Solar-Driven Advancements for Water Purification: Harnessing Sustainable Energy for Potable Water Provisioning

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Abstract- In many developing nations, a substantial portion of the population confronts the persistent challenge of accessing potable water characterized by safety and cleanliness. Water sourced from diverse origins within these regions often exhibits the presence of pathogenic microorganisms and deleterious chemical constituents, thereby engendering a spectrum of waterborne diseases upon consumption. The amelioration of this predicament necessitates recourse to multifaceted purification methodologies, encompassing: (1) physical mechanisms such as filtration, sedimentation, and distillation to effect separation; (2) biological treatments including the deployment of sand filters and activated carbon matrices for biotic purification; and (3) chemical treatments typified by flocculation, chlorination, and the utilization of ultraviolet irradiation to induce disinfection. This scholarly exposition engenders an exhaustive appraisal of solar-driven technologies as employed in the domain of water purification, as pertains to both domiciliary and industrial milieus. The inquiry delves into the efficacious application of solar-based systems, dissecting their underlying principles and operational intricacies. Through a systematic analysis of extant literature, the investigation affords a comprehensive evaluation of the advantages, limitations, and optimal conditions governing the deployment of solar-based water purification technologies. In sum, this paper serves to furnish a cogent compendium of contemporary advancements in solar-driven methodologies, illuminating their pivotal role in the global pursuit of potable water provisioning, particularly within resource-constrained settings.

Keywords: Solar Water purification, Booster Pump, Solar Charge Controller, Solar Panel, DC Water Pump.

1. Introduction:

The global deficiency in access to clean water, identified by the World Health Organization (WHO) is affecting approximately 780 million individuals, constitutes a critical issue for maintaining sanitation and averting potentially fatal dehydration. The enhancement of water purification processes not only contributes to economic expansion but also facilitates holistic development. Notably, nations with deficient economies witness an average yearly economic growth of 3.7% when equipped with upgraded water treatment facilities, in stark contrast to similarly underprivileged countries lacking corresponding improvements in water quality, which exhibit a mere annual growth of 0.1% [1].

Enhanced water treatment contributes to the reduction of waterborne illnesses, the reinforcement of workforce vitality, the amplification of productivity, and the alleviation of healthcare burdens. Furthermore, it engenders educational improvements by diminishing school absenteeism among children due to ailments, thereby enhancing the pool of skilled labour and fostering economic growth. Notably underscored in the World Health Organization (WHO) report is the imperative to focus on impoverished populations, particularly within developing countries, and more notably in rural locales. Recent strides have been taken in elevating water quality standards in densely populated regions endowed with robust infrastructure and established power grids. Nevertheless, the exigency for less advanced water sanitation methodologies prevails in areas characterized by lower population densities, necessitating water purification methods that are independent of electrical dependency. In the pursuit of furnishing rural communities in developing nations with cleaner domestic water supplies, the emergence of cost-effective and economically viable water sanitation approaches is pivotal. This encompasses the consideration of potential skill and knowledge limitations, alongside the absence of electrical access. The selected purification modality must be facile to maintain, operate autonomously without reliance on electricity, and be accommodated within low-capital and minimally demanding maintenance infrastructures. The economic dimension bears significant relevance for both resident populations and other vested stakeholders, thereby motivating humanitarian organizations to channel resources towards the establishment of water purification facilities within rural environs. Solar water purification entails the refinement of water for potable and domestic use by harnessing solar energy in a diversified array of methodologies. The utilization of solar energy in water treatment has gained prevalence due to its inherent attributes as a typically uncomplicated and low-tech solution that harnesses solar heat and energy to render water safer and more salubrious for human consumption. Particularly advantageous for remote communities bereft of traditional water purification infrastructure and notably devoid of electrical access, solar water treatment obviates the requirement for combustible fuels. This attribute delineates solar applications as conspicuously superior to conventional energy sources, as they mitigate the propagation of pollution-linked phenomena such as global warming, acid rain, and ozone depletion, which are accompanied by health risks. Solar water purification is categorized into four principal typologies: solar water disinfection (SODIS), solar distillation, solar water pasteurization, and solar water treatment systems. While some of these technologies exhibit historical lineage, most entail novel adaptations within the solar energy paradigm. Characterized by simplicity and ease of comprehension, these technologies typically necessitate limited financial investment, yet reliably demonstrate efficacy [2].

This research endeavour harnesses solar energy as the primary power source, accumulating it within a battery unit, which serves as a cost-free reservoir of energy. Subsequently, this stored energy is utilized to activate budget-friendly heating coils, thereby elevating the water temperature to a specific level, situated below the boiling threshold. Following this, the condensed water undergoes an additional purification phase through a filtration substrate. During this juncture, the water is once again subjected to condensation, resulting in its attainment of ambient temperature. This iterative process culminates in the production of potable water. The research journey encompassed various stages inherent to product development, spanning from the acquisition of customer requisites to the finalization of the proposed design. The solar-driven water purification system thus emerges as a pivotal mechanism for generating clean water. The utilization of solar energy, characterized by its absence of polluting implications, has established itself as a dependable energy source for practical applications. The blueprint for a solar-powered water purification system is rooted in the principles of thermal methodology, effectively harnessing sunlight's thermal energy. Central to this process is the vital role of heat absorption, which instigates the evaporation of water. Empirical findings indicate that flat plate collectors engender heat at relatively moderate temperatures (ranging from 27°C to 60°C) and are conventionally employed for heating liquids. A solar-powered water purification system comprises a solar collector responsible for solar energy absorption, facilitating the initial vaporization stage, a cornerstone of the purification process. Complementing this, a filtration mechanism is integrated to eliminate contaminants. The developmental trajectory has spawned four distinct conceptual frameworks [3, 4].

Gazi Nazia Nur and Mohammad Ahnaf Sadat have postulated that the limitations of conventional energy sources coupled with their detrimental impact on the environment have spurred the exploration of alternative avenues. By leveraging the potency of renewable energy, specifically solar power, for water purification, the adverse repercussions associated with traditional energy sources can be circumvented. The solar water purifier represents a paradigmatic advancement within the contemporary water purification landscape. This paper expounds upon the design methodology underpinning the solar water purifier. Functioning as an innovative departure from prevailing water treatment systems, the solar water purifier harnesses solar energy as its primary power input while obviating environmental pollutants. The design blueprint outlined in this study integrates a series of essential components. These encompass the solar panel for energy capture, a battery for energy storage, heating coils for temperature elevation, filtering chalk for particulate removal, a dual-layer condenser for condensation, and a consortium of water vessels for fluid manipulation. Notably, this purification apparatus employs a filtration mechanism to effectively extract impurities from water and deploys a boiling process to eliminate microbial organisms. This orchestrated sequence culminates in the attainment of potable drinking water characterized by its purity [5].

Lamma OA & Abubaker M. Outhman put forth the notion that the purification of raw water using reverse osmosis (RO) technology has significantly progressed, aiming to create energy-efficient and productive systems. The main focus of their research is to enhance energy efficiency, extend membrane lifespan, and boost energy recovery. These aspects have become the central objectives driving advancements in this field. The core aim of their study is to optimize the parameters within the pre-treatment process of various water sources (such as ponds, canals, and surface water) in RO plants. This optimization seeks to elongate the membrane's lifespan by reducing the solid content in the original water source. Their experiments were designed to achieve optimal reduction in total solids as well as various chemical indicators (like BOD, TDS, and bacteria). These indicators are crucial for ensuring that the pre-treated water can be effectively channeled into the reverse osmosis section of the plant. Ultimately, the purified water from the RO plant is intended for drinking purposes, devoid of contaminants [4].

Yogita V. Gaikwad and Pooja V. Gavande put forth the concept of a reverse osmosis purification technique. The framework is primarily composed of three main components: a power supply circuit, a purification circuit, and a control circuit. The power supply segment comprises a solar panel, a charge controller, a battery, and an inverter. Within the purification unit, there exists a booster pump, a Reverse Osmosis system, and the control circuit encompassing sensors, a microcontroller, and relays. The booster pump generates high pressure essential for the reverse osmosis process. The microcontroller oversees the water tank's water level, preventing potential overflows. Through the application of this method, pristine water is obtained and stored in the water tank [4].

