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Integrated Solar Photovoltaic and Water Purification Systems for Rural Tanzania: A Review of Technologies and Deployment Barriers

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REVIEW ARTICLES

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Abstract: In rural Tanzania, unreliable electricity constrains decentralized water treatment. This review evaluates Photovoltaic (PV) powered ultraviolet (UV) disinfection and reverse osmosis/nanofiltration (RO/NF), chlorination, filtration and photocatalysis. A structured narrative search of one engineering database (ScienceDirect) and one academic search engine (Google Scholar) covered 2016–2026. The cited evidence base comprised 45 publications from 2016–2026, three earlier foundational sources and five institutional/report sources (53 sources total). Tanzanian Photovoltaic (PV) powered ultrafiltration–nanofiltration (UF–NF) field tests produced about 1,200 L per solar day at approximately 1.5 kWh/m³; auxiliary air bubbling could add about 0.8 kWh/m³. Tanzania receives about 4–7 kWh/m²/day of solar irradiation, but rainy-season cloud cover can reduce PV output when treatment demand may rise. Filtration plus chlorination is the most deployable near-term pathway. The proposed decision framework integrates source-water type, specific energy consumption (SEC), solar/grid reliability, operator capacity, supply chain and maintenance.

Keywords Solar photovoltaic, Water purification, Tanzania, Decentralized water treatment, Waste stabilization ponds, Specific energy consumption

1. Introduction

Access to clean water and energy is one of the major interconnected pillars in rural development. Water extraction, pumping, filtration, disinfection, desalination, monitoring of the treatment process, and water distribution require a stable supply of energy, whereas good-quality water contributes to better health, education, productivity, and resilience. In many rural areas, problems with water safety do not result from an absence of water but microbial pollution, seasonal turbidity, poor protection of water sources, improper water storage, inadequate disinfection, and poor monitoring (Aydamo et al., 2024). Simultaneously, unstable access to energy makes water treatment hard due to an inability of pumps, UV lamps, dosing pumps, sensors, membrane technology, and control units to function properly. Therefore, water and energy insecurity should be perceived as the water-energy security issue (Ijoma et al., 2022).

Solar photovoltaic (PV) technology is increasingly important for decentralized water-treatment applications because electricity can be generated at the point of water use. Recent reviews show growing

application of PV in water pumping, disinfection, membrane separation, desalination, filtration, and hybrid treatment systems (Vivar et al., 2024). PV-powered purification is particularly attractive in rural areas because it can reduce dependence on unreliable grid connections and diesel fuel. Integrated PV systems for household- and community-scale water disinfection and electricity production have been evaluated for developing-country applications (Vivar et al., 2020), while renewable-energy-driven membrane technologies have demonstrated potential for drinking-water production in off-grid and remote regions (Schäfer et al., 2018).

In Tanzania, the risks associated with water quality in rural and peri-urban areas vary based on the water source, land use practices, geology, sanitary status and the rainy season. Surface water may have pathogens, suspended particles, nutrients and organic matter whereas groundwater may have fluoride, nitrate, salt, iron, manganese and other dissolved components. Systems that are affected by wastewater can have pathogens, organic contaminants, nutrients and industrial waste. For this reason, no single purification process can be used for all communities since each community faces different types of pollution in its water; thus, water treatment methods should rather be chosen based on the main pollutants, energy needed for treatment, operation ability, costs, spares availability, and monitoring requirements (Eliamringi & Kazumba, 2017).

The objective of this paper is to assess solar PV-integrated water-purification technologies for rural Tanzania. The review focuses on five pathways: PV and ultraviolet (UV) disinfection; PV and reverse osmosis (RO); PV and chlorination; PV and filtration; and PV and photocatalysis. These pathways respectively address microbial inactivation, dissolved contaminant removal, residual disinfection, turbidity reduction, and advanced oxidation. The technologies are compared in terms of energy demand, pollutant-removal capability, operating complexity, implementation and operating cost, maintenance requirements, and rural applicability. The discussion is linked to the Kalobe Waste Stabilization Ponds in Mbeya as an illustrative Tanzanian wastewater-treatment context (Gerson et al., 2025a, 2025b).

Accordingly, this review addresses two research questions: (RQ1) What are the treatment-performance, specific energy-consumption, operational and maintenance characteristics of solar PV-powered water-purification technologies applicable to rural Tanzania? (RQ2) How can source-water characteristics, solar-resource variability, grid reliability, operator capability and local supply-chain constraints be integrated into a practical decision framework for selecting PV-powered water-treatment systems in rural Tanzania?

This review makes four principal contributions. First, it quantitatively introduces specific energy consumption (SEC, kWh/m³) into the comparison of PV-integrated treatment pathways. Second, it links technology selection with Tanzania-specific water conditions, solar-resource availability and seasonal variability. Third, it integrates technical performance with grid reliability, operator capacity, maintenance requirements and local supply-chain constraints. Fourth, it develops a practical decision framework for matching source-water risks and local operating conditions with appropriate PV-powered treatment configurations.

2. Methodology of the Review

This review employed a structured narrative and comparative design, with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 principles used to report the sequence of evidence identification, screening, retrieval, eligibility assessment and inclusion transparently (Page et al., 2021). The review scope was defined around five PV-water-treatment pathways: ultraviolet (UV) disinfection, reverse osmosis/nanofiltration (RO/NF), chlorination/electrochlorination, filtration/membrane treatment, and photocatalysis/advanced oxidation. The core scholarly search covered publications from 2016 to 2026. Studies published before 2016 were considered only when they provided foundational evidence that remained necessary for interpreting the selected technologies. Tanzanian institutional, regulatory, climate and solar-resource documents were handled through a separate other-method evidence stream so that peer-

reviewed technology evidence could be distinguished from contextual evidence used to assess national deployment conditions.

Identification was conducted using ScienceDirect as the principal engineering database and Google Scholar as a cross-publisher academic search engine. Four predefined Boolean search strings, reported in Appendix Table 9, combined terms for solar photovoltaic energy, water purification/treatment and the five selected treatment pathways. The searches returned 2,594 ScienceDirect hits and approximately 3,400 Google Scholar hits, giving 5,994 search-interface hits. Google Scholar results were examined in relevance-ranked order for each predefined search string. Screening continued while new potentially eligible sources were being identified and was stopped only when successive result pages, together with backward-citation checking, yielded no additional eligible evidence. Because Google Scholar reports approximate interface-level hit counts and the original search did not preserve an exportable record-level Google Scholar file, the approximately 3,400 hits were treated as discovery-interface results rather than as 3,400 unique records. Because the four searches and the two discovery platforms produced substantial overlap, the archived search output was reconciled at title and bibliographic-record level during revision. A total of 4,142 duplicate or overlapping records and 24 non-article/interface items were removed before screening, leaving 1,828 records for title-and-abstract assessment. These intermediate PRISMA counts represent a retrospective audit reconstruction from the archived search material rather than prospectively logged screening statistics. Scopus and Web of Science were considered in preparing this review, but full document-level institutional access and reproducible export were unavailable; consequently, no unverifiable counts from those databases were reported. Coverage was strengthened instead through publisher site verification, backward citation searching and targeted Tanzanian institutional sources.

Screening and eligibility assessment followed the chronological PRISMA sequence. Of the 1,828 records screened by title and abstract, 1,548 were excluded: 1,527 were not sufficiently related to the solar/PV-water-treatment scope or target decentralized application context, and 21 fell outside the five predefined treatment pathways. The remaining 280 reports were sought for full-text retrieval. Eleven reports could not be retrieved beyond title/abstract information and were recorded as not retrieved, leaving 269 full-text reports for eligibility assessment. Full texts were eligible when they addressed at least one selected treatment pathway and contributed evidence on treatment performance, specific energy consumption or other energy requirements, implementation or operating cost, operating complexity, maintenance, field deployment or rural applicability. At full-text assessment, 224 reports were excluded: 195 were not sufficiently aligned with the rural/decentralized/Tanzanian PV-water-treatment context, 19 did not address one of the five predefined pathways, and 10 provided insufficient technical or field evidence for comparative synthesis. This process retained 45 scholarly publications from 2016–2026 for the principal technology evidence synthesis.

Identification through other methods yielded 17 candidate reports: six from websites, eight from organizations and three through citation searching. All 17 were sought and successfully retrieved, and all proceeded to eligibility assessment. Nine were excluded at this stage: four were duplicate or superseded reports, three were outside the PV-water-treatment scope, and two provided insufficient technical or Tanzania-specific relevance. Eight other-method sources were therefore retained, comprising three earlier foundational studies and five institutional/report sources from EWURA, the Ministry of Water/RUWASA, REA, UN-Habitat and the World Bank. Combining these eight sources with the 45 scholarly publications produced a final evidence base of 53 sources. The first author performed the initial screening, full-text assessment and evidence extraction, while the second author independently cross-checked final eligibility and synthesis decisions; disagreements were resolved through discussion and consensus. Evidence was extracted and compared using treatment pathway, source-water/application context, treatment performance, energy or SEC information, cost, operating complexity, maintenance requirements, grid/solar reliability, operator capacity, supply-chain requirements and rural applicability.

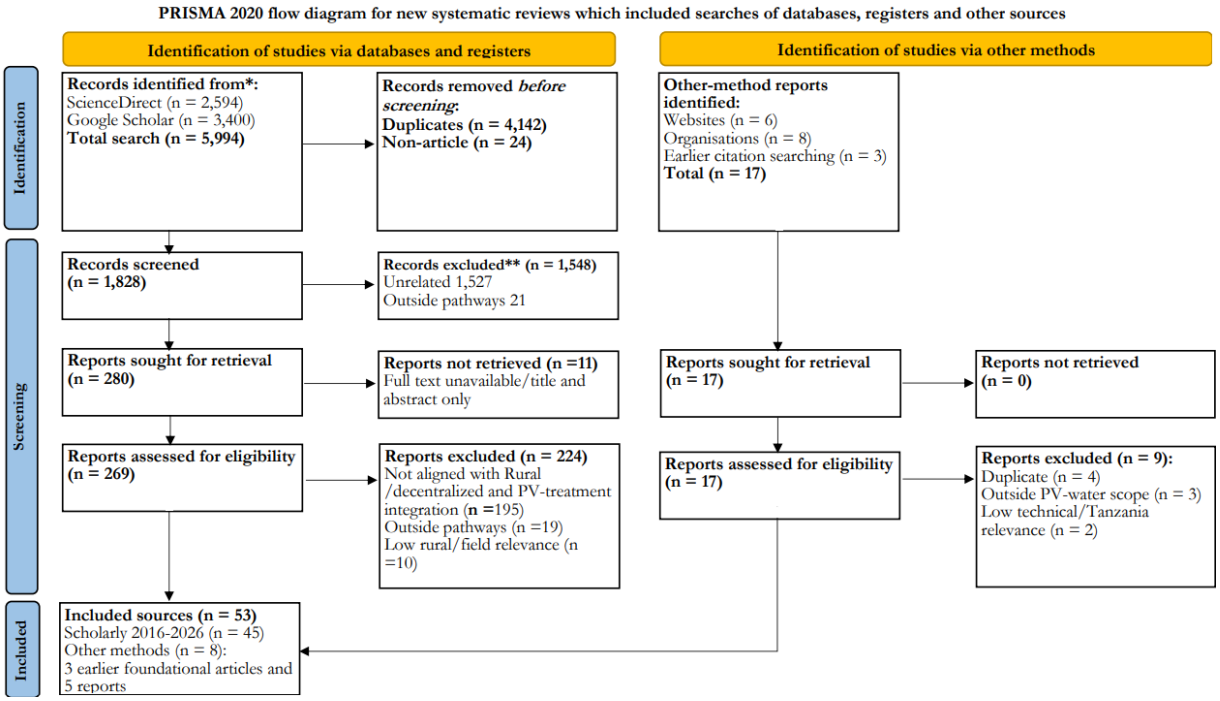


Figure 1 PRISMA 2020 flow diagram showing the chronological sequence of identification, screening, retrieval, eligibility and inclusion. Adapted from (Page et al., 2021)

The comparative assessment was based on six practical criteria. First, energy demand represented the electrical energy required for pumping, treatment, control, and monitoring. Second, pollutant-removal capability represented the ability of each technology to address microbial, dissolved, particulate, and organic contaminants. Third, implementation and operating cost considered both initial system requirements and recurring expenditure associated with operation. Fourth, operating complexity represented the level of technical skill, process control, and operator involvement required for reliable performance. Fifth, maintenance needs included cleaning, replacement of consumables and components, preventive maintenance, and requirements for specialist service. Sixth, rural suitability represented the combined influence of energy availability, operational simplicity, maintainability, local technical capacity, spare-part accessibility, and robustness under decentralized operating conditions. These criteria were used consistently to compare the five PV-integrated treatment pathways and to support the qualitative ratings presented in the comparative assessment.

The Kalobe Waste Stabilization Ponds in Mbeya, Tanzania, were considered as an illustrative application based on published secondary evidence rather than as a primary field case study. No new water-quality measurements, flow measurements, or site-specific energy data were collected for the present review. Published evidence indicates that the Kalobe system operates below its designed treatment capacity (Gerson et al., 2025a, 2025b). The facility therefore provides a relevant Tanzanian context for examining the potential application of PV-assisted monitoring, filtration, effluent polishing, final disinfection, and safe wastewater reuse without implying that the proposed PV-supported treatment configuration has already been implemented at the site.

3. Water and Energy Challenges in Rural Tanzania

Problems related to water treatment in rural areas of Tanzania are site-specific. Sources of surface water are susceptible to contamination through runoffs, open defecation, livestock, farming practices, and seasonal turbidity. The shallow wells and springs could get contaminated either during the rainy seasons or due to lack of proper security. Sources from the boreholes have reduced levels of microbial contamination;

however, they might contain dissolved salts such as fluoride, nitrate, iron, manganese, and salinity depending on the nature of the aquifer. Wastewater contaminated sources of water could contain bacteria, organic content, nutrients, and heavy metals. It is, therefore, necessary to choose the appropriate purification technique depending on the quality problem faced.

This uncertainty over electricity supply makes the management of a water treatment facility much harder. Pump(s) are needed to draw the water up from bore holes, rivers or service reservoirs. UV systems depend on a steady supply of electricity in order to drive and light the lamps. RO technology requires good pressure which necessitates significant electricity supply. Chlorination systems can involve small electric driven dosage pumps, mixing equipment and possibly residual monitors. Water filters often involve pumps and may require backwash controls. Photocatalysis often requires a pump, mixing device, an ultraviolet light-emitting diode (UV-LED) or controlling instrumentation. This is where solar PV can displace the need for diesel generators or intermittent electricity supply from a utility grid.

However, PV integration alone does not guarantee long-term sustainability. Evidence from rural water services in Tanzania indicates that sustained service delivery depends not only on appropriate technology but also on effective management, tariff collection, technical capacity for operation and repair, and clearly defined institutional responsibilities (Eliamringi & Kazumba, 2017). Consequently, solar-powered water purification should be planned as a service system that integrates technology, operation, maintenance, financing and monitoring rather than as a stand-alone equipment package.

Recent Tanzanian institutional evidence reinforces the need to treat PV-water systems as service infrastructure rather than isolated equipment. The Ministry of Water reports continuing investment by the Rural Water Supply and Sanitation Agency (RUWASA) in rural water points, household connections and boreholes, while Energy and Water Utilities Regulatory Authority (EWURA) performance reviews show that water-service reliability, operating costs and maintenance remain important sector constraints (EWURA, 2026; Ministry of Water, 2024). The Rural Energy Agency (REA) has also continued result-based financing for stand-alone solar systems in remote communities where grid extension is impractical, demonstrating an active institutional pathway for decentralized solar deployment (REA, 2024). These national programmes strengthen the case for integrating water-treatment design with local energy-service, maintenance and financing arrangements.

Integrated PV-water systems for rural Tanzania should satisfy four practical requirements: (1) source-specific treatment, whereby raw-water quality is characterized before technology selection; (2) energy matching, whereby treatment demand is aligned with the local solar resource, PV capacity, storage strategy, and daily water requirement; (3) maintainability, whereby components can be operated and repaired using accessible local skills and spare parts; and (4) verification, whereby treated water is routinely monitored for turbidity, microbial safety, pH, electrical conductivity, and locally relevant chemical contaminants.

3.1. Solar resource and seasonal energy-water mismatch in Tanzania

Tanzania has a strong solar resource for decentralized PV applications. Published assessments report a national global horizontal irradiation (GHI) of approximately 4–7 kWh/m²/day, while a recent Mbeya Rural District study reported a scaled annual-average solar irradiation of about 6.11 kWh/m²/day (Mwakitalima et al., 2023). World Bank/Global Solar Atlas data for Tanzania provide long-term layers for GHI, photovoltaic power potential (PVOUT), diffuse irradiation(DIF), direct normal irradiation(DNI), Global Tilted Irradiation (GTI), and optimum tilt, which can be used for site-specific design (World Bank, 2023). These data support the technical feasibility of PV-powered pumping and treatment, but annual averages should not be used alone for reliability sizing.

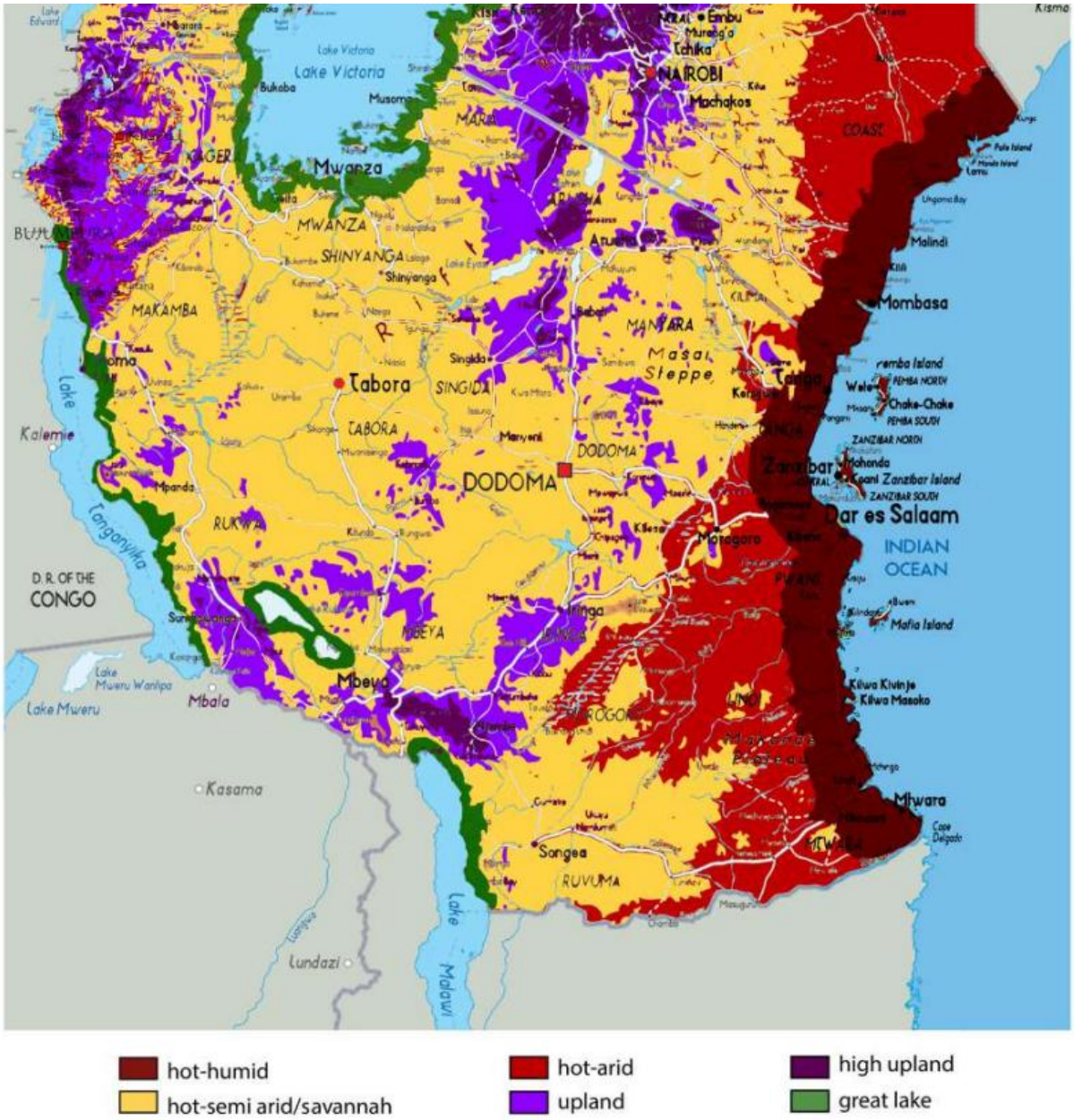


Figure 2 Tanzania climatic-zone map. Source: cropped from (UN-Habitat, 2016).

The climate-zone distribution further shows why a single national solar-resource value should not be used for all PV-water systems. Tanzania includes hot-humid coastal areas, hot semi-arid/savannah regions, Great Lakes environments and upland zones. Dar es Salaam and Tanga represent hot-humid conditions, Dodoma and Tabora represent hot semi-arid/savannah conditions, Mwanza represents the Great Lakes zone, while Mbeya and Arusha are upland locations. These climatic differences affect rainfall seasonality, cloudiness, solar availability and therefore the appropriate PV sizing and water-storage strategy for decentralized treatment systems (UN-Habitat, 2016).

Seasonality is particularly important for PV-water systems. During rainy periods, runoff and source disturbance can increase turbidity, suspended solids and microbial loading in surface and shallow-water sources, which may raise pretreatment and disinfection requirements. At the same time, increased cloud cover can reduce solar irradiance and instantaneous PV output. Field evidence from Tanzania shows that cloud passages reduce membrane permeate flow and alter SEC in directly coupled PV-membrane systems

(Schäfer et al., 2018). The resulting energy-water mismatch means that treatment demand may increase during periods when PV output is lower. Design should therefore consider wet-season solar conditions, treated-water storage, battery support where justified, and sufficient pretreatment capacity rather than relying only on annual-average irradiation.

The Mbeya typical meteorological year (TMY) monthly climate record provides a quantitative illustration of this mismatch. From December to April, the reported rainfall totals approximately 730 mm, equivalent to about 91% of the 800 mm annual total, while mean global solar radiation over these five months is about 5.70 kWh/m²/day. From May to November, rainfall totals only about 70 mm and mean global solar radiation rises to approximately 6.54 kWh/m²/day. Thus, the mean solar resource during the principal wet period is about 13% lower than during the drier part of the year. For directly coupled PV-water treatment, this seasonal contrast supports sizing against the wet-season solar envelope and using treated-water storage, adequate pretreatment and, where justified, electrical storage or backup supply to maintain treatment reliability (UN-Habitat, 2016).

Table 1 Tanzania solar-resource indicators relevant to PV-powered water treatment

Indicator	Tanzania / Mbeya value	Design significance	Source
National GHI	~4–7 kWh/m²/day	Confirms strong overall PV resource, but local/seasonal variation must be considered.	(Mwakitalima et al., 2023)
Mbeya Rural average solar irradiation	~6.11 kWh/m²/day	Supports PV-powered rural treatment in the Mbeya context.	(Mwakitalima et al., 2023)
Global Solar Atlas layers	GHI, PVOUT, DIF, GTI, DNI and optimum tilt	Enables site-specific PV yield, tilt and seasonal-resource assessment.	(World Bank, 2023)
Seasonal design consideration	Wet/cloudy periods can reduce instantaneous PV yield	Use wet-season sizing, storage and treatment-buffering strategies.	(Schäfer et al., 2018)
Tanzania climate-zone variation	Hot-humid coast: ~5.0–5.4; hot semi-arid/savannah: ~6.3; Great Lakes: ~5.5; upland: ~5.0–6.0 kWh/m²/day global solar radiation	Confirms substantial spatial variation; PV-water systems should use local rather than national-average resource assumptions.	(UN-Habitat, 2016)
Mbeya TMY climate	Upland climate; annual-average global solar radiation ~6.2 kWh/m²/day; annual rainfall ~800 mm; main rainy period December–April	Provides a location-specific basis for wet-season PV sizing in the Mbeya context.	(UN-Habitat, 2016)
Mbeya wet/dry seasonal contrast	Dec–Apr: mean solar radiation ~5.70 kWh/m²/day and 730 mm rainfall; May–Nov: ~6.54 kWh/m²/day and 70 mm rainfall	About 91% of annual rainfall occurs in the wetter period while mean solar radiation is ~13% lower, quantifying the seasonal energy–water mismatch.	(UN-Habitat, 2016)

3.2. Field evidence from solar powered membrane treatment in Tanzania

In developing countries such as Tanzania, Renewable-energy-powered membrane systems, including solar-powered ultrafiltration (UF) and nanofiltration (NF), offer practical treatment options for rural communities affected by unsafe water, elevated fluoride concentrations, and unreliable grid electricity. A field study in northern Tanzania tested a solar powered ultrafiltration and nanofiltration system at Mdori in Manyara and Ngare Nanyuki in Arusha, where both waters contained very high fluoride levels of about 50–60 mg/L, far above the World Health Organization (WHO) guideline of 1.5 mg/L. The NF90 membrane successfully reduced fluoride to safe drinking water levels and produced approximately 1200 L of potable water per solar

day, showing that solar driven membrane systems can provide clean water without permanent grid infrastructure. However, the study also shows that successful implementation in developing countries depends not only on technical performance, but also on maintenance capacity, spare part availability, community acceptance, trained local operators, governance, and sustainable financing. Therefore, solar powered membrane treatment can be considered a promising decentralized water purification option for rural Tanzania and similar developing country contexts, provided that non-technical barriers are properly addressed (Schäfer et al., 2018). For the water-quality indicators reported below, nephelometric turbidity unit (NTU) and specific ultraviolet absorbance (SUVA) are used as abbreviated terms. The corresponding source-water quality characteristics measured at Mdori and Ngare Nanyuki are summarized in Table 3.

Table 2 Monthly global solar radiation and rainfall pattern for Mbeya, Tanzania (UN-Habitat, 2016)

Month / period	Global solar radiation (kWh/m²/day)	Rainfall (mm)	Seasonal interpretation
January	5.5	190	Wet period
February	6.1	150	Wet period
March	5.6	150	Wet period
April	5.9	110	Wet period
May	6.4	10	Dry/transition
June	6.4	0	Dry period
July	6.3	0	Dry period
August	6.5	0	Dry period
September	6.8	0	Dry period
October	7.1	10	Dry/transition
November	6.3	50	Dry/transition
December	5.4	130	Wet period

Table 3 Water quality of the Mdori and Ngare Nanyuki waters, sampled during the field trials on 1 March 2014 and 19 March 2014, respectively (Schäfer et al., 2018)

Coordinates	Mdori	Ngare Nanyuki
	S03°47.273', E035°51.138'	S03°10.929', E036°51.676'
Altitude (m)	971	1450
pH (–)	10.5	8.3
Conductivity (µS/cm)	4920	3530
Turbidity (NTU)	0.3	1.5
Inorganic carbon (mg/L)	469	395
Total organic carbon (mg/L)	3	255
Dissolved organic carbon	2	249
UV absorbance 254 nm (mg/L)	0.1	11.7
SUVA (L/mg.cm)	5.4	4.7
Fluoride (mg/L)	58	53
Calcium (mg/L)	0.5	12
Sodium (mg/L)	1479	948
Chloride (mg/L)	277	152

3.3. International field evidence from decentralized ultraviolet disinfection

International field evidence shows that decentralized ultraviolet disinfection and solar photovoltaic powered ultraviolet disinfection have been applied in different low-resource settings depending on water source, energy availability, system scale and local maintenance capacity. In Tanzania, solar powered ultraviolet systems installed in rural healthcare facilities used rainwater harvesting with first-flush removal and sedimentation before disinfection, but lamp burnout, damaged wiring, difficult cleaning access and weak maintenance showed that ultraviolet units must be protected, regularly inspected and supported by trained operators (Moore et al., 2026; Ngasala et al., 2020).

Similar lessons are reported in Kenya and Rwanda, where rainwater, spring water and community water

supplies were treated using biosand, biochar, bag, gravel or sand filtration followed by ultraviolet disinfection, demonstrating that pretreatment is essential for reducing turbidity before ultraviolet exposure, although high equipment cost, power surges, weak spare-part supply and limited operator skills remain important barriers (Gold et al., 2007; Moore et al., 2026; Onyango-Ouma et al., 2005). In India, ultraviolet light emitting diode systems have been tested for community taps, ponds and hand-pump water supplies, including a zero-energy ultraviolet reactor driven by hand-pump movement, showing that low-energy disinfection can serve remote areas when appropriate operation and maintenance are provided (Song et al., 2016; Sundar & Kanmani, 2021). In the Philippines and Mexico, solar powered and household ultraviolet systems improved microbial water quality, but the studies also showed that higher dose, longer contact time, protection against photoreactivation and safe storage are required to prevent post-treatment recontamination (Jeco et al., 2019; Reygadas et al., 2015).

Evidence from developed and emergency contexts further confirms that ultraviolet systems can achieve reliable pathogen inactivation when dose validation, ultraviolet transmittance monitoring, lamp-status indicators, cartridge or slow sand filtration, backup power and trained operators are included (Beck et al., 2017; Hull et al., 2019; Makuei & Peleato, 2023; Pousty et al., 2024). Therefore, for rural Tanzania, photovoltaic powered ultraviolet disinfection should not be applied as a stand-alone unit, but as part of a treatment train that includes source-water testing, sedimentation or filtration, stable solar or backup power, protected electrical components, lamp cleaning or replacement, safe storage, routine microbial monitoring and a clear operation and maintenance plan.

4. Solar PV System Architecture for Water Purification

A standard photovoltaic (PV)-powered water-purification system comprises PV modules, a support structure, optional battery storage, a charge controller, an inverter where alternating-current (AC) loads are present, direct-current (DC) and/or AC pumps, instrumentation, a water-treatment unit, a storage tank, and control equipment. Depending on the treatment objective, the treatment unit may consist of a UV reactor, RO membrane module, chlorination-dosing system, filtration train, photocatalytic reactor, or a hybrid configuration. The energy-design objective is to ensure that PV generation can meet the combined requirements for pumping, treatment, control, monitoring, and storage during the intended operating period. Low-energy pathways such as chlorination can generally be supported by relatively small PV arrays, whereas RO requires greater installed capacity because of high-pressure pumping. Consequently, PV-assisted membrane systems require careful sizing, pressure control, and fouling management (Zewdie et al., 2021).

Three PV-system architectures are particularly relevant to rural Tanzania. In a direct-PV configuration, treatment equipment operates primarily during daylight hours, and treated water is stored in a tank, thereby reducing the need for electrical-energy storage. A PV-battery configuration stores electricity for treatment during cloudy periods or outside solar-production hours but increases capital cost and maintenance requirements. A PV-grid or PV-diesel hybrid can provide backup where a grid connection or generator is available, although this may be uneconomical for small systems. Where feasible, storing treated water in an elevated tank is generally simpler and less maintenance-intensive than oversizing electrochemical battery storage.

4.1. Specific energy consumption of PV-powered water treatment

For an Electrical Engineering and Energy assessment, treatment technologies should be compared using specific energy consumption (SEC), expressed as electrical energy consumed per unit volume of treated water. $SEC = E_{electrical} / V_{treated}$, where SEC is in kWh/m³, $E_{electrical}$ is the electrical energy consumed in kWh, and $V_{treated}$ is the treated-water volume in m³. SEC should include the treatment load and, where reported, relevant auxiliary loads such as high-pressure pumping, backwashing, aeration, dosing, controls and monitoring.

The Tanzanian field study by (Schäfer et al., 2018) provides a direct quantitative anchor. At Mdori and Ngare Nanyuki, the directly coupled solar UF–NF system produced about 1,200 L of potable water per solar day and reported an SEC of approximately 1.5 kWh/m³ under both field conditions. For the high-organic-water case at Ngare Nanyuki, continuous air bubbling would add about 0.8 kWh/m³ in the reported worst-case estimate. The same study notes that cloud passages reduced transmembrane pressure and permeate flow, illustrating why SEC and treatment throughput should be evaluated together with variable PV input. For the quantitative comparison in Table 4, electrical conductivity (EC) and total organic carbon (TOC) are used as abbreviated source-water indicators.

Table 4 Quantitative energy-performance evidence for PV-powered membrane treatment in Tanzania

Site / process	Source-water issue	Water production	Reported SEC	Auxiliary energy	Energy implication	Reference
Mdori, Manyara; PV–UF–NF	Fluoride ~58 mg/L; EC 4920 µS/cm	~1,200 L/solar day	~1.5 kWh/m³	No additional air-bubbler term reported	Small-scale PV membrane treatment can achieve drinking-water quality at moderate SEC.	(Schäfer et al., 2018)
Ngare Nanyuki, Arusha; PV–UF–NF	Fluoride ~53 mg/L; high TOC ~255 mg/L	Just under 1,200 L/solar day	~1.5 kWh/m³	Worst-case continuous air bubbling: +~0.8 kWh/m³	Pretreatment/auxiliary loads can materially increase total SEC and should be included in sizing.	(Schäfer et al., 2018)

4.2. PV and UV disinfection

Ultraviolet disinfection works by using ultraviolet radiation to damage the genetic material of micro-organisms and thus stop them from reproducing. It is capable of inactivating bacteria, viruses, and protozoa as long as the right dose is applied. Solar-powered UV is appealing since it does not involve the addition of chemicals, does not cause a chlorine taste, and can be designed for use in households, kiosks, schools, clinics, and communities. New possibilities have arisen due to UV LEDs, as they are small in size, contain no mercury, switch quickly, and may be suitable for point of use applications (Song et al., 2016). Moreover, experimental studies have demonstrated that UV C LEDs can achieve microbial inactivation when the wavelength, dose, and reactor design are properly controlled (Beck et al., 2017).

A major technical limitation of UV treatment is its dependence on water clarity. Suspended particles can shield microorganisms from UV radiation and reduce disinfection effectiveness. Therefore, sedimentation and filtration are commonly required before UV treatment. UV also provides no residual disinfectant, so treated water may be recontaminated during storage or distribution. Where residual protection is necessary, UV should be complemented by low-dose chlorination or stringent safe-storage practices. Evidence from decentralized UV systems further shows that reliable field performance depends on routine lamp maintenance, appropriate flow control, adequate water clarity, and operator training (Moore et al., 2026).

In rural Tanzania, solar photovoltaic and ultraviolet (UV) treatment is appropriate in cases where the water is microbiologically unsafe but is fairly clear after simple filtration. The approach is particularly suitable for use in schools, health centres, water kiosks and at the point of use, since the treated water can be drunk immediately after treatment. Figure 3 illustrates a practical sequence of operations involving the collection of raw water, sedimentation, pre-filtration, UV disinfection, and then covered storage. When the water is to be stored for long periods or distributed via pipes, UV treatment should be combined with low-dose chlorination or with strict storage hygiene.

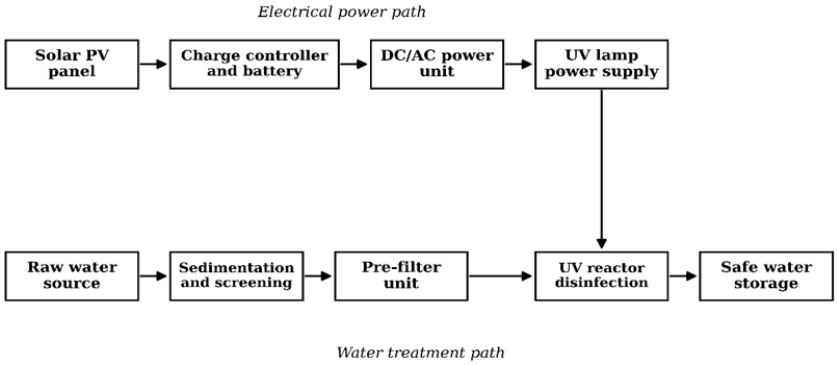


Figure 3 Schematic pathway for PV-powered UV disinfection. Source: Authors' original illustration based on the working principles described in the text.

Figure 3 shows that the solar PV panel generates electricity, which is regulated by the charge controller and supplied to the battery and DC/AC power unit. Raw water passes through sedimentation, screening, and pre-filtration to remove coarse particles and reduce turbidity before entering the UV reactor. Ultraviolet radiation then inactivates microorganisms, after which the disinfected water is transferred to protected storage.

4.3. PV and reverse osmosis (RO)

Reverse osmosis is a pressure driven membrane process that removes dissolved salts, fluoride, nitrate, heavy metals, many organic contaminants, and pathogens. It is one of the most powerful purification technologies when the dominant water quality problem is dissolved contamination rather than microbial risk alone. PV powered RO is therefore important for brackish groundwater, saline water, fluoride affected groundwater, and chemically contaminated sources. Reviews of PV powered desalination show that solar energy can support RO systems for remote water production, especially where conventional energy access is weak (Al-Addous et al., 2024; Elfaqih et al., 2024).

Although reverse osmosis provides high removal efficiency for dissolved contaminants, it is the most operationally demanding of the treatment pathways considered in this review. RO requires high operating pressure, effective membrane protection, adequate pretreatment, regular cleaning, trained operators and appropriate concentrate management. Membrane fouling may result from suspended solids, organic matter, iron, manganese, scaling salts and microbial growth. Process cost and energy consumption depend on membrane permeability, operating pressure, feed-water salinity, recovery ratio, energy recovery, membrane replacement and pretreatment design (Okamoto & Lienhard, 2019). Renewable-energy-powered desalination is therefore technically attractive, but economic and maintenance requirements must be carefully evaluated for small decentralized systems (Prado de Nicolás et al., 2023).

In Tanzania, PV-powered RO should be selected only where water-quality testing confirms significant dissolved contamination such as salinity, fluoride, nitrate or heavy metals. Where microbial contamination is the principal risk, RO may impose unnecessary cost and operational complexity. A functional PV-RO treatment train should include raw-water screening, sediment filtration, cartridge or carbon filtration, antiscalant dosing or softening where required, RO membrane separation, post-disinfection, treated-water storage and controlled management of reject brine. Inadequate brine management may create environmental risks, particularly at inland sites. Figure 4 illustrates the proposed PV-powered reverse-osmosis pathway.

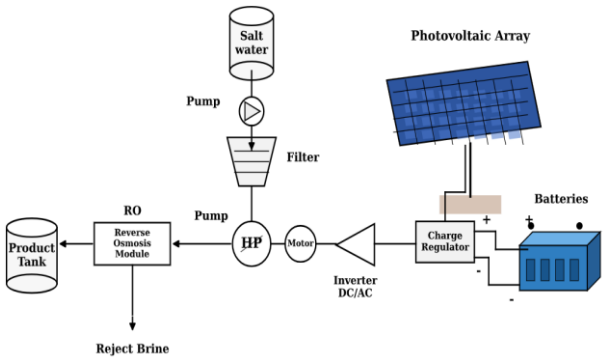


Figure 4 Schematic diagram of a PV-powered reverse-osmosis system. Reproduced from (Tigrine et al., 2016).

Figure 4 indicates that the solar PV panels generate electricity. This electricity flows through the charge regulator to charge the batteries and supply the inverter. The inverter powers the motor and the pump. Salt water is first pumped through a filter. After filtering the high-pressure pump forces the salt water into the RO membrane. Clean water then enters the product tank. The brine that is rejected is discharged.

4.4. PV and chlorination

Chlorination remains one of the most practical disinfection methods for small community water systems. It is effective against a broad range of bacteria and viruses and, importantly, provides a disinfectant residual during storage and distribution. This residual protection is particularly valuable where treated water is stored, transported over long distances or conveyed through distribution systems that may be vulnerable to recontamination. Solar PV systems can support chlorination by powering dosing pumps, mixers, electrochlorination units and residual-chlorine monitoring devices.

Solar-driven electrochlorination is particularly relevant where transport or reliable supply of chlorine chemicals is difficult. In this process, electrical energy is used to generate disinfectant on site from a saline solution. Combining riverbank filtration with solar-powered electrochlorination has demonstrated the potential of decentralized treatment to improve drinking-water safety for river-dependent communities (Otter et al., 2019). Recent research further indicates that single-pass electrochlorination systems can generate disinfectant effectively for remote applications when reactor design, flow conditions, and operational control are appropriately managed (García-López et al., 2024).

Evidence used to characterize PV-powered chlorination is restricted to studies that explicitly couple solar electricity with electrochlorination or dosing (Otter et al., 2019, 2020). Conventional in-line chlorination studies such as (Crider et al., 2018; Pickering et al., 2019) are retained only for operational evidence on residual chlorine, dose acceptability and monitoring; they are not presented as PV-powered installations.

The principal limitations of chlorination include dosing accuracy, chlorine taste, chemical-handling requirements and the potential formation of disinfection by-products when natural organic matter is present. High turbidity can reduce disinfection effectiveness because suspended particles may protect microorganisms, while organic matter increases chlorine demand. Filtration before chlorination is therefore recommended to improve treatment performance. Field trials indicate that low-cost in-line chlorination can improve water quality, provided that residual chlorine is routinely monitored and user acceptance is maintained (Lowe et al., 2026; Pickering et al., 2019).

For rural Tanzania, the combination of PV-powered filtration and chlorination is particularly attractive because of its low energy requirement, relatively low cost, operational simplicity and residual protection during storage. The approach is suitable for community storage tanks, small piped schemes, schools, clinics and village water points. Local operators should be trained to measure residual chlorine, clean filters, inspect dosing pumps and store treatment chemicals safely. Figure 5 presents the proposed PV-powered chlorination pathway.

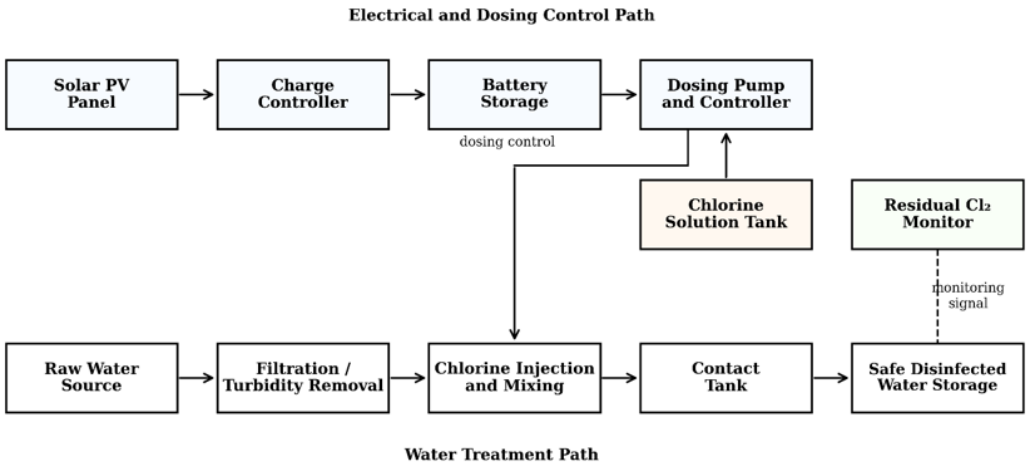


Figure 5 Schematic PV-powered chlorination pathway. Source: Authors' original illustration based on the working principles described in the text.

Figure 5 shows that the solar PV panel generates electricity and sends it to the charge controller. The charge controller manages the power, charges the battery storage and the stored power runs the dosing pump and the controller. Raw water flows through filtration to remove turbidity, then chlorine is mixed with the water and the water remains in the contact tank, for disinfection before going into storage.

4.5. PV and filtration

Filtration frequently constitutes the first treatment barrier in rural water systems. It removes suspended solids, reduces turbidity and sediment, and, depending on the process, can also reduce microorganisms and organic matter. Effective filtration also protects downstream processes: UV disinfection performs more reliably in clear water, chlorination is more efficient when chlorine demand is reduced, RO membranes are less susceptible to fouling after adequate pretreatment, and photocatalytic reactors perform better when light penetration is not limited by suspended particles. Filtration should therefore be considered a core component of an integrated treatment train rather than an optional unit process.

PV can support filtration by powering raw-water pumps, pressure pumps, backwash pumps, flow-control valves, and turbidity-monitoring equipment. Slow-sand and biosand filters can operate with minimal external energy but require appropriate design and routine maintenance. Cartridge filters are simple to install but require periodic replacement, while ultrafiltration can physically remove bacteria and protozoa but requires pressure control, membrane cleaning, and backwashing. Solar-powered ultrafiltration has demonstrated feasibility for rural water supply when system design and maintenance are appropriately managed (Chew & David Ng, 2019). Reviews of solar-assisted membrane treatment similarly confirm its technical potential while identifying fouling and cleaning as persistent operational challenges (Zewdie et al., 2021).

For Tanzania, filtration should be incorporated into most PV-powered water-purification systems. Figure 6 presents a sequence comprising screening, settling, sand or media filtration, cartridge or membrane polishing, and final disinfection. The level of treatment should match local operational capacity: simple media filtration followed by chlorination may be more sustainable for village systems, whereas cartridge filtration combined with UV or chlorination may be suitable for schools and clinics where replacement elements are available. For chemically contaminated groundwater, filtration should function as pretreatment before RO rather than as the final treatment stage.

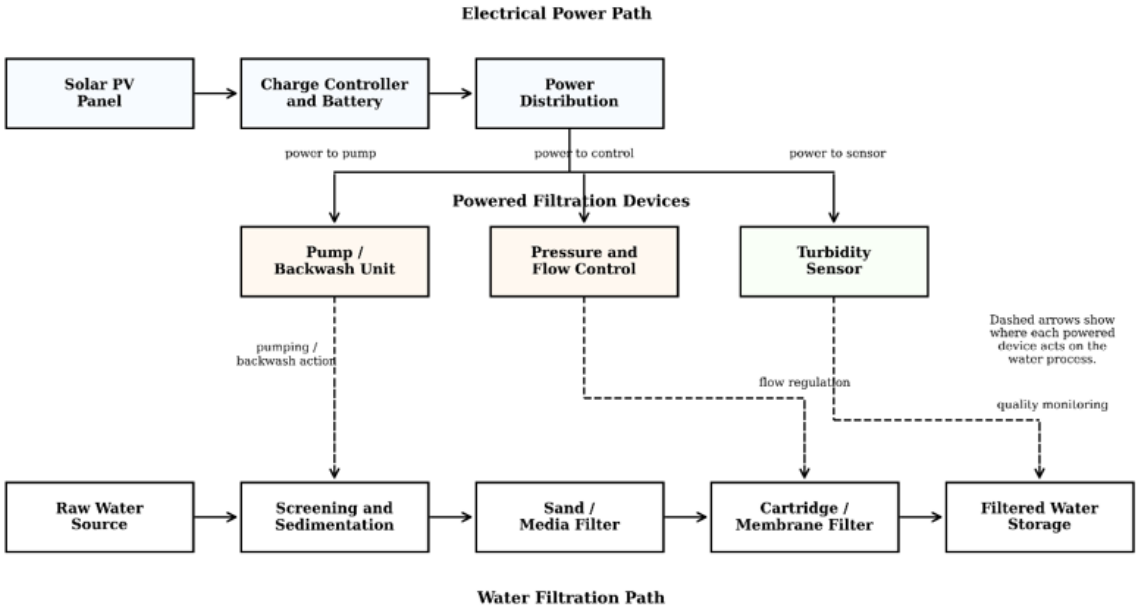


Figure 6 Schematic pathway for PV-powered filtration. Source: Authors' original illustration based on the working principles described in the text.

Figure 6 shows that the solar PV panel generates electricity and sends it to the charge controller and battery. The battery supplies power through the power distribution unit to the pump, flow control, and turbidity sensor. Raw water passes through screening, sedimentation, sand/media filtration, and cartridge/membrane filtration. The sensor checks water clarity before the filtered water enters storage.

4.6. PV and photocatalysis

Photocatalysis is an advanced oxidation process in which a light activated semiconductor produces reactive species capable of degrading organic pollutants and inactivating microorganisms. Titanium dioxide(TiO_2) is the most widely studied photocatalyst because it is chemically stable, relatively low cost, non toxic, and widely available (Armaković et al., 2022). Other photocatalysts and modified materials, including Zinc Oxide(ZnO), Tungsten Oxide(WO_3), Iron Oxide/Hematite(Fe_2O_3), doped TiO_2, and heterojunction materials, are being investigated to improve visible light absorption and pollutant degradation (Yang et al., 2024).

PV can support photocatalytic systems by powering pumps, mixers, UV LEDs, sensors, and control units. Solar photocatalytic filters have demonstrated the possibility of water decontamination using photocatalytic nanocomposites (Horváth et al., 2022). Photocatalytic membrane reactors are also being developed to combine membrane separation with catalytic degradation (Zheng et al., 2017). Immobilization approaches such as 3D printed photocatalytic structures are being studied to reduce catalyst recovery problems (Xue et al., 2023).

Although photocatalysis has substantial potential for advanced water treatment, it is less mature for routine field deployment than filtration, chlorination, UV, or RO. Current limitations include low quantum efficiency, catalyst recovery, reactor scale-up, restricted light penetration in turbid water, catalyst deactivation, and limited long-term field validation. Recent reviews therefore identify photocatalysis as a promising but still developing technology. For rural Tanzania, PV-powered photocatalysis is more appropriately considered for pilot-scale wastewater polishing and research demonstration than as a primary treatment option for village drinking-water supply.

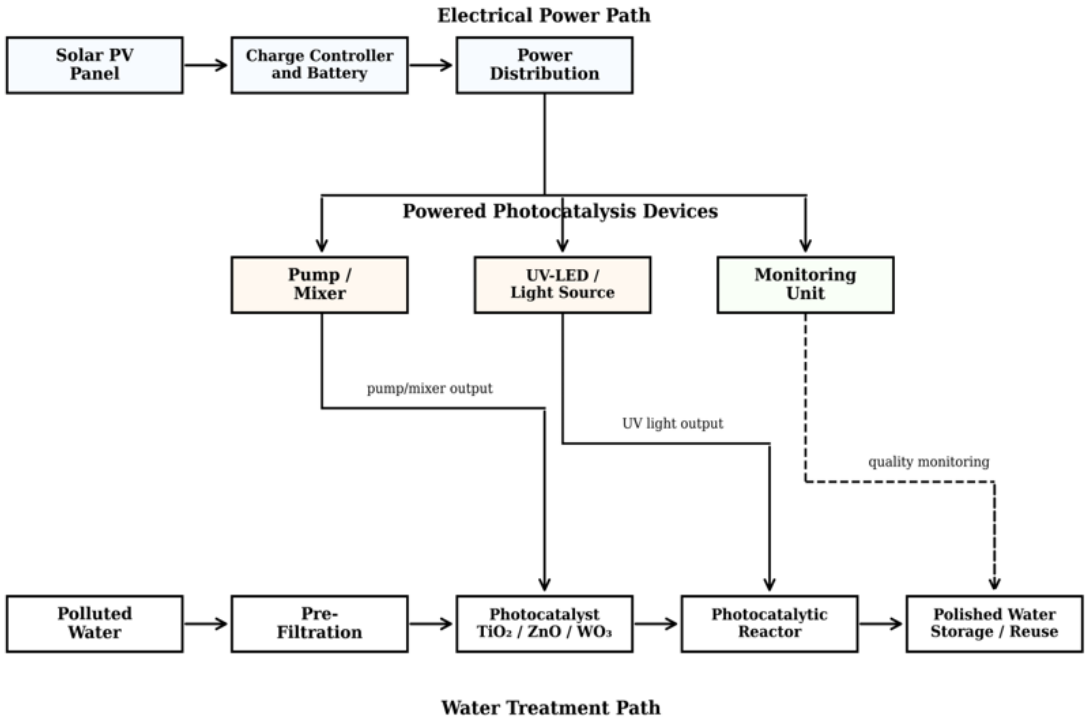


Figure 7 Schematic pathway for PV-powered photocatalysis. Source: Authors' original illustration based on the working principles described in the text.

Figure 8 illustrates the photocatalytic mechanism initiated when UV light or sunlight irradiates the photocatalyst surface. Absorbed photon energy excites an electron from the valence band (VB) to the conduction band (CB), leaving a positive hole in the valence band. The excited conduction-band electron (e^-) can react with dissolved oxygen to form superoxide radicals ($O_2^{\bullet -}$), which participate in the oxidation of adsorbed pollutants such as azo dyes.

At the valence band, the positive hole (h^+) reacts with water or hydroxide ions to form hydroxyl radicals (OH•). These highly reactive oxidizing species attack adsorbed dye molecules and progressively break down their chemical structures. The reactive species shown in Figure 8 ultimately promote mineralization of the pollutants to products such as water, carbon dioxide, and other less harmful inorganic products.

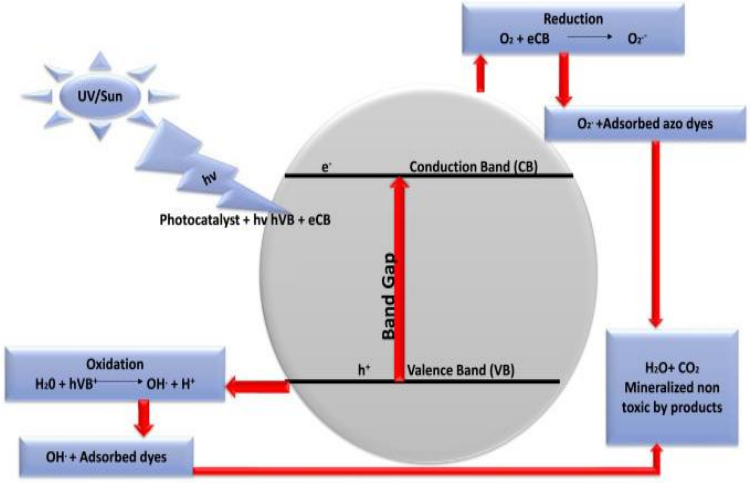


Figure 8 Mechanism of azo-dye degradation in photocatalysis. Adapted from (Oyetade et al., 2022).

Table 5 presents the permissible wastewater discharge limits based on Tanzania Bureau of Standards (TBS) and WHO and Environmental Protection Agency (EPA) guidelines. In this paper, the table is important

because it provides the standard values used to judge whether textile wastewater is safe for discharge after treatment. Parameters such as pH, total dissolved solids (TDS), total suspended solids (TSS), turbidity, color, chemical oxygen demand (COD), biochemical oxygen demand (BOD), ammonia, nitrate and phosphorus indicate the pollution strength of the wastewater. High COD and BOD show strong organic pollution, while high TSS, turbidity and color indicate the presence of suspended solids and dye residues. Therefore, the table acts as a reference for comparing the performance of different treatment systems used in Tanzanian textile industries. The table also uses Tanzania Standard (TZS), dissolved oxygen (DO), percentage dissolved oxygen (%DO), and not available (N/A) as abbreviated terms. If the treated effluent values are higher than these limits, further treatment or process improvement is required before discharge.

Table 5 Parameter limits for wastewater

S/N	Parameter	Unit	TBS (TZS 860:2019)	WHO/EPA
1	pH	–	6.5–8.5	6.5–8.5
2	TDS	mg/L	N/A	2,000
3	Conductivity	µS/cm	N/A	7,000
4	DO	mg/L	N/A	>2.0
5	% DO	%	N/A	N/A
6	Temperature	°C	20–35	≤40
7	Color Pt Co	Pt Co	300	500
8	TSS	mg/L	100	140
9	Turbidity	NTU	300	300
10	NO_3^-	mg/L	20	45
11	Phosphorus (P)	mg/L	6	33
12	PO_4^{3-}	mg/L	N/A	15
13	P_2O_5	mg/L	N/A	N/A
14	NH_3	mg/L	N/A	15
15	NH_3-N	mg/L	N/A	10
16	COD	mg/L	60	150
17	BOD	mg/L	30	60

TBS = Tanzania Bureau of Standards; WHO = World Health Organization; EPA = Environmental Protection Agency; N/A = not available.

4.7. Comparative review matrix

Table 6 summarizes the condensed international evidence supporting the five solar photovoltaic water purification pathways. The table replaces the repeated developed and developing country practice tables by retaining only the evidence needed for technology selection, operation and rural deployment. The abbreviated terms used in the quantitative matrix are ultraviolet-C (UV-C), light-emitting diode (LED), electrical energy per order (E_{EO}), activated filter media (AFM), solar water disinfection (SODIS), carbon nanotube (CNT), polyaniline (PANI), and not reported (NR).

The five PV-water-purification pathways differ substantially in energy demand, pollutant-removal capability, cost, operating complexity, and maintenance requirements. Table 7 therefore evaluates rural suitability as a combined deployment criterion rather than as a measure of removal efficiency alone. Rural suitability reflects whether a system can be operated reliably, maintained using accessible skills and components, monitored routinely, and financed over its service life. Consequently, the most appropriate rural option may be a simple and robust treatment train rather than the most technologically advanced process.

For the qualitative comparison in Table 7, the evidence for each pathway was synthesized using a four-level ordinal scale (low, medium, high, and very high). For energy demand and operating complexity, higher categories indicate greater resource or skill requirements; for rural suitability, higher categories indicate more favorable deployment conditions. Energy demand was classified from the relative electrical requirements for pumping, dosing, irradiation, pressure generation, and auxiliary equipment. Operating complexity was assessed from process-control requirements and operator skill, while maintenance need was evaluated from

cleaning frequency, consumables, component replacement, and specialist servicing. Implementation and operating cost was assessed qualitatively in the pathway discussions and deployment-barrier analysis using reported capital, consumable, replacement, and servicing requirements. Rural suitability integrated energy requirements, operational simplicity, maintainability, spare-part accessibility, and evidence of field deployment. Ratings were assigned by triangulating the literature cited for each pathway and the comparative evidence summarized in Tables 1–6; they should therefore be interpreted as comparative evidence-based judgments rather than absolute numerical scores.

Table 6 Compilation of international evidence supporting solar photovoltaic water-purification pathways

Pathway	Source-water / application	Energy / SEC and quantitative performance	Grid / solar reliability	Operator need	Supply-chain need	Main deployment lesson	Key references
PV and UV	Microbial contamination after turbidity control	UV-C LED electrical energy per order (E_{EO}) for E. coli: ~0.347 kWh/m³ per log reduction at 280 nm and ~0.464 kWh/m³ per log reduction at 260 nm; these are not whole-system SEC values. PV/SODIS household system: 100 Wp PV, ≥37.5 L/day for five people, three (3 h) treatment cycles/day, and ~5–10% PV-energy loss caused by the water reactor.	Requires stable PV/battery supply for electrically powered UV or controlled daylight treatment; adequate UV dose must be maintained.	Medium	Replacement UV lamps/LEDs, pretreatment filters, electrical components and sensors	Use UV after adequate turbidity control. Include solar availability, UV dose and treated-water storage; add residual protection where storage/distribution creates recontamination risk.	(Beck et al., 2017; Moore et al., 2026; Vivar et al., 2020)
PV and RO/NF	Fluoride, salinity, nitrate and other dissolved contaminants	Tanzanian PV-UF/NF field tests reduced fluoride from ~50–60 mg/L to ~1.5 mg/L; production was ~1,200 L per solar day, recovery ~30% at Mdori and ~25% at Ngare Nanyuki, and SEC ~1.5 kWh/m³. Ngare Nanyuki water contained ~255 mg/L TOC. Broader PV/RO evidence reports ~0.5–5.0 kWh_e/m^3, generally <100 m³/day, with reported production costs ~€6.5–15.6/m³.	Variable irradiance changes transmembrane pressure and permeate flow. Water storage and controlled operating windows can improve reliability.	High	NF/RO membranes, UF pretreatment, cartridges, high-pressure pumps, valves, cleaning chemicals and antiscalants	Reserve RO/NF for confirmed dissolved contaminant problems. Include pretreatment, pressure control, membrane cleaning and appropriate concentrate/brine management.	(Okamoto & Lienhard, 2019; Prado de Nicolás et al., 2023; Schäfer et al., 2018)

Pathway	Source-water / application	Energy / SEC and quantitative performance	Grid / solar reliability	Operator need	Supply-chain need	Main deployment lesson	Key references
PV and chlorination / electrochlorination	Microbial risk; community tanks, kiosks and small piped schemes	Solar riverbank-filtration/electrochlorination system: ~0.06 kWh/m³ for pumping/AFM filtration, 0.19 kWh/m³ for inline electrolysis, 0.02 kWh/m³ for auxiliary monitoring, 0.26 kWh/m³ for water treatment and 0.40 kWh/m³ including bank-filtrate pumping; trial volume 1,037 m³. A 2024 single-pass system produced >0.5 mg/L free chlorine under optimized conditions, reaching 3.70 mg/L maximum; minimum SEC was 0.59 Wh/mg free chlorine.	Generally compatible with small PV systems. One reported configuration used ~800 Wp PV + 96 Ah battery and modelled ~22 h/day operation with capacity shortage below ~1%.	Low–medium	Chlorine chemicals or salt, electrodes, dosing/electrochlorination unit, pumps, residual-chlorine test kits and replacement electrical components	Attractive for decentralized systems because energy demand can be low and chlorine provides residual protection. Dose control and residual monitoring remain essential.	(García-López et al., 2024; Otter et al., 2019, 2020)
PV and filtration	Turbid surface water; rainwater; pretreatment for UV, chlorination and RO/NF	Slow-sand filtration evidence reports E. coli reductions of ~1.5–3.7 log10 in field systems and ~2–4.2 log10 in pilot systems; one household-filter study reported ~93% mean reduction. A reviewed rainwater case reported cost savings up to 60%. In the Otter et al. PV system, pumping through the system including AFM filtration required ~0.06 kWh/m³.	Gravity filtration can operate with little or no direct electrical demand; pumped/membrane systems must be matched to available PV. Backwashing can introduce intermittent peak loads.	Low–medium	Sand/media, cartridges, valves, pumps where required and backwash components	Filtration should normally be the first treatment barrier. Simple gravity filtration minimizes electrical demand; membrane/pumped filtration requires closer PV and maintenance planning.	(Maiyo et al., 2023; Otter et al., 2019; Zewdie et al., 2021)

Pathway	Source-water / application	Energy / SEC and quantitative performance	Grid / solar reliability	Operator need	Supply-chain need	Main deployment lesson	Key references
PV and photocatalysis	Advanced wastewater polishing; dyes, pharmaceuticals, pesticides and other organic/emerging contaminants	A sunlight-driven TiO2-nanowire/CNT prototype with 0.3 m² active surface produced ~2 L/day of decontaminated water using sunlight alone; an electrical SEC should therefore not be inferred. PANI-based composite photocatalysts were reported reusable for >4 cycles while maintaining >90% efficiency. Whole-system electrical SEC remains NR for the cited solar prototype.	Performance depends strongly on solar intensity, irradiated surface area, reactor geometry, water turbidity, and light transfer.	High	Photocatalyst, reactor materials, pumps/mixers where required, and analytical monitoring	Promising for advanced polishing, but evidence remains mainly laboratory/prototype scale. Verify field durability, catalyst recovery, transformation products, and lifecycle cost before large rural deployment.	(Horváth et al., 2022; Oyetade et al., 2022; Paiu et al., 2025)

Note: SEC = specific energy consumption; E_{EO} = electrical energy per order; AFM = activated filter media; TOC = total organic carbon; SODIS = Solar Water Disinfection; NR = not reported. Quantitative metrics are not directly comparable where system boundaries, source-water quality or treatment scale differ.

Table 7 Comparative review matrix of PV integrated water purification pathways for rural Tanzania

Treatment pathway	Main pollutants removed	Energy demand	Operating complexity and cost	Maintenance need	Rural suitability	References
PV and UV disinfection	Bacteria, viruses, protozoa	Medium	Medium	Lamp/LED cleaning and replacement	High if turbidity is low or filtration is provided	(Beck et al., 2017; Moore et al., 2026; Vivar et al., 2020)
PV and reverse osmosis	Salts, fluoride, nitrate, heavy metals, pathogens	High	High	Membrane cleaning, pump service, pretreatment, and brine management	Medium: best for dissolved contaminants	(Prado de Nicolás et al., 2023)
PV and chlorination	Bacteria, viruses, residual protection	Low	Low	Chlorine supply, dosing control, residual testing	Very high for community systems	(Otter et al., 2019)
PV and filtration	Turbidity, sediments, suspended solids, and some microbes	Medium	Medium	Filter cleaning or replacement	Very high as pretreatment and stand alone clarification	(Maiyo et al., 2023)
PV and photocatalysis	Organic pollutants, dyes, some microbes, and emerging contaminants	Medium	High	Catalyst/reactor cleaning and process control	Medium for pilot wastewater polishing	(Oyetade et al., 2022)

5. Illustrative Application to the Kalobe Waste Stabilization Ponds in Mbeya, Tanzania

The Kalobe Waste Stabilization Ponds are used in this review as an illustrative secondary-data application rather than as a primary field case study. No new site sampling, flow measurement, treatment-performance testing, or energy monitoring was undertaken by the present authors. Published studies identify Kalobe as a

municipal wastewater-treatment facility in Mbeya, Tanzania, receiving mixed wastewater and designed for approximately 28,800 m³/day, while the reported operating flow is below the design capacity (Gerson et al., 2025a, 2025b). The published evidence is therefore used to evaluate conceptually where PV-powered monitoring, filtration, disinfection and polishing could complement the existing pond system.

Waste stabilization ponds are widely used for wastewater treatment in warm climates because of their comparatively simple operation and low external-energy requirements. Nevertheless, additional polishing may be required before treated effluent can be reused or discharged safely. Pond performance is influenced by hydraulic conditions, short-circuiting, sludge accumulation, seasonal variability, organic loading, operational management and influent characteristics. At Kalobe, the contribution of industrial wastewater is particularly relevant because it can alter organic loading, nutrient concentrations, pH, and other physicochemical characteristics of the influent (Gerson et al., 2025a, 2025b).

PV-powered treatment at the Kalobe Waste Stabilization Ponds should therefore be considered an incremental polishing and monitoring intervention rather than a replacement for the existing pond system. PV electricity could support water-quality instrumentation for pH, turbidity, electrical conductivity, flow and temperature, while low-energy filtration could reduce suspended solids and improve downstream disinfection. UV irradiation or chlorination could then provide microbial control. PV systems can supply pumps, sensors, UV units and dosing equipment with reduced dependence on unreliable grid electricity (Otter et al., 2020; Vivar et al., 2024; Zewdie et al., 2021). Photocatalysis could be evaluated as a pilot polishing process for color, organic pollutants and emerging contaminants; however, catalyst recovery, light penetration and reactor scale-up remain important constraints (Oyetade et al., 2022; Paiu et al., 2025). Reverse osmosis should be reserved for limited-volume applications where dissolved contaminants are confirmed because it requires substantial pretreatment, pressure control, membrane maintenance and appropriate concentrate management (Okamoto & Lienhard, 2019; Prado de Nicolás et al., 2023).

The proposed Kalobe PV-assisted polishing train can therefore consist of pond effluent → settling/equalization → filtration → UV disinfection or chlorination → water-quality monitoring → reuse or controlled discharge. This approach emphasizes improvement, manageable energy requirements and continuous verification of treatment performance. It could support non-potable reuse applications, including irrigation and cleaning or improve the quality of effluent discharged to the environment provided the required water-quality standards are achieved. Such an integrated approach could also serve as a demonstration model, for peri-urban Tanzania by showing how PV-powered monitoring, filtration and disinfection can strengthen wastewater-treatment reliability without requiring extensive centralized electricity infrastructure. (Okamoto & Lienhard, 2019; Reyneke et al., 2023; Vivar et al., 2024).

6. Deployment Barriers

International evidence from decentralized water-treatment and UV-disinfection projects shows that deployment barriers are not unique to Tanzania. Similar systems in Africa, Asia, Latin America, Europe, and North America encounter recurring constraints related to financing, spare-part availability, operator training, water-quality monitoring, user acceptance, and technology mismatch. Although PV-powered water-treatment systems can achieve strong technical performance, long-term sustainability depends on viable financing and service models, maintenance systems, local supply chains, monitoring arrangements, and clearly assigned institutional ownership (Moore et al., 2026; Reyneke et al., 2023; Vivar et al., 2024).

6.1. Capital cost and financing

Capital cost remains a major barrier to PV-powered water purification because investment extends beyond PV modules to batteries, pumps, membranes, UV lamps, dosing equipment, tanks, sensors, spare parts, installation and routine servicing. International decentralized UV projects demonstrate that technically functional systems may fail or operate intermittently when financing covers installation but not replacement lamps, battery renewal, monitoring and operator support. Membrane and desalination systems additionally

require pressure pumps, pretreatment, membrane replacement and brine management. PV-powered water-treatment projects should therefore be evaluated using life-cycle cost rather than purchase price alone, with financing provisions for consumables, maintenance contracts, water-quality testing and operator support (Moore et al., 2026; Prado de Nicolás et al., 2023; Reyneke et al., 2023).

6.2. Spare parts and supply chains

International evidence shows that weak spare-part availability and unreliable supply chains can cause prolonged system downtime. UV installations have experienced lamp failures, power surges and limited access to replacement components, while membrane systems depend on periodic replacement of RO/NF membranes, cartridge filters, pressure pumps and sensors. Technology selection should therefore prioritize components that can be sourced or serviced locally, including standardized pipe fittings, modular pumps, simple filtration units, protected electrical enclosures and clearly defined maintenance arrangements before more advanced systems are adopted (Moore et al., 2026; Schäfer et al., 2018; Zewdie et al., 2021).

6.3. Technical training and operation

International experience demonstrates that operator training is as important as technology selection. Decentralized UV projects in schools, households, healthcare facilities and community systems have encountered staff turnover, irregular maintenance, limited testing capacity and insufficient understanding of UV operation. Operators should therefore be trained in PV-system operation and water-treatment management, including module cleaning, battery safety, charge-controller inspection, pump protection, filter cleaning, UV lamp and quartz-sleeve maintenance, membrane flushing, chlorine dosing, residual-chlorine measurement, turbidity monitoring and record keeping. For Tanzania, training should be supported by practical local-language manuals, routine inspection forms, refresher training and clearly assigned responsibility for fault reporting (Afitiri & Afrifa, 2025; Elevli et al., 2016; Moore et al., 2026).

6.4. Water quality monitoring

Water-quality monitoring is essential because equipment operation alone does not demonstrate treatment safety. UV systems require control of turbidity and UV transmittance because particles and natural organic matter can reduce disinfection effectiveness. Treated water may also become recontaminated during storage when no residual disinfectant is present. Drinking-water systems should therefore monitor turbidity, pH, electrical conductivity, microbial indicators and free residual chlorine where chlorination is used. Groundwater systems should additionally monitor locally relevant dissolved contaminants such as fluoride, nitrate, salinity, iron and manganese. Wastewater systems such as Kalobe should monitor BOD, COD, TSS, nutrients, microbial indicators and relevant chemical contaminants because mixed domestic and industrial influent can vary substantially over time (Makuei & Peleato, 2023; Moore et al., 2026; Reyneke et al., 2023).

Table 8 shows the drinking water and wastewater monitoring parameters that matter most for rural solar photovoltaic water purification systems.

6.5. Institutional ownership and community acceptance

International evidence shows that institutional ownership and community acceptance strongly influence whether decentralized treatment systems remain functional after installation. Experience from UV and chlorination projects demonstrates that sustained use depends on community trust, trained local operators, clear maintenance responsibility, safe-storage practices, and acceptance of treated-water characteristics such as chlorine taste. A PV-powered water system should therefore be supported by an accountable institution or water committee responsible for fee collection, consumable procurement, technician engagement, maintenance records, filter replacement, pump repair, and routine water-quality testing. Community engagement and clear allocation of responsibilities among local government, utilities, schools, health facilities, water committees, and service providers should be established before commissioning (Afitiri & Afrifa, 2025; Crider et al., 2018; Moore et al., 2026).

Table 8 Key water quality parameters essential for monitoring treated potable water and wastewater polishing

S/N	Parameter	Unit	Indicative value or monitoring guidance	Relevance to PV-water treatment
1	Turbidity	NTU	TBS ≤5; ultraviolet disinfection performs better at low turbidity	Controls filtration need and ultraviolet effectiveness
2	pH	–	TBS 6.5-8.5; chlorination preferably below pH 8	Affects chlorine performance, corrosion and acceptability
3	Electrical conductivity	µS/cm	TBS ≤1500	Indicates salinity and possible membrane treatment need
4	Total dissolved solids	mg/L	TBS ≤1000; WHO palatability concern increases above 1000	Supports reverse osmosis or nanofiltration selection
5	Fluoride	mg/L	WHO/TBS ≤1.5	Key dissolved contaminant for Tanzanian groundwater
6	Nitrate	mg/L	WHO ≤50; TBS ≤45	Indicates agricultural or sanitation related chemical risk
7	Free residual chlorine	mg/L	TBS 0.2-0.5; WHO commonly requires residual at delivery	Confirms residual protection after chlorination
8	E. coli or thermotolerant coliforms	CFU/100 mL	0 or absent in 100 mL	Primary indicator of microbial safety
9	Total coliform bacteria	CFU/100 mL	TBS absent	Operational indicator for treatment and storage contamination
10	Total suspended solids	mg/L	Wastewater discharