Design and Experimental Evaluation of a Solar-Powered Portable Water Filtration System*

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Abstract

This study presents the design and preliminary evaluation of a portable solar-powered water filtration system integrating a photovoltaic energy module with a low-power micro-pump and multi-stage filtration unit. The system is designed for small-scale water purification using photovoltaic panels to provide off-grid energy autonomy. The work focuses on system integration, electrical compatibility between the solar module and pump system, and operational stability under variable solar irradiance. The proposed approach demonstrates a sustainable and modular solution for decentralized water treatment applications.

Keywords

solar energy, portable filtration, photovoltaics, sustainable water treatment, off-grid systems

1. Introduction

Access to clean water and sustainable energy are closely linked global challenges. Decentralized purification systems powered by renewable energy sources provide a promising solution for remote and emergency environments. Recent developments in lightweight photovoltaic technologies enable compact energy systems capable of powering small-scale filtration units. This study investigates the integration of a solar panel, voltage adaptation system, and micro-pump-driven filtration module. Lightweight and flexible photovoltaic technologies such as CIGS thin-film modules provide new opportunities for powering decentralized systems, including portable water purification units in remote or off-grid environments. Lightweight and flexible photovoltaic technologies such as CIGS thin-film modules create new opportunities for portable and decentralized energy systems. Such photovoltaic technologies can play a key role in powering small-scale water purification devices in off-grid environments. In this study, a prototype solar-powered portable water filtration system is developed and experimentally evaluated as a validation platform for future thin-film photovoltaic integration within the SunGel project.

2. System Architecture

The developed system consists of four main components: a solar panel, a voltage adaptor/regulator, a low-power micro water pump, and a multi-stage filtration unit.The solar panel generates direct current (DC) electricity, which is delivered to the pump through a voltage-matching adaptor. The pump uses this energy to drive water through the filtration unit at a controlled flow rate. In this way, the system operates using solar energy without requiring an external power source,

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enabling off-grid water filtration. The SunGel study focuses on the development of advanced photovoltaic technology, and the current prototype water purification setup utilises a 50 W monocrystalline silicon solar panel for system validation and operational testing. This monocrystalline panel serves as a baseline reference system.

2.1 Solar-powered water purification validation system

The portable filtration system is powered by a photovoltaic module. The configuration of the module is illustrated in Figure 1. The portable filtration system is powered by a flexible photovoltaic module. The structural configuration of the flexible thin film module is illustrated in Figure 1. The system consists of a 50 W solar panel connected to a 12 V–10 A solar charge controller and a 12 V–12 Ah battery for energy storage and stable operation. The stored electrical energy drives a 12 V DC micro-pump that transfers water from the source through an inline three-stage filtration unit (sediment and activated carbon filters). The setup is used for system validation and operational testing of solar-driven water treatment under low-power conditions. The configuration is used as a baseline validation platform for solar-driven water purification under low-power operating conditions.

Figure 1: Solar-powered portable water purification prototype developed within the SunGel study.

3. Experimental Evaluation

Initial tests were carried out to evaluate how the system performs under real operating conditions. We observed how the pump starts up, how stable the water flow remains during operation, and how the system responds to different levels of solar irradiance.

Special attention was given to the behavior of the system under changing light conditions throughout the day. As the filtration process remained stable under moderate sunlight, and the system continued to operate reliably without requiring an external power source a 50 W monocrystalline silicon photovoltaic module is used in the prototype stage for system-level validation.

CIGS thin-film Structure

CIGS thin films are widely used in high-efficiency thin-film photovoltaic devices due to their direct bandgap and high absorption coefficient. Various deposition techniques have been reported in the literature, including vacuum-based processes and solution-based approaches such as sol–gel deposition. Solution-derived CIGS films provide advantages in low-cost fabrication and flexible substrate compatibility [1-3].

CIGS Solar Cell Layer Structure

A typical CIGS thin-film solar cell consists of a layered structure including a transparent conductive oxide (TCO), CdS buffer layer, CIGS absorber layer, and a metallic back contact such as molybdenum deposited on a substrate [1-3]. Cross-sectional structure of the thin-film photovoltaic cell was presented in Figure 2 showing the transparent electrode, CdS buffer layer, CIGS absorber, molybdenum back contact on flexible substrate.

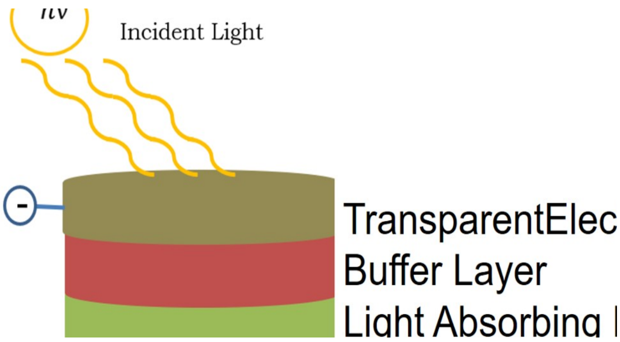

Figure 2: Schematic structure of a thin-film photovoltaic device showing the transparent electrode, buffer layer, light-absorbing layer, and back electrode.

Figure 3 shows the current–voltage (I–V) characteristics of the CIGS thin-film solar cell under illumination. The device exhibits a nonlinear diode-like behavior typical for thin-film photovoltaic structures. The measured data were fitted using a polynomial function with a high correlation coefficient ($R^2 \approx 0.999$). This indicates an agreement between the experimental data and the fitted model. The electrical response reflects the charge transport processes occurring within the multilayer structure of the device, including the absorber layer and the interface regions. I–V analysis provides important information about the electrical performance and diode characteristics of the CIGS thin-film solar cell.

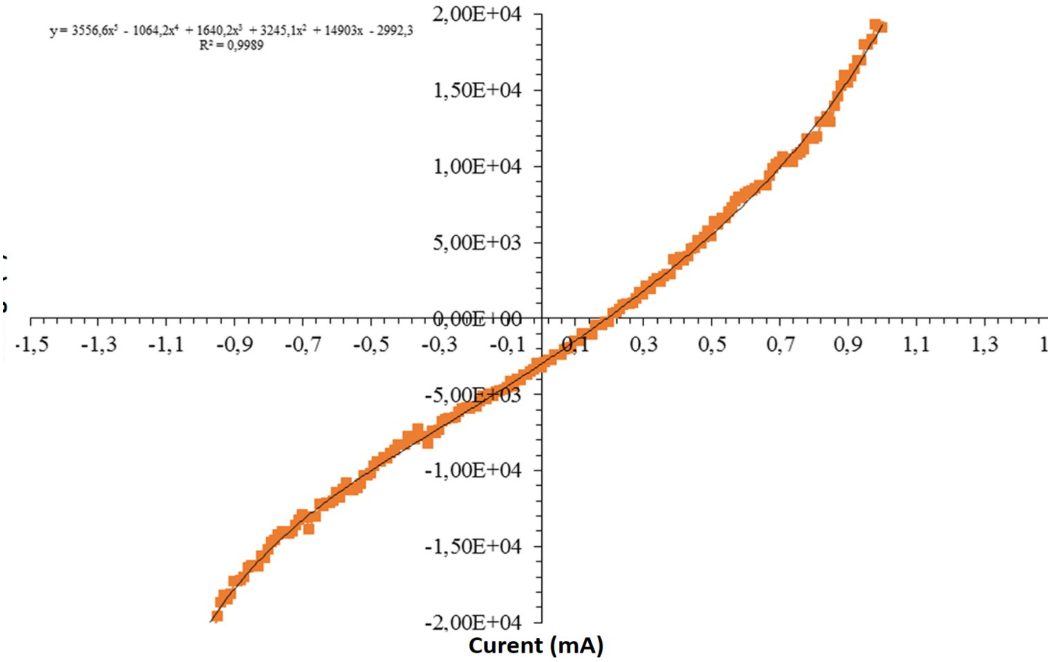

Figure 3: Current–voltage (I–V) characteristics of the CIGS thin-film solar cell measured under illumination. The fitted curve shows good agreement with the experimental data.

Efficiency and Stability Indicator

The electrical performance of photovoltaic devices is typically characterized using parameters such as open-circuit voltage (Voc), short-circuit current density (Jsc), fill factor (FF), and power conversion efficiency [4-7]. Table 1 is presented the extracted photovoltaic parameters of the SLSG/Mo/CIGS/CdS/ZnO:Al/Al thin-film solar cell measured under illumination.

Table 1
Photovoltaic parameters of the CIGS thin-film solar cell under illumination

CIGS Thin-Film Solar Cell Structure	Band Gap Eg (eV)	Voc (V)	Isc (A)	Fill Factor (FF)	Efficiency (%)	Ideality Factor (η)
SLSG/Mo/CIGS/CdS/ZnO:Al/Al	1.5	0.200	3	0.33	~0.2	1.5

The CIGS thin-film solar cells with the structure SLSG/Mo/CIGS/CdS/ZnO:Al/Al were illuminated under UV light (100 mW/cm²), and current–voltage (I–V) measurements were performed. The forward current region of the obtained I–V curve was plotted on a logarithmic scale in Fig.4. This figure was presented the current–voltage (I–V) characteristics of the CIGS thin-film device measured under simulated solar illumination.

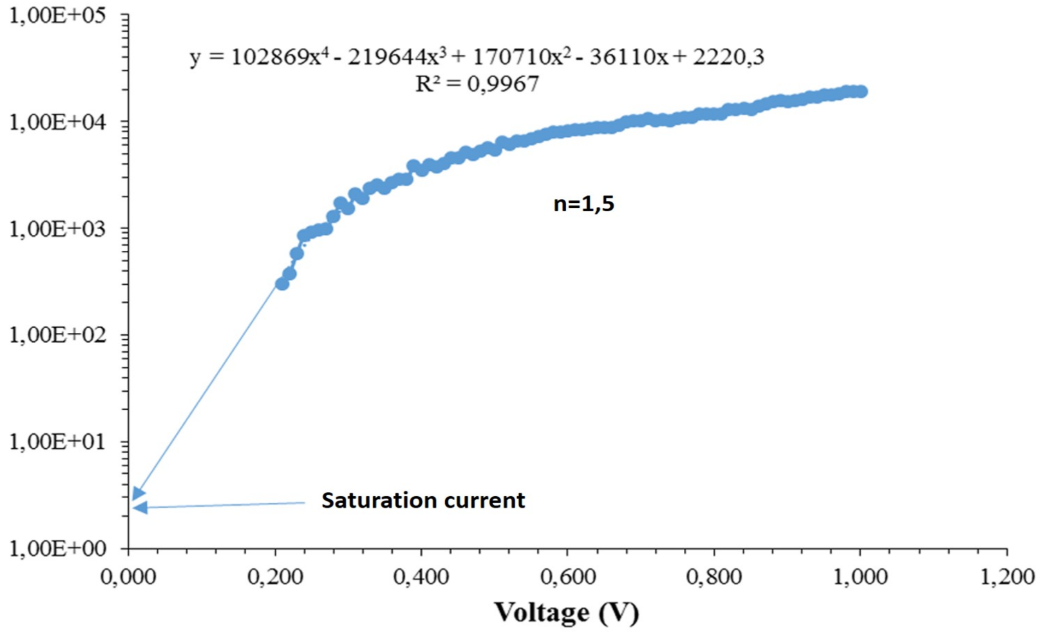

Figure 4: Log(I)–V Characteristic under Illumination.

Using the extracted photovoltaic parameters, the maximum power output of the device can be estimated from $P_{max}=V_{oc}\times I_{sc}\times FF$. The maximum power was calculated as approximately 0.198 mW according to the measured values (V_{oc}=0.200 V, I_{sc}=3 mA, FF=0.33)**.** The energy supplied by the photovoltaic module was sufficient to drive the micro-pump continuously under moderate solar irradiance conditions.

4. Electrical Compatibility and Power Matching

The pump was selected by considering its operating voltage, power consumption, and water flow rate. These parameters were chosen to ensure that the pump could work efficiently with the available solar panel output.

To make sure the solar panel and the pump operate properly together, a DC voltage regulation module was used. This module adjusts and stabilizes the voltage coming from the photovoltaic panel so that it matches the pump's requirements. As a result, the system can continue to function even when sunlight intensity changes during the day.

The electrical performance of the solution-processed CIGS films was evaluated through current–voltage (I–V) characterization under simulated solar illumination. Key performance parameters including Voc, Jsc, fill factor (FF), and power conversion efficiency were extracted. The results provide insight into the charge transport behavior and interfacial quality of the thin-film architecture. Electrical performance parameters were extracted and interpreted in the context of interface quality, charge transport, and long-term material stability for flexible photovoltaic architectures. The fill factor values indicate the influence of series resistance and possible recombination mechanisms at grain boundaries within the solution-processed absorber layer. Stability-related variations in electrical output suggest that long-term material reliability must be considered when implementing solution-processed CIGS architectures in lightweight and flexible photovoltaic systems. These effects are consistent with the microstructural characteristics typically observed in solution-derived CIGS thin films. From a material stability perspective, minimizing recombination at grain boundaries remains critical for long-term device reliability in flexible thin-film photovoltaic systems.

The micro-pump used in the prototype operates at 12 V DC with a nominal power consumption of approximately 5 W in Table 2. Under typical operating conditions, the pump provides a flow rate of about 2 L min^{-1}, corresponding to an approximate filtration capacity of 120 L h^{-1}.

Table 2
Pump and filtration system parameters

Parameter	Value
Pump voltage	12 V
Pump power	5 W
Flow rate	2 L/min
Filtration capacity	120 L/h

Table 3 presents the power compatibility between the photovoltaic module and the micro-pump used in the portable water filtration system. The prototype system employs a 50 W photovoltaic panel as the primary energy source, while the selected micro-pump requires approximately 5 W of electrical power during operation. This results in an available power margin of about ten times the pump demand. Such a margin ensures stable pump operation under variable solar irradiance conditions and compensates for possible electrical losses in the charge controller, wiring, and filtration system resistance. Therefore, the photovoltaic module provides sufficient energy to maintain continuous operation of the filtration unit under typical outdoor conditions.

Table 3
Solar module and pump power matching

Parameter	Value
Solar panel power	50 W
Pump power	5 W
Power margin	10× safety margin

Initial tests were carried out to evaluate how the system performs under real operating conditions. We observed how the pump starts up, how stable the water flow remains during operation, and how the system responds to different levels of solar irradiance. Preliminary filtration tests indicated that the multi-stage filtration unit effectively removed suspended particles and visibly improved the clarity of the treated water. Based on the operating characteristics of the micro-pump, the average flow rate of the system is approximately 2 L min^{-1}. This corresponds to a theoretical filtration capacity of about 120 L h^{-1} under continuous operation. In practical conditions, the effective filtration rate may vary depending on solar irradiance, pump performance, and filter resistance. Nevertheless, the obtained capacity is sufficient for small-scale portable water purification applications.

The prototype system developed in this study also provides a validation platform for future integration of thin-film photovoltaic technologies being developed within the SunGel study. In addition to photovoltaic cell efficiency, the overall system energy efficiency can be estimated by comparing the electrical power supplied by the photovoltaic module with the power required by the micro-pump. The overall system efficiency can be estimated by comparing the electrical power supplied by the photovoltaic module with the power required by the micro-pump. The system efficiency can be expressed as the ratio between the useful pump power and the available solar power in (1). For the prototype system, the photovoltaic module provides approximately 50 W of power, while the micro-pump requires about 5 W during operation. Therefore, the estimated system energy efficiency is approximately 10%**,** indicating that the available solar power is sufficient to sustain stable operation of the water filtration unit.

$$\eta_{system}=P_{pump}/P_{solar} \quad (1)$$

Table 4 compares previously reported solar-powered water purification systems with the prototype developed in this study. Earlier studies commonly employ membrane filtration or simple passive filters, whereas the present work integrates a compact multi-stage filtration system driven by a low-power micro-pump.

Table 4
Comparison of Solar-Powered Water Filtration Systems Reported in the Literature

Study	Energy Source	Pump	Filtration Type
Li et al., 2019 [8]	Solar PV	DC pump	Membrane filtration
Suyitno et al., 2023 [9]	Solar PV	Manual / passive	Sand / simple filtration
This study	Solar PV	Micro pump	Multi-stage filtration

5. Discussion

Integrating solar energy with a portable water filtration system offers several important advantages. First, the system can operate independently without relying on an external power source, providing energy autonomy. It can also be scaled according to need, making it suitable for small household use or larger decentralized applications. In addition, the system reduces dependency on conventional grid infrastructure, which is particularly valuable in remote or off-grid areas. Such portable solar-driven purification systems may offer practical solutions for decentralized water treatment in remote communities, disaster relief operations, and off-grid environments where reliable access to electricity and clean water remains limited.

Future work will focus on long-term performance testing to better understand system durability over time. It is planned to evaluate the filtration efficiency in more detail and optimize the photovoltaic module to improve overall energy performance. Furthermore, integration with advanced membrane technologies will be explored to enhance water purification capacity and reliability. Previous studies have also shown that the electrical and structural stability of CIGS absorber layers can be affected by radiation exposure and environmental stresses. Therefore, understanding the durability and reliability of CIGS thin-film architectures is essential for long-term photovoltaic applications [4-7].

Solution-based deposition techniques provide advantages in terms of lower fabrication cost and compatibility with large-area or flexible substrates [1-3]. Device performance parameters such as efficiency and fill factor are influenced by film quality, grain boundaries, and interface properties [4-7]. While the efficiencies achieved by solution-processed CIGS devices are generally lower than those obtained using vacuum-based deposition methods, the solution approach offers important advantages such as reduced fabrication cost, improved scalability, and compatibility with flexible substrates (in Table 5) [1-7].

Table 5
Comparison of CIGS fabrication approaches.

Parameter	Vacuum-deposited CIGS	Solution-processed CIGS
Fabrication method	Co-evaporation / sputtering	Solution or sol–gel process
Efficiency	Higher (≈20%+)	Lower (typically <10%)
Production cost	High	Lower
Scalability	Limited by vacuum systems	High scalability
Substrate compatibility	Mostly rigid	Flexible substrates possible

6. Conclusion

The proposed solar-powered micro-filtration system demonstrates the feasibility of combining photovoltaic energy systems with compact water purification modules. The approach supports sustainable and decentralized water treatment applications. The proposed solar-powered portable filtration system demonstrates the feasibility of integrating photovoltaic energy supply with compact water purification modules. The prototype system provides a practical platform for evaluating decentralized water treatment technologies powered by renewable energy sources. The results indicate that lightweight photovoltaic technologies, including thin-film CIGS modules, have significant potential for future portable water purification systems designed for off-grid and remote environments.

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Declaration on Generative AI

The authors confirm that generative AI tools were used only for language editing and clarity improvement. All scientific content, analysis and conclusions were produced by the authors.

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