Dr. S. Prakash and Deepak Toppo are the proponents of this project, which is rooted in the concept of reverse osmosis. The fundamental mechanism involves harnessing solar radiations via a solar panel, followed by the storage of this energy within a battery. The connection between the battery and the purification unit is established through an electromagnetic relay. Within the purification setup, essential components include a high-pressure motor, a reverse osmosis system, and a water tank. The high-pressure motor generates the requisite pressure crucial for the execution of reverse osmosis. Overseeing the water tank's water level and averting potential overflow is the role of the microcontroller 8051. By following this method, the outcome is the acquisition of purified water, stored within the water tank [6].

At present, substantial investments are required to establish efficient, large-scale desalination systems, a challenge that many developing countries are unable to meet. Paradoxically, these countries are the ones with the most pressing need for clean drinking water, given the contamination or insufficiency of their existing water sources. Consequently, around 1.8 million people succumb to waterborne diseases annually. Water purification is pivotal for ensuring drinking water safety, encompassing the elimination of inorganic matter and the treatment of bacteria. To tackle this issue, numerous ongoing initiatives are dedicated to supplying clean water to economically disadvantaged communities. In Africa, a significant number of these initiatives involve drilling wells to tap into groundwater resources. Nonetheless, groundwater in Africa is finite, necessitating deeper drilling as the resource depletes over time. Hence, alternative sources like ocean water can supplement the considerable demand for clean water, especially in comparison to groundwater. The Solar Water Purification System is aimed at conceptualizing and developing a solar-powered water purification solution that is cost-effective and compact, offering clean and safe drinking water to individuals and communities residing in areas with restricted access to clean water sources. This system will employ an array of purification techniques, including filtration, disinfection, and advanced methods such as reverse osmosis or distillation, contingent on the intended beneficiaries and water quality. The incorporation of solar power will harness clean and renewable energy, propelling pumps, filters, and other essential components. This approach will decrease dependence on conventional electricity sources, rendering the system sustainable and economically viable. Furthermore, the system will be reasonably priced and within reach of communities with limited financial means, designed for ease of portability and installation. Its compact design will facilitate effortless transportation and deployment in diverse locations, rendering it suitable for emergency scenarios, remote regions, or places lacking infrastructure. A user-friendly interface featuring lucid instructions, intuitive controls, and minimal maintenance demands will characterize the system. It will also exhibit durability and reliability, capable of enduring challenging environmental conditions while consistently delivering effective water purification performance. Components will be meticulously chosen for their resilience, and rigorous testing will ascertain the system's dependability and longevity.

By achieving these goals, the solar water purification system will significantly enhance the overall quality of life for both communities and individuals by granting access to clean and safe drinking water.

2. Methods and Materials

2.1. Components Specifications

Illustrated in the block diagram are the fundamental constituents of our system, encompassing filters, a Solar Panel, a booster pump, a Solar Charge Controller, and a Reverse Osmosis Membrane, among others [7]. The purification process within this setup relies solely on the power generated by the solar panel, subsequently stored within a battery. The solar panel comprises photovoltaic cells, converting solar energy into electrical power. The energy harnessed by the solar panel is then stored within a battery, with the solar charge controller governing the amperage and voltage supply. This regulation ensures the battery remains properly loaded while avoiding the risk of overcharging. The power supply initiates the activation of the filters, setting the motor rotor into motion. Simultaneously, the assembly of three cameras, interconnected near the eccentric tread wheel, undergoes a reversal, propelling the diaphragm. The continual rotation of the motor sustains the replication of the diaphragm within the Reverse Osmosis (RO) booster pump. This replication facilitates the pumping and amplification of water. The RO membrane, a pivotal component, eliminates a vast majority of impurities by propelling water through a semi-permeable membrane. This process effectively eradicates contaminants like nutrients, bacteria, chemicals, and viruses. The membrane's composition comprises three layers: a polyamide sheet with a size of 0.2 microns, a polysulfide layer responsible for extracting nutrients, bacteria, chemicals, and viruses, and a polyester base through which the purified water passes. Subsequent to the purification process, the separation of dirty and clean water takes place, with this procedure iterated until the water becomes devoid of contaminants. This meticulous process guarantees the safety of the purified water, rendering it suitable for consumption.

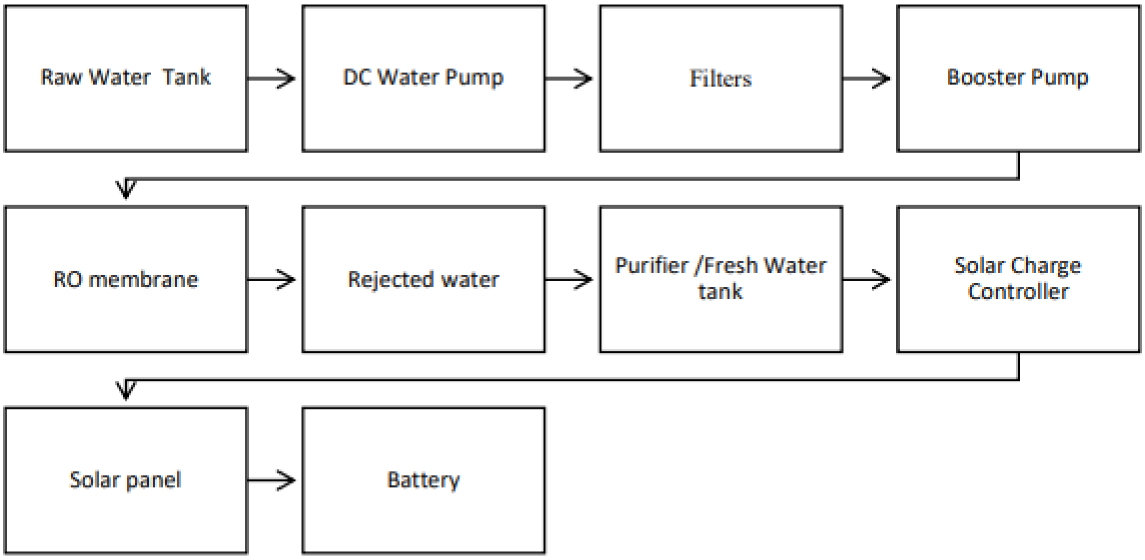

Fig. 1 Block Diagram of Solar Energy Based Water Purification System

2.2. Solar Panel

In this model the solar panel, made from a photovoltaic cell, collects solar energy that's depends on light intensity. We use two mini 30-watt panels connected in parallel for charging two 12-volt batteries. This lightweight, portable solar panel finds numerous applications. The dimension of the solar panel is 18 X 21(inches).

Table 1: Values of Voltage and Current

Solar Panel	Voltage (V)	Current (A)	Total Voltage (V)	Total Current (A)
Solar Panel 1	12	1.6	12	3.2
Solar Panel 2	12	1.6		

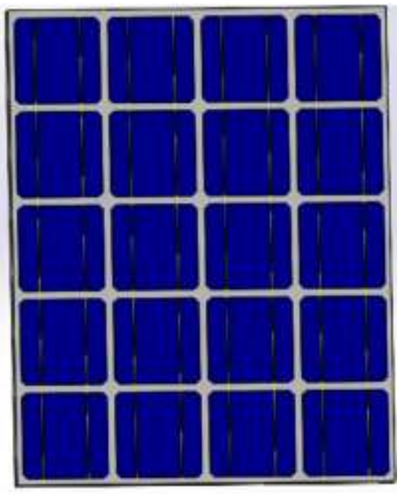

Fig. 2 Solar Panel

2.3. Solar Charge Controller

A solar charge controller, alternatively known as a solar regulator, serves as a device responsible for managing and overseeing the charging process of batteries utilizing solar panels. Positioned as an intermediary between solar panels and batteries, its primary role entails achieving an ideal charging state while averting potential issues such as overcharging or excessive discharging. The core functionalities encompassed by a solar charge controller encompass charge regulation, battery safeguarding, load management, battery monitoring, and temperature adjustment. To elaborate, charge controllers are tasked with the regulation of both voltage and current originating from solar panels, aligning these parameters with the specific requirements of batteries. This synchronization guarantees an effective and secure charging process. Additionally, they undertake the monitoring of battery voltage and capacity, a measure taken to prevent overcharging that could compromise the longevity of the battery. Incorporating load control capabilities, these controllers have the ability to automatically activate or deactivate devices based on criteria like battery voltage or predetermined conditions. This functionality contributes to efficient energy utilization and extends battery life. Battery monitoring represents another key aspect, furnishing users with essential data encompassing battery voltage, charging current, and capacity. This data empowers users to track the state of their batteries and make well-informed decisions. A distinctive feature, temperature compensation, involves the integration of temperature sensors. These sensors facilitate the adaptation of charging parameters in accordance with battery temperature, a process that ensures optimal charging irrespective of the prevailing environmental conditions.

2.4. Booster Pump

Booster pumps are employed to elevate water pressure, typically countering the existing osmotic pressure. The purification process necessitates the movement of water from areas of high concentration to those of lower concentration. Consequently, for the reverse osmosis procedure to take place effectively, it's imperative that the lateral pressure of higher concentration surpasses the osmotic pressure.

Fig. 3 Booster Pump Model

2.5. Reverse Osmosis Membrane

When two solutions with varying concentrations are divided by a semi-permeable membrane, the solvent (water) tends to move from an area of lower concentration to one with higher concentration. This phenomenon is known as osmosis, and the energy driving this movement is referred to as osmotic pressure. However, when a hydrostatic pressure that exceeds the osmotic pressure is applied to the side with higher concentration, the solvent's flow is reversed. In other words, the solvent moves from the region of higher concentration to the area of lower concentration. This reversal process is termed reverse osmosis. Therefore, within the reverse osmosis process, clean water is effectively separated from saline water.

There are four types of filters in a standard three stages reverse osmosis system [8].

- Sediment filter that traps larger particles suspended in water, such as dirt and rust
- The Carbon filter removes VOC, Chlorine and other small contaminants from water.
- Semi-Permeable reverse osmosis membrane that removes virtually all remaining impurities.
- The extra filtration membrane is used for further purification of water.

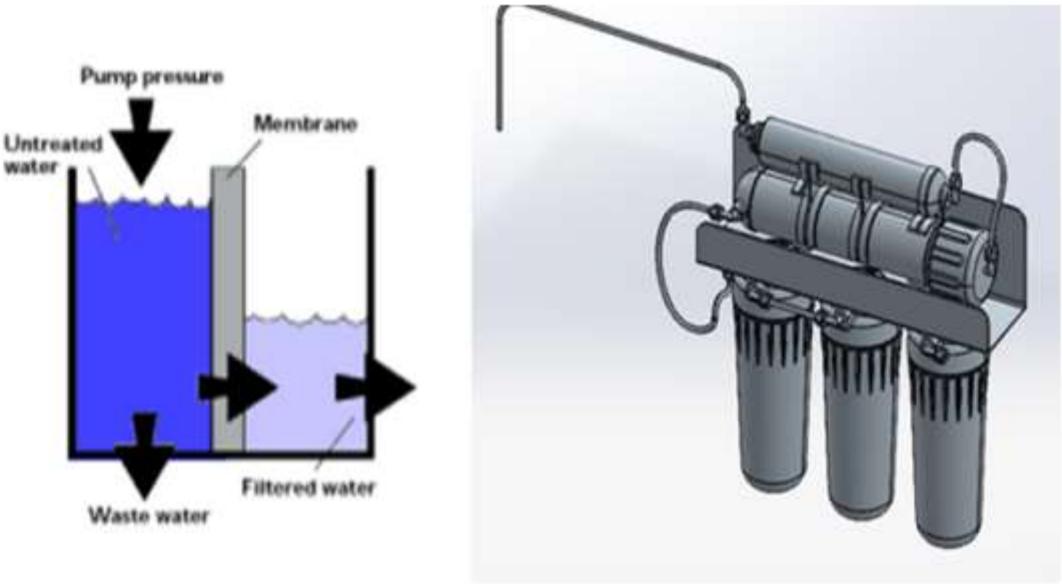

Fig. 4 Reverse osmosis and reverse osmosis filter model [8]

2.6. Batteries

In this system we are using two 7.0A 12-volt batteries. The batteries are being charged by the solar panel through a charge control relay. A charge controller has been connected across the battery to prevent it from getting overcharged. A diode has been used in this circuit to maintain the current in one direction. The batteries are connected in parallel connection so the output current from the batteries is 14 A.

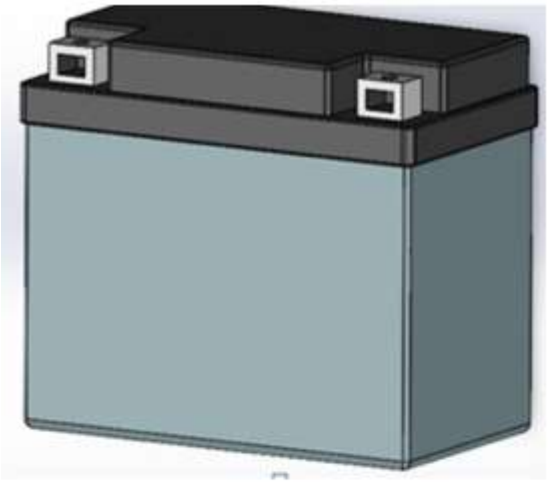

Fig. 5 Battery Model

2.7. Twelve-volt DC Motor Pump

For the transfer of water from the untreated water tank to the filter, a direct current (DC) pump is employed. The pump's details are as follows: Operating under a voltage of 12V, it draws a current ranging from 130 to 220mA. The rate of water flow is between 80 to 120 liters per hour, and it can achieve a maximum lift of 40 to 110 mm.

3. Results and Discussions

A compact and lightweight water purifier, powered by solar energy, has been effectively created as shown in Fig. 7. This device has demonstrated its capability to efficiently eliminate contaminants from diverse water sources. Through optimization of the purification process, remarkably efficient water purification has been achieved. User feedback highlighted the device's user-friendly design and intuitive controls, both of which were well-received. Rigorous testing confirmed the device's effectiveness and reliability. Field tests further validated its practicality and functionality in real-world conditions. Furthermore, assessments of its environmental impact underscored the sustainability of the purification method employed by the device.

In regions marked by insufficient infrastructure, the compact and easily transportable solar-powered water purifier has proven to be a potent solution for addressing challenges related to water scarcity and pollution. The device's design, tailored for user convenience, coupled with its efficient purification process, positions it as a pivotal instrument in the provision of clean and safe water. It's worth noting that all readings or tests conducted are denominated in milligrams per liter (mg/l).

Table 2: Comparison of TDS values before and after filtration

S. No.	TDS BEFORE FILTERATON (mg/l)	TDS AFTER FILTERATION (mg/l)
1	423	46
2	487	52
3	520	57
4	546	63
5	662	72
6	692	92
7	842	110

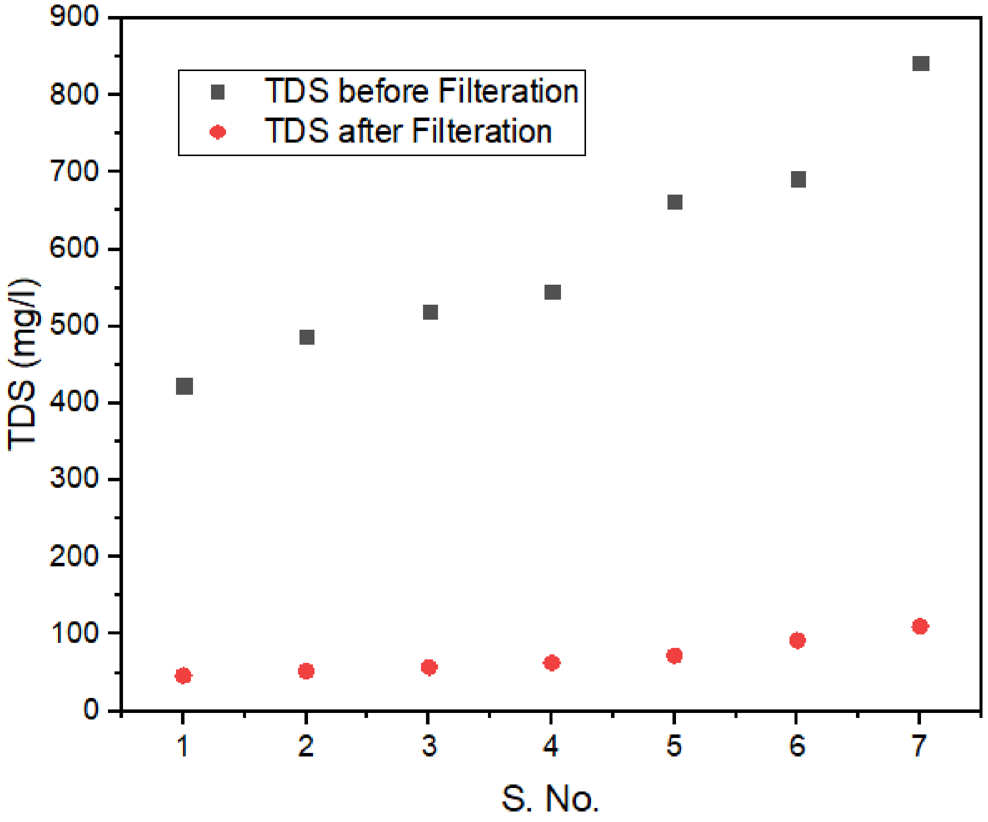

Fig. 6 Comparison of TDS values before and after filtration

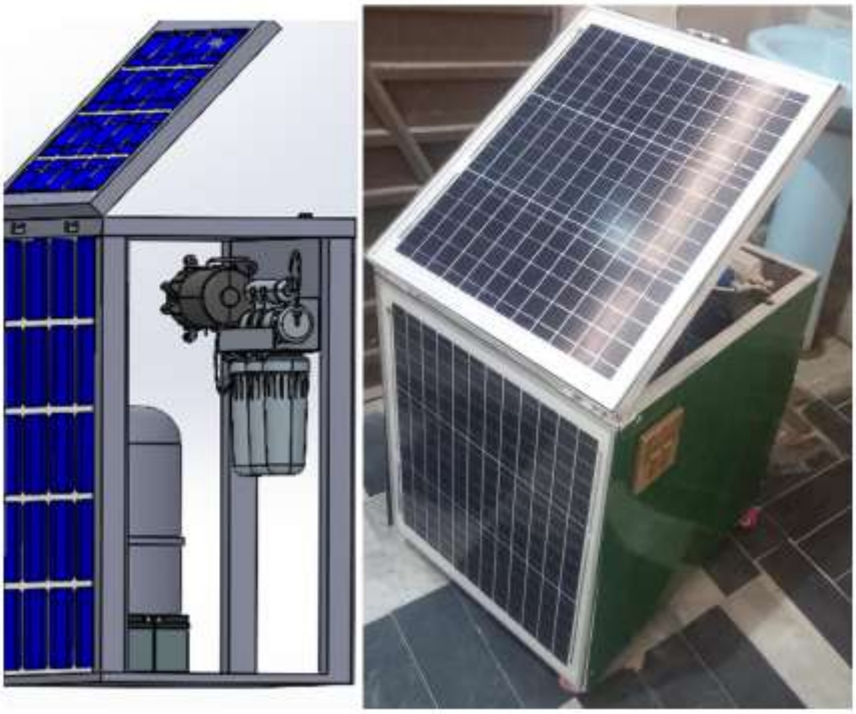

Fig. 7: Solar Water Purification System

4. Conclusion

In summary, the solar water purification project represents a multifaceted endeavour poised to address pressing global imperatives encompassing water accessibility, renewable energy integration, climate change mitigation, and the promotion of sustainable developmental trajectories. By harnessing the untapped potential of solar energy, this initiative proffers a definitive mechanism for furnishing potable water within regions plagued by inadequate reliable water reservoirs. This inventive modality harmoniously converges with the overarching objectives of attaining ecologically sound and economically viable energy solutions, as well as abating the deleterious effects of greenhouse gas emissions, thereby marshalling a concerted response to the exigencies of climate change. Notably, the solar water purification systems exhibit substantial promise as enduring antidotes to the exigencies of water scarcity, while simultaneously cultivating an environment of environmental equilibrium and enriching the quality of communal existence. The present study thereby contributes substantively to the burgeoningly comprehensive compendium of knowledge germane to the deployment of renewable energy modalities and the judicious management of water resources, thereby laying a robust foundation for the evolution of solar-centric technologies and their cascading implications in expediting the realization of the Sustainable Development Goals.

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