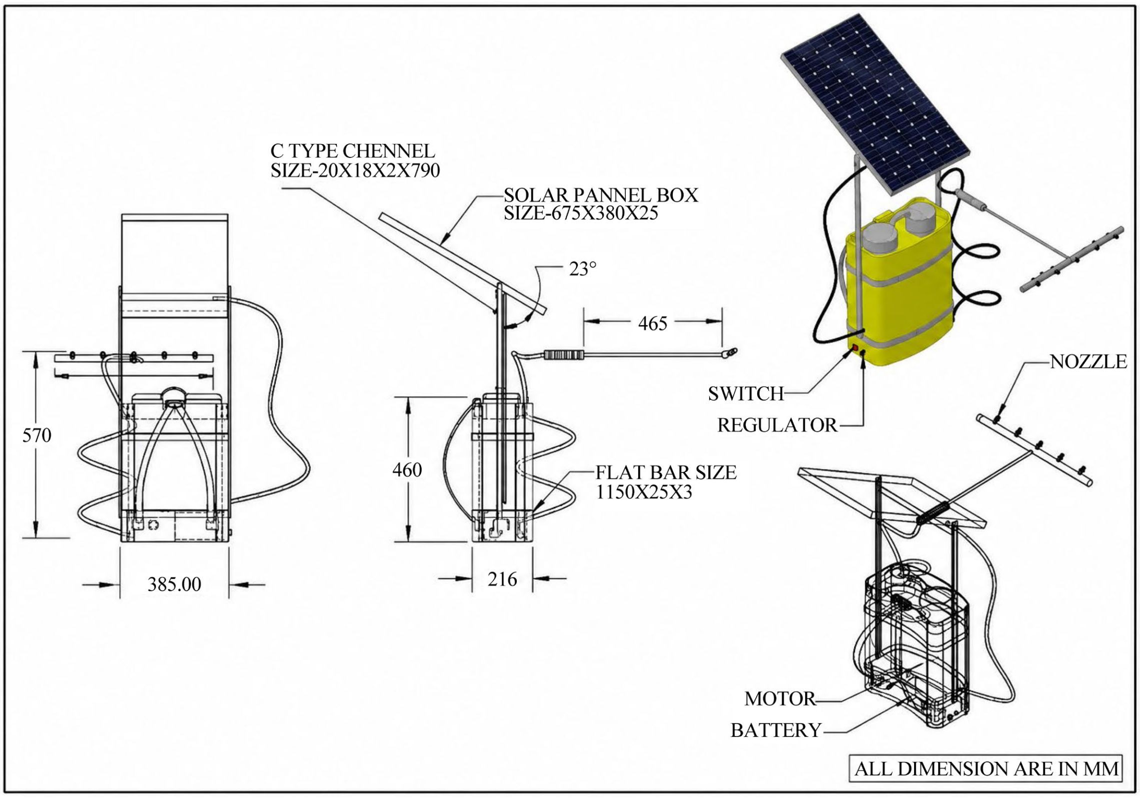

Figure 2. Layout of backpack solar-powered sprayer.

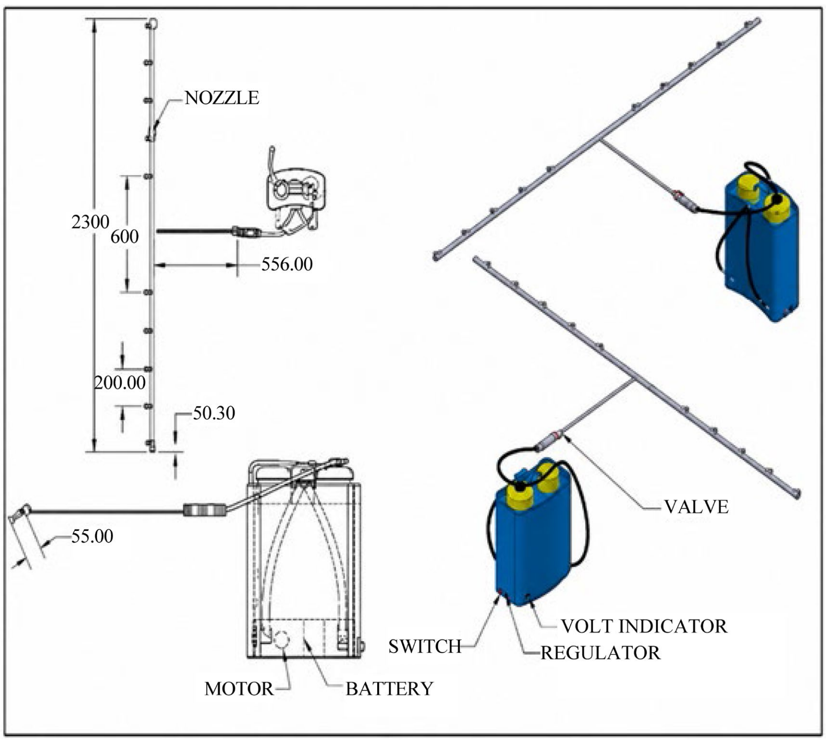

Figure 3. Layout of a multi-nozzle sprayer.

The development of the solar operated sprayer began with detailed Solidworks and drawings to outline the system's components and layout. Once the design was finalized, the fabrication process proceeded at the WMM workshops. Solidworks drawings provided a clear blueprint for constructing the sprayer, including the placement of the 16 L tank, 12 V motor, 0.75 mm nozzle, and 15 W solar panel. **Figure 2** and **Figure 3** show some drawing views of the backpack solar-operated sprayer and multi-nozzle sprayer respectively. Components were fabricated and assembled according to the design. The solar operated sprayer was fabricated in WMM workshop (**Figure 4**). The 12 V motor and nozzle were mounted on the tank, while the solar panel was positioned to ensure optimal sunlight exposure. The 15 W solar panel was connected to a 12 V battery, which powers the motor. Connecting wires were used to link all electrical components, ensuring proper operation. The sprayer operates by harnessing solar energy to charge the 12 V battery through the 15 W solar panel. The charged battery then powers the 12 V motor, which drives the nozzle to spray liquid from the 16 L tank.

Figure 4. Fabrication of solar operated sprayer in WMM workshop.

3. Performance Evaluation of Solar Operated Sprayer

The performance evaluation of the solar operated sprayer was conducted in two distinct phases to comprehensively assess its functionality and efficiency, lab-based test at the WMM Divisional Workshop and a field trial at BRRI Farm in Gazipur. The initial phase of evaluation took place at the BRRI field where the initial focus was on testing and calibrating the sprayer's components (**Figure 5**). The 15 W solar panel was examined for its efficiency in converting solar energy into electrical power. Performance of voltage output and charging capability were measured. The 12 V DC battery was tested for its capacity to store and supply power to the sprayer. The battery charge and discharge were monitored to evaluate its reliability. The 12 V motor and 0.75 mm nozzle were assessed for their operational efficiency. The motor works to drive the nozzle effectively was tested by measuring discharge rates and flow consistency. The integration of the solar panel, battery, motor, and nozzle was checked to ensure seamless operation. Various parameters like wiring and component alignment were inspected. Following successful lab testing, the multi nozzle sprayer was taken to BRRI Farm in Gazipur for a field trial (**Figure 6**). This phase aimed to evaluate the sprayer performance in practical conditions. During the testing, data such as discharge rates, battery voltage, and system efficiency were collected. This information provided a baseline for the sprayer capabilities and identifying any necessary adjustments before field trial.

Figure 5. Backpack sprayer.

Figure 6. Multi-nozzle sprayer.

3.1. Parameters of the Sprayer

3.1.1. Volume Application

The sprayer was tested across various volumes of liquid to assess its capacity and performance. The volume of liquid applied was recorded along with the time taken for each application.

3.1.2. Discharge Rate

The rate at which the sprayer discharged liquid was measured to determine its efficiency. This included calculating discharge rates in liters per hour (L/h) and assessing how well the sprayer maintained consistent output.

Discharge rate,

$$Q = \frac{V}{T}$$

where,

V = volume collected (L),

T = time taken (h).

3.1.3. Application Rate

The amount of liquid applied per hectare (L/ha) was evaluated to understand the sprayer's effectiveness in covering the intended area. This metric was crucial for determining the sprayer's suitability for different types of agricultural tasks.

Application rate,

$$\text{Ar} = \frac{V}{A}$$

where,

V = volume collected (L),

A =Area covered (ha).

3.1.4. Field Capacity

The sprayer's field capacity, measured in hectares per hour (ha/h), was recorded to evaluate how efficiently it covered the area. This included assessing how the sprayer's performance varied with different volumes and application.

Field capacity,

$$\text{fc} = \frac{A}{T}$$

where,

fc = Field capacity (ha/h),

A = Total area covered by the sprayer (ha),

T =Time required for area covered (h).

3.1.5. Theoretical Field Capacity (TFC)

The theoretical field capacity (TFC) represents the ideal rate of field coverage assuming no losses due to turning, refilling, or operational delays. It was calculated using the forward speed and effective spray width of the sprayer.

$$\text{TFC} = \frac{S \times W}{10}$$

where:

TFC = Theoretical field capacity (ha/h),

S = Forward speed of the sprayer (km/h),

W = Effective spray width (m),

10 = Conversion factor.

3.1.6. Effective Field Capacity (EFC)

The effective field capacity (EFC) accounts for actual working conditions, including time losses during turning, refilling, adjustments, and minor stoppages.

$$\text{EFC} = \frac{A}{T}$$

where:

- EFC = Effective field capacity (ha/h),
- A = Actual area covered (ha),
- T = Total time consumed including delays (h).

3.1.7. Field Efficiency (FE)

The field efficiency (FE) indicates how efficiently the sprayer operates under real field conditions compared to its theoretical performance.

$$\text{FE} = \frac{\text{EFC}}{\text{TFC}} \times 100$$

where:

FE = Field efficiency (%),

EFC = Effective field capacity (ha/h),

TFC = Theoretical field capacity (ha/h).

4. Results and Discussion

The discharge rate of the sprayer generally fluctuates throughout the day but remains relatively stable. There is a general trend where a higher battery voltage corresponds to a higher discharge rate (**Table 2**). The sprayer performs best around midday when the solar panel efficiency is highest. Performance declines slightly in the morning and late afternoon, likely due to less optimal solar conditions and reduced battery charge. the solar operated sprayer discharge rate is positively correlated with battery voltage and shows optimal performance around midday. The variations in discharge rate throughout the day align with changes in solar intensity and battery charge. **Figure 6** shows variation of sprayer discharge with day time. The discharges rate, which is the volume of liquid sprayed per minute, showed minimal variation across the day. It ranged from 1.49 to 1.55 liters per minute, with the highest rate occurring at 1:00 PM (1.55 l/min) and the lowest at 5:00 PM (1.49 l/min). This consistency suggests that the sprayer can deliver a uniform application of liquids, regardless of the time of day. The volume of liquid sprayed and the corresponding time increased. At 9:00 AM, 1 liter was sprayed in 0.65 minutes, while by 5:00 PM, 5 liters were sprayed in 3.36 minutes. The data indicates that the sprayer efficiently managed larger volumes as the day advanced, maintaining a steady discharge rate even as the volume increased. The discharge rate, which measures the volume of liquid sprayed per minute (l/min), exhibits only slight variations throughout the day. It starts at 1.54 l/min at 9:00 AM, slightly decreases to 1.41 l/min by 11:00 AM, then increases to 1.55 l/min at 1:00 PM, and remains fairly consistent, ending at 1.49 l/min by 5:00 PM (**Figure 7**). The discharge rate correlates somewhat with these voltage changes; it is highest when the battery voltage is at its peak (1:00 PM) and decreases slightly as the voltage drops towards the end of the day.

The battery voltage remained relatively stable during the testing period, ranging from 11.24 V in the morning (9:00 AM) to a peak of 11.70 V at 1:00 PM, followed by a slight decrease to 11.51 V by 5:00 PM (**Figure 7**). The battery voltage slightly increases from 11.24 V in the morning to a peak of 11.70 V at midday and gradually decreases to 11.51 V by the late afternoon. This indicates that the solar-powered system effectively maintained a steady voltage, ensuring consistent power supply throughout the day. The sprayer delivers liquid at a relatively constant rate showing reliable performance across different volumes. Increases with volume, reflecting higher liquid application per hectare as more volume is used. Decreases with increasing volume, indicating that more time is needed to cover the same area as the volume applied increases. The application rate increases as the volume applied increases. Application rate is calculated as the volume applied divided by the area covered (0.048 ha). The application rate rises from 20.83 l/ha at 1.00 L volume to 104.16 l/ha at 5.00 L volume. **Table 1** shows that as more volume is applied, the amount of liquid per hectare increases, which might be due to the increase in total volume applied over the same area. Field capacity decreases as the volume applied increases. This is because field capacity is calculated as the area covered per hour, which declines with higher volumes due to longer application times. The field capacity decreases from 4.36 ha/h at 1.00 l volume to 0.85 ha/h at 5.00 L volume. This indicates that the sprayer's efficiency in covering the area decreases as more volume is applied, leading to more time required for each additional liter of liquid. **Figure 8** shows discharge rate, application rate, field capacity of solar operated sprayer.

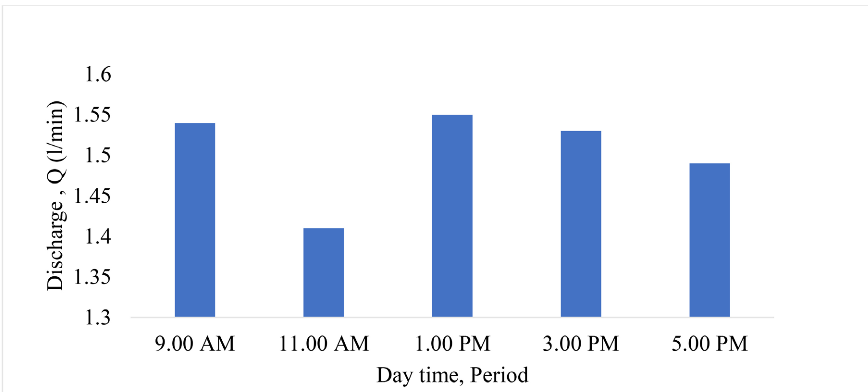

Figure 7. Variation of sprayer discharge with day time.

Table 1. Performance evaluation of solar operated sprayer (Area covered = 0.048 ha).

Time (h)	Volume (L)	Discharge rate (l /h)	Application rate (l/ha)	Field capacity (ha/h)
0.011	1.00	90.91	20.83	4.36
0.024	2.00	83.33	41.67	2.00
0.032	3.00	93.75	62.5	1.5
0.043	4.00	93.02	83.33	1.11
0.056	5.00	89.28	104.16	0.85
Average		90.05	62.49	1.96

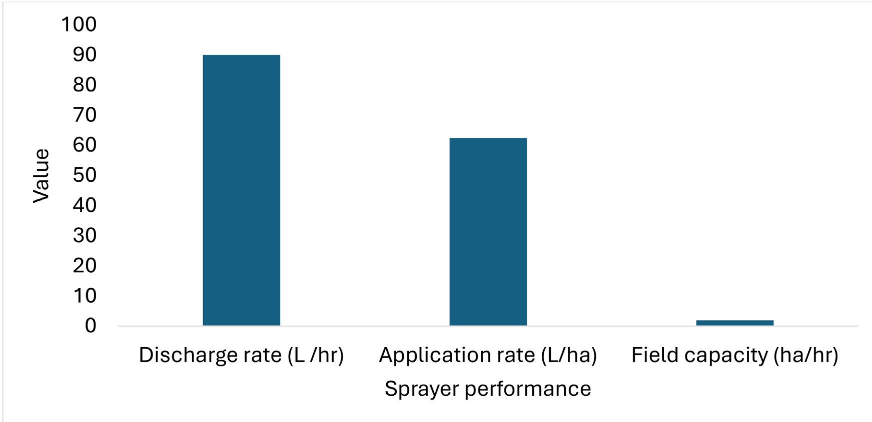

Figure 8. Discharge rate, application rate, field capacity of solar operated sprayer.

Table 2 shows that the trolley-mounted sprayer achieved the highest average effective field capacity (0.182 ha/hr), followed by the multi-nozzle (0.159 ha/hr) and backpack sprayers (0.136 ha/hr). **Table 3** indicates the multi-nozzle and back-pack sprayers achieved 74.67% and 71.39%, respectively. These results demonstrate that the trolley-mounted sprayer provides greater coverage and efficiency compared to the other types.

Table 2. Effective Field capacity of different sprayers.

Sprayer Type	Obs. No.	Area Coverage (ha)	Time Taken (sec)	Effective Field Capacity (ha/hr.)	Average Effective Field Capacity (ha/hr.)
Backpack sprayer	1	0.0025	64	0.141	0.136
	2		66	0.136	
	3		68	0.132	
Multi-nozzle sprayer	1	0.0025	55	0.164	0.159
	2		57	0.158	
	3		59	0.155	

Table 3. Field efficiency of different sprayers.

Sprayer Type	Obs. No.	Spraying Width (m)	Forward Speed (km/hr)	Theoretical Field Capacity (ha/hr)	Effective Field Capacity (ha/hr)	Field Efficiency (%)	Average Field Efficiency (%)
Backpack sprayer	1	0.60	2.00	0.199	0.141	70.83	71.39
	2	0.60	2.00	0.185	0.136	73.33	
	3	0.60	2.00	0.189	0.132	70.00	
Multi-nozzle sprayer	1	1.50	2.50	0.220	0.164	74.67	74.67
	2	1.50	2.50	0.208	0.158	76.00	
	3	1.50	2.50	0.211	0.155	73.33	

Battery voltage increases with daytime as solar charging progresses, while current follows a similar trend (Figure 9). Solar irradiance peaks midday and decreases thereafter, causing a corresponding drop in flow rate (Figure 10). Solar irradiance shows a typical diurnal pattern, peaking around midday and gradually declining toward evening.

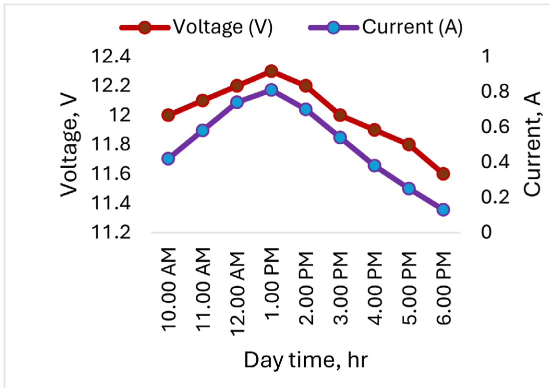

Figure 9. Variation of voltage and flowrate with day time in back pack sprayer.

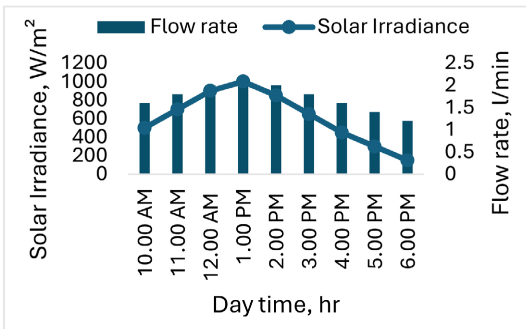

Figure 10. Variation of solar irradiance rate with daytime in backpack sprayer.

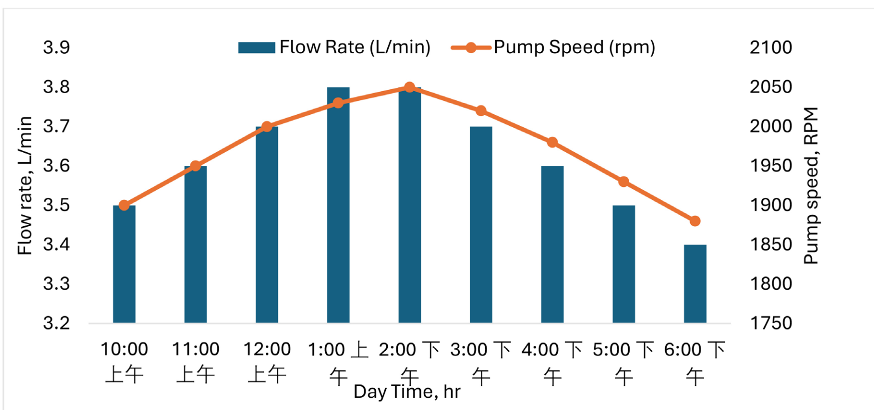

Figure 11. Variation of flow rate and pump speed during daytime in multi nozzle sprayer.

Figure 11 shows flow rate and pump speed increase until early afternoon, peaking around 2:00 PM, and then gradually decrease toward evening, reflecting the effect of solar energy availability on system performance. Table 4 presents the technical specifications of the backpack solar-powered sprayer and multi-nozzle boom sprayer. The multi-nozzle sprayer showed higher spraying capacity, flow rate, and number of nozzles, while the backpack sprayer provided portable solar-powered operation suitable for small-scale field applications.

Table 4. Detailed technical specifications of solar-operated sprayers.

Items	Back pack solar powered sprayer	Multi-Nozzle Sprayer
Type of sprayer	Solar operated	Multi nozzle boom sprayer
Capacity of the tank	16 L	18L
Solar panel power	15 W	-
Solar panel size	675 mm × 380 mm × 25 mm	-
Battery current	1.7 A	2.5
Pump voltage	12 V (DC)	12 V (DC)
Charging time (hr)	4	5.5
Number of nozzle (nos.)	5	10
Max Pressure (MPa)	0.45	0.50
Open Flow (L/min)	2.8	3.7
Battery Voltage (VDC)	12	12
Max Current (A)	2.0	2.5
Net weight	6 kg	5.2 kg

5. Recommendation

- ❖ Design the sprayer to be lightweight and easy to carry, especially for small-scale farmers. This includes using materials that are both durable and light.
- ❖ Ensure that the battery capacity is sufficient to operate the sprayer throughout the day, even under low sunlight conditions. Consider using high-efficiency batteries that can store more energy in a compact form.
- ❖ Incorporate adjustable nozzles that allow farmers to control the spray pattern and volume, catering to different crops and application needs.
- ❖ Focus on reducing production costs through the use of locally available materials and simple manufacturing processes, making the technology accessible to smallholder farmers.

6. Conclusions

This study demonstrated the successful design, development, and evaluation of a solar-operated backpack sprayer as an energy-efficient and sustainable alternative to conventional agricultural spraying systems. The developed sprayer, powered by a 15 W photovoltaic panel and a 12 V rechargeable battery driving a DC motor pump, effectively utilized solar energy to perform spraying operations under both laboratory and field conditions. The integration of renewable energy into the system reduced dependence on fossil fuels and minimized manual effort, making it particularly suitable for smallholder farmers and rural applications. The performance evaluation indicated that the sprayer maintained a relatively stable discharge rate throughout the day, ranging from 1.49 to 1.55 L min^{-1}, with an average discharge rate of 90.05 L h^{-1}. The system exhibited optimal performance during midday due to higher solar irradiance and increased battery voltage. The application rate increased proportionally with the volume of liquid applied, while field capacity decreased from 4.36 to 0.85 ha h^{-1} as application volume increased, highlighting a trade-off between spray volume and operational efficiency. Furthermore, the effective field capacity and field efficiency were recorded as 0.136 ha h^{-1} and 71.39%, respectively, demonstrating acceptable performance under practical field conditions.

The results also revealed that solar irradiance and battery voltage significantly influence the operational stability of the sprayer. Despite minor variations in performance due to changing sunlight conditions, the system provided consistent discharge and reliable field performance. Overall, the developed solar-operated backpack sprayer offers a cost-effective, environmentally friendly, and energy-efficient solution for agricultural spraying, particularly in off-grid and resource-limited areas. Future improvements should focus on enhancing energy storage capacity, optimizing system efficiency, and integrating advanced technologies such as sensors and automation to improve precision and adaptability in agricultural operations.

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Statement of Informed Consent

Informed consent was obtained from all individual participants included in the study.

Conflicts of Interest

The authors declare no conflict of interest in this work. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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