



Solar-Powered Clean Water Treatment: Applications, Future Prospects, and Challenges

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ABSTRACT

Access to safe drinking water remains a critical global challenge, exacerbated by population growth, industrialization, and climate change. Solar-powered water treatment systems offer a sustainable alternative by harnessing renewable solar energy to drive purification processes, including distillation, reverse osmosis, and photocatalysis. This paper reviews the principles, applications, performance evaluations, future prospects, and challenges of solar-powered water treatment technologies. Key findings indicate that these systems can effectively remove chemical contaminants and pathogens while reducing dependency on conventional electricity. However, limitations such as intermittent solar availability, high initial costs, and maintenance requirements pose challenges to widespread adoption. Future innovations—including nanomaterials, hybrid renewable energy integration, and IoT-based monitoring—can enhance efficiency, scalability, and sustainability. The study concludes that solar-powered water treatment represents a viable and environmentally friendly strategy for ensuring clean water access globally.

INTRODUCTION

Access to clean and safe drinking water remains one of the most critical challenges facing humanity in the 21st century. Despite advances in global infrastructure and technology, billions of people still lack reliable access to potable water for domestic and agricultural use. According to UNESCO (2023), around 26% of the world's population does not have access to safely managed drinking water services, particularly in developing countries in Africa and Asia. The growing impacts of industrialization, population expansion, and climate change further intensify the scarcity of clean water sources (UN-Water, 2024). As freshwater resources diminish and pollution increases, the development of decentralized, sustainable, and energy-efficient water treatment systems becomes increasingly urgent.

Conventional water treatment facilities are typically energy-intensive and dependent on centralized power grids, which poses challenges for remote and off-grid communities. In many developing regions, the lack of stable electricity supply limits the operation of conventional purification systems, leading to reliance on untreated or contaminated water sources. To address this issue, renewable energy technologies—particularly solar power—have emerged as promising alternatives for sustainable water treatment (Zhang et al, 2023). Solar energy is abundant, clean, and cost-effective over the long term, making it ideal for supporting autonomous purification systems that can function without continuous grid power (García-Gil Á et al, 2021).

Solar-powered clean water treatment encompasses a variety of methods, including solar distillation, solar-driven reverse osmosis (RO), photocatalysis, and solar disinfection (SODIS). Each method utilizes solar radiation or photovoltaic (PV) energy to drive key purification processes such as evaporation, filtration, oxidation, or microbial inactivation (Gheraout et al., 2023). For instance, SODIS has proven to be an inexpensive and effective method for disinfecting water at the household level by using UV-A radiation to deactivate pathogens. Similarly, solar-powered RO systems integrate photovoltaic modules with membrane separation technologies to remove dissolved salts, heavy metals, and organic pollutants, producing water that meets World Health Organization (WHO) standards (Zhang et al, 2023).

Recent technological developments have improved the performance and scalability of these systems. Hybrid configurations combining PV panels with battery storage and intelligent control systems have enhanced operational stability, even during periods of low sunlight. Moreover, the use of advanced materials—such as nanomembranes and photocatalysts like titanium dioxide (TiO_2)—has increased treatment efficiency and reduced fouling issues (Gheraout et al., 2023). However, despite these advancements, significant challenges remain. These include high initial investment costs, the need for periodic maintenance, variability in solar radiation, and degradation of materials over time. Environmental issues such as the management of brine waste in desalination processes also remain unsolved.

Therefore, this paper aims to analyze the applications, future prospects, and challenges of solar-powered clean water treatment systems. The study focuses on

technological developments, sustainability potential, and economic feasibility of solar-driven purification methods. By exploring recent innovations and identifying key limitations, this research seeks to contribute insights into how solar-powered systems can be optimized to ensure reliable, low-cost, and environmentally sustainable access to clean water worldwide. Figure 1 shows data of hourly clean water production from the solar system shows a clear pattern corresponding to solar availability. Production gradually increases in the morning, reaching its peak around midday when solar intensity is highest, and then gradually decreases in the late afternoon. This trend is clearly visualized in the line chart, which helps identify peak and low production hours, enabling better planning and optimization of water usage.

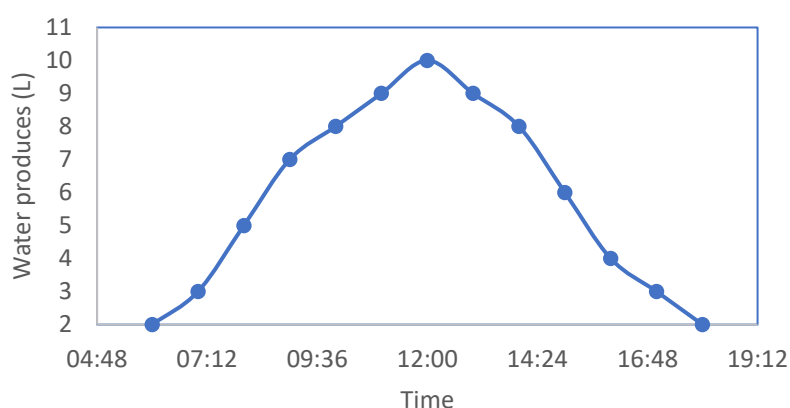


Figure 1. The hourly clean water production from the solar system (Ghimire et al, 2020).

Principles of Solar-Powered Water Treatment Systems

Basic Concept of Solar Energy Utilization

Solar-powered water treatment systems rely on the conversion of sunlight into usable energy for water purification processes. There are two primary approaches to harnessing solar energy: photovoltaic (PV) and solar thermal systems. Photovoltaic systems directly convert solar radiation into electricity through semiconductor materials, typically silicon-based cells, which can power pumps, filtration units, and control devices (Zhang et al, 2023). In contrast, solar thermal systems capture solar radiation as heat, which is then used to drive evaporation, distillation, or thermal disinfection processes (Gheraout et al., 2023). In solar distillation, for example, heat energy is used to evaporate water and subsequently condense the vapor into purified liquid, effectively removing salts, heavy metals, and microbial contaminants. This method mimics the natural hydrological cycle but in a controlled environment using solar energy as the driving force (García-Gil Á et al, 2021). Photovoltaic-driven systems, on the other hand, are often integrated with reverse osmosis (RO) or ultrafiltration units, providing greater efficiency for removing dissolved ions and organic pollutants (UN-Water, 2024).

The overall efficiency of solar-powered treatment systems depends on several environmental and technical factors. These include solar irradiance,

ambient temperature, tilt angle of solar panels, and the quality of materials used in photovoltaic modules and membranes. Moreover, dust accumulation, shading, and panel degradation can significantly reduce energy output and water treatment capacity. Studies have shown that hybrid systems combining photovoltaic energy with auxiliary storage can maintain more stable operation and higher throughput in fluctuating weather conditions (Gheraout et al., 2023). Therefore, optimizing energy capture and conversion efficiency is critical to achieving consistent water purification performance.

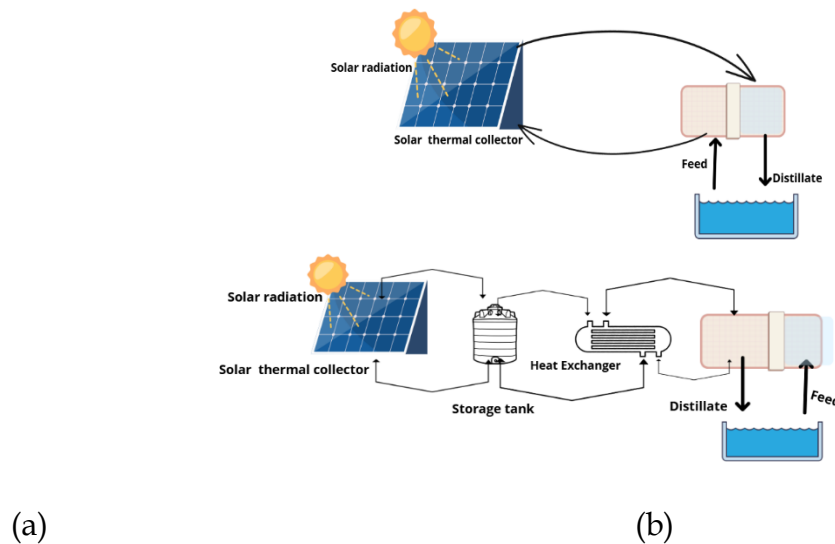


Figure 2. Solar thermal purification system (Kumar et al, 2023).

Figure 2. (A) – *Simple Direct Solar Thermal Desalination* illustrates a basic single-effect solar desalination system. In this setup, a solar thermal collector captures solar radiation and converts it into heat, which is then transferred to the brine chamber. The heated water undergoes an evaporation-condensation process, where water evaporates and leaves salts and impurities behind. The resulting vapor condenses and is collected as fresh water (distillate), while concentrated brine remains in the system. Feedwater, typically brine or seawater, enters the system and is gradually concentrated through evaporation. This simple design is suitable for small-scale or decentralized applications but does not include storage or heat recovery.

Figure 2. (B) – *Solar Thermal Desalination with Storage and Heat Recovery* shows an enhanced system that improves efficiency and operational flexibility. Like the simple system, a solar thermal collector captures sunlight to heat the feedwater. However, this design incorporates a storage tank to retain thermal energy for use during periods of low sunlight, and a heat exchanger that recovers energy from the brine or distillate stream to preheat incoming feedwater. The feedwater evaporates, leaving brine behind, and the vapor condenses into distillate, producing fresh water more efficiently than the basic system.

Energy Storage and Control Mechanisms

Energy storage plays a crucial role in ensuring continuous operation of solar-powered water treatment systems, especially during periods of low sunlight or nighttime. The most common approach involves the use of battery storage systems, such as lithium-ion or lead-acid batteries, which store excess electricity generated during peak sunlight hours (Zhang et al, 2023). This stored energy can then be used to power pumps, filtration membranes, and control systems when solar irradiance drops below operational thresholds. Some systems also incorporate thermal energy storage (TES), in which heat is stored in materials like phase-change substances or water tanks for later use in distillation or sterilization processes (Gheraout et al., 2023).

To enhance energy utilization, modern solar water treatment setups integrate smart controllers and power management units. These controllers optimize the distribution of power between direct system operation and storage, preventing overcharging or deep discharge of batteries. They also regulate the flow rate, pressure, and timing of filtration or distillation cycles to maintain consistent output quality (García-Gil Á et al, 2021). Additionally, the adoption of Internet of Things (IoT)-based monitoring systems allows for real-time performance tracking, predictive maintenance, and fault detection, improving system reliability and efficiency (UNESCO, 2023).

Proper design of energy storage and control systems not only improves energy efficiency but also extends component lifespan and reduces operational costs. By combining smart energy management with modular solar components, these systems can be effectively scaled for household, community, or industrial water treatment applications. As technology advances, integration of high-capacity batteries and adaptive power electronics is expected to further enhance the resilience and sustainability of solar-powered clean water treatment systems (UN-Water, 2024).

Applications of Solar-Powered Water Treatment

Solar-powered clean water technologies have evolved significantly, offering multiple configurations for purifying water in both rural and urban environments. These systems utilize renewable solar energy to power various treatment mechanisms, reducing dependency on grid electricity and minimizing environmental impact (UNESCO, 2023). The main applications include solar distillation, solar-powered filtration and reverse osmosis (RO), photocatalytic and ultraviolet (UV)-based disinfection, and solar water disinfection (SODIS) methods. Each approach has distinct operational principles, advantages, and challenges that determine its suitability for specific conditions and water quality requirements.

Solar Distillation Systems

Solar distillation mimics the natural hydrological cycle by utilizing solar thermal energy to evaporate and condense water, leaving contaminants behind. A typical solar still consists of a transparent cover, a blackened basin to absorb heat, and a condensation surface (Gheraout et al., 2023). The sunlight heats the impure water in the basin, causing evaporation; the vapor condenses on the cooler cover surface and is collected as distilled water. This method effectively

removes salts, heavy metals, and biological impurities, making it suitable for coastal or arid regions with saline groundwater (García-Gil Á et al, 2021).

The efficiency of solar stills depends on factors such as solar intensity, ambient temperature, and surface area of the collector. Recent innovations include multi-effect distillation and wick-type stills, which increase productivity by reusing latent heat or enhancing evaporation surfaces. Although simple and low-cost, the major limitation of solar distillation is its relatively low yield—typically 3–5 L/m²/day—making it better suited for small-scale domestic use rather than large-scale municipal applications.

Solar-Powered Filtration and Reverse Osmosis (RO)

Integration of photovoltaic energy with membrane filtration technologies, such as ultrafiltration (UF) and reverse osmosis (RO), has become a promising solution for producing potable water from brackish or contaminated sources. In these systems, solar panels supply electricity to pumps that generate the necessary pressure to force water through semipermeable membranes, removing dissolved ions, organic matter, and microbial contaminants (UN-Water, 2024).

Solar-powered RO systems are especially beneficial in remote or off-grid communities. Advances in energy recovery devices and low-pressure membranes have significantly reduced energy consumption, improving cost-effectiveness. Moreover, hybrid configurations that combine solar energy with battery storage or wind energy enable continuous operation under fluctuating weather conditions (Gheraout et al., 2023). However, membrane fouling and maintenance requirements remain critical challenges. Research into self-cleaning membranes and photocatalytic coatings offers potential to enhance performance and longevity.

Photocatalytic and UV-Based Disinfection

Photocatalytic and ultraviolet (UV) systems leverage the germicidal properties of high-energy photons to destroy microorganisms and degrade organic pollutants. The process typically involves semiconductor catalysts, such as titanium dioxide (TiO₂), that become photoactivated under UV or visible light, generating reactive oxygen species capable of oxidizing contaminants (UNESCO, 2023).

Solar-powered photocatalytic reactors have been tested for removing bacteria, viruses, pesticides, and dyes from water, demonstrating high disinfection efficiency without chemical additives (Gheraout et al., 2023). Additionally, UV-based systems can be powered directly by photovoltaic panels, making them suitable for decentralized, small-scale water purification units. Despite their potential, photocatalytic processes are influenced by light intensity, water turbidity, and catalyst surface area. Ongoing research aims to develop visible-light-activated photocatalysts and reactor geometries that maximize light utilization and contact efficiency (Zhang et al, 2023).

Solar Water Disinfection (SODIS)

Solar Water Disinfection (SODIS) is a simple, low-cost technique developed for household-level water treatment. It relies on the synergistic effects of UV-A radiation (320–400 nm) and mild thermal heating to inactivate pathogens (García-Gil Á et al, 2021). Typically, transparent PET bottles filled with contaminated water are exposed to direct sunlight for 6–8 hours. The UV radiation damages

microbial DNA, while the temperature rise accelerates disinfection. SODIS is particularly effective in tropical and subtropical regions with high solar irradiance and has been endorsed by the World Health Organization as a viable method for improving water safety in developing areas (UN-Water, 2024). However, its performance declines under cloudy conditions or with highly turbid water. Recent innovations include SODIS bags, UV-enhanced glass bottles, and combined filtration-SODIS units, which improve effectiveness and user convenience (UNESCO, 2023).

Performance Evaluation and Case Studies

Solar-powered systems effectively reduce Fe, Mn, turbidity, and other contaminants to meet water quality standards. Field studies showed river water Fe decreased from 1.42 mg/L to 0.81 mg/L and Mn from 8.55 mg/L to 0.08 mg/L after solar filtration (Effendi, 2003; Zulfikar, 2014). Bore well water also improved to safe levels, confirming system reliability. Energy efficiency analysis shows PV-RO systems achieve >95% ion removal with SEC of 2–6 kWh/m³ (UN-Water, 2024). Hybrid systems outperform single-method units, while IoT-based monitoring enhances real-time operation and predictive maintenance.

Performance Parameters and Efficiency Analysis

The performance of a solar-powered treatment system is commonly evaluated based on energy conversion efficiency, water recovery rate, and contaminant removal efficiency. For example, solar distillation systems achieve high removal efficiency for total dissolved solids (TDS), heavy metals, and microbial contaminants, but are limited by their low daily water output—typically ranging from 3–5 L/m²/day (Gheraout et al., 2023). Conversely, photovoltaic (PV)-driven reverse osmosis (RO) systems can produce higher yields with stable operation, achieving more than 95% removal of dissolved ions and 99.9% microbial reduction under optimal solar irradiance conditions (García-Gil Á et al, 2021).

Energy efficiency plays a vital role in determining system sustainability. The specific energy consumption (SEC) in solar-RO systems typically ranges between 2–6 kWh/m³ depending on the salinity level and membrane type (UN-Water, 2024). System optimization through the use of energy recovery devices, efficient pumps, and hybrid power integration (solar with battery or wind energy) can further reduce energy demand. Moreover, the life cycle cost analysis (LCCA) indicates that although the initial capital cost of solar systems is higher, the operational cost is significantly lower due to the absence of fuel expenses and minimal maintenance requirements (UNESCO, 2023).

Case Studies on Water Quality Improvement

Field studies have shown substantial improvements in water quality after solar-powered filtration and distillation. For instance, in a study conducted on river water and bore well water samples in tropical regions, solar filtration systems demonstrated remarkable reductions in iron and manganese concentrations. Before treatment, river water exhibited Fe levels of 1.42 mg/L and Mn of 8.55 mg/L—both exceeding the permissible limits of 1.0 mg/L and 0.5 mg/L, respectively. After solar filtration, Fe decreased to 0.81 mg/L and Mn to 0.08 mg/L, aligning with clean water standards (Effendi, 2003; Zulfikar, 2014).

Similarly, bore well water showed reductions from 0.04 mg/L Fe and 0.05 mg/L Mn to 0.26 mg/L and 0.04 mg/L after filtration, confirming the system's effectiveness in removing trace metals.

Turbidity and color levels also showed significant improvement. River water that initially appeared murky became visibly clear after treatment, while the pH increased from slightly acidic (6.05) to a near-neutral range (6.88), indicating balanced acidity levels suitable for consumption (Febrina & Ayuna, 2015). These findings validate that solar-based filtration systems not only meet national and WHO water quality standards but also demonstrate strong potential for sustainable water supply in rural areas (UNESCO, 2023).

Comparative Evaluation of System Types

Comparative assessments reveal that hybrid solar filtration systems combining photovoltaic power with membrane or adsorptive media outperform single-method systems in both efficiency and cost-effectiveness. While solar distillation excels in desalination and removal of inorganic salts, solar-powered RO and photocatalytic systems provide faster throughput and better microbial control (Gheraout et al., 2023). The integration of smart controllers and IoT-based monitoring systems further enhances real-time performance, enabling automated adjustments to solar input and filtration rates, thus ensuring consistent water quality (UN-Water, 2024).

Economic analysis from various case studies indicates that the payback period for community-scale solar-powered systems ranges between 3–6 years, depending on system size and solar irradiance levels (Zhang et al, 2023). This underscores the long-term cost advantage and environmental sustainability of solar technologies over fossil-fuel-driven treatment units.

Future Prospects

The future of solar-powered water treatment systems lies in the integration of advanced materials, intelligent control technologies, and hybrid renewable configurations that enhance efficiency, affordability, and scalability. As global water scarcity intensifies due to population growth and climate change, innovation in solar-driven purification is essential to ensure sustainable access to clean water, especially in developing regions (UNESCO, 2023). The next generation of solar water treatment systems will prioritize technological innovation, sustainability, and scalability, enabling deployment across a broader range of environmental and socioeconomic contexts.

Technological Innovations

Recent advancements in material science and renewable energy engineering have significantly expanded the potential of solar-powered clean water technologies. One key area of innovation involves the use of nanomaterials—such as titanium dioxide (TiO₂), zinc oxide (ZnO), and graphene-based composites—in photocatalytic systems. These materials enhance light absorption, accelerate reaction rates, and improve the degradation of organic pollutants under visible light conditions (Gheraout et al., 2023). Similarly, nanofiltration (NF) and hybrid membrane technologies are being developed to achieve higher selectivity and permeability with lower energy requirements, reducing operational costs and maintenance intervals.

In parallel, hybrid energy systems combining solar, wind, and bioenergy are gaining attention as strategies to overcome the intermittent nature of solar radiation. Hybrid configurations can provide continuous power for treatment units, stabilize energy supply, and extend the lifespan of battery storage systems (UN-Water, 2024). Research also points to the growing adoption of IoT-based sensors and artificial intelligence (AI)-driven controllers for real-time optimization of energy use, fault detection, and predictive maintenance (UNESCO, 2023). These smart systems enable autonomous operation and adaptive control, allowing water treatment units to dynamically adjust to changes in solar irradiance, water turbidity, or demand levels. Emerging designs also focus on modularity and portability, allowing compact treatment units to be rapidly deployed in disaster-prone or remote areas. Portable solar purification systems equipped with rechargeable batteries and integrated UV or filtration modules can serve as emergency water supply solutions for humanitarian aid, military operations, or rural development projects.

Sustainability and Scalability

Ensuring the long-term sustainability and scalability of solar-powered water treatment technologies requires attention not only to technical innovation but also to economic feasibility, social acceptance, and environmental impact. A sustainable system must balance performance with affordability – especially in low-income or off-grid communities where initial investment costs can be a barrier. Efforts to localize production, use recyclable materials, and simplify maintenance procedures can reduce lifecycle costs and enhance user adoption. From an environmental perspective, replacing fossil-fuel-powered treatment units with solar alternatives can substantially reduce greenhouse gas emissions and operational waste. Life cycle analyses show that solar-powered water systems produce up to 70% lower CO₂ emissions compared to conventional electric-powered units (Gheraout et al., 2023). Furthermore, policy support through green financing, government incentives, and community engagement programs is essential for expanding access to clean water in underserved areas (UNESCO, 2023).

Scalability also depends on integrating solar water purification into regional water management frameworks. Decentralized treatment networks – comprising small, solar-powered modules connected to local reservoirs or wells – can provide resilient water infrastructure capable of withstanding power disruptions and droughts (UN-Water, 2024). Such distributed systems align with global sustainability goals, particularly the United Nations' Sustainable Development Goal 6 (SDG 6): Clean Water and Sanitation for All, by promoting equitable, environmentally responsible water access worldwide (UNESCO, 2023).

Challenges and Limitations

Despite their growing adoption and technological progress, solar-powered water treatment systems face several technical, economic, environmental, and social challenges that hinder large-scale implementation. These limitations must be addressed through interdisciplinary research, policy

support, and community involvement to ensure that solar-based solutions can deliver sustainable and equitable access to clean water (UNESCO, 2023).

Technical Challenges

A primary technical limitation is the dependence on solar irradiance, which directly affects the performance of photovoltaic and solar thermal systems. Cloud cover, diurnal variations, and seasonal changes significantly influence energy output, leading to fluctuations in water treatment capacity. In regions with low sunlight availability or during monsoon seasons, system reliability can decrease sharply unless supported by auxiliary power or battery storage systems. Another major issue involves efficiency losses due to dust accumulation, shading, or degradation of solar panels over time. Regular maintenance is required to sustain optimal performance, but this can be difficult in remote areas with limited technical support (Gheraout et al., 2023). Additionally, membrane fouling in reverse osmosis (RO) or ultrafiltration systems remains a persistent problem. Accumulation of organic matter, minerals, and biological growth on membranes reduces permeability and increases energy consumption. Although self-cleaning and photocatalytic membranes are under development, they are not yet widely available or cost-effective.

Thermal systems also face limitations related to heat losses and low productivity. Solar distillation, for instance, produces a relatively small quantity of distilled water per unit area, making it impractical for large-scale municipal use (UN-Water, 2024). Therefore, improving material efficiency, incorporating advanced coatings, and integrating hybrid systems remain key areas of research to overcome these technical barriers.

Economic and Infrastructural Limitations

Although solar-powered treatment systems reduce long-term operational costs, their initial capital investment remains high compared to conventional methods. The cost of photovoltaic panels, storage batteries, and advanced filtration components can limit adoption, particularly in low-income or developing regions (UNESCO, 2023). Furthermore, the lack of standardized designs and limited local manufacturing capacity often lead to higher import and maintenance expenses.

Infrastructure also poses a significant barrier. In many rural areas, the absence of trained technicians, inadequate supply chains for spare parts, and unreliable transportation networks impede system deployment and long-term sustainability (Gheraout et al., 2023). To mitigate these issues, partnerships between governments, research institutions, and private sectors are essential for providing technical training, establishing maintenance centers, and developing locally adapted technologies. Moreover, while life cycle cost analyses (LCCA) have demonstrated that solar systems become economically favorable over time, their financial feasibility depends heavily on policy incentives, such as subsidies, tax reductions, or green financing programs. Without institutional support, the high upfront investment remains a deterrent to large-scale implementation (UN-Water, 2024).

Environmental and Social Challenges

From an environmental standpoint, solar-powered systems are often perceived as “zero-emission,” but their manufacturing and disposal processes present sustainability concerns. The production of photovoltaic cells and batteries involves energy-intensive procedures and the use of hazardous materials such as cadmium and lead, which may cause secondary pollution if not properly managed (Gheraout et al., 2023). Similarly, end-of-life disposal of membranes and filters can generate non-biodegradable waste, necessitating effective recycling frameworks (UNESCO, 2023).

Social factors also play a crucial role in the success of solar water treatment projects. Limited community engagement and lack of user awareness can lead to neglect or misuse of installed systems, reducing their operational lifespan. In some cases, communities perceive solar technologies as complex or unreliable, particularly when technical maintenance is infrequent. Therefore, social integration through education, participatory design, and local ownership models is essential to ensure long-term acceptance and success.

Future Directions to Overcome Limitations

Addressing these challenges requires a multidimensional approach combining technological innovation, economic policy, and social participation. Research should prioritize developing cost-effective materials, self-sustaining hybrid systems, and recyclable components. Governments and NGOs must provide financial incentives and technical support to facilitate widespread adoption in marginalized regions. In addition, integrating IoT-based monitoring and AI-driven diagnostics will enhance system reliability and allow predictive maintenance, reducing downtime and operational costs (UNESCO, 2023).

Ultimately, achieving global scalability of solar-powered clean water systems will depend on how effectively these limitations are addressed through innovation, policy, and inclusive development. The transition from pilot projects to sustainable infrastructure requires collaboration between scientists, engineers, policymakers, and communities to ensure both environmental protection and universal access to safe water (UN-Water, 2024).

CONCLUSION

Solar-powered water treatment systems offer a sustainable solution for providing clean drinking water through technologies such as solar distillation, PV-driven reverse osmosis (RO), photocatalysis, and SODIS, effectively removing chemical and microbial contaminants (Gheraout et al., 2023; UNESCO, 2023; Effendi, 2003; Zulfikar, 2014). Adoption is limited by challenges including dependence on solar irradiance, high costs, membrane fouling, and low thermal system output, requiring innovation in materials, hybrid energy, IoT monitoring, and supportive policies. Advances in nanomaterials, smart controllers, hybrid systems, and modular designs promise greater efficiency, scalability, and alignment with SDG 6 for universal clean water access (UNESCO, 2023; UN-Water, 2024). Overall, solar-powered water treatment represents an environmentally friendly, socially impactful approach to addressing global water scarcity.

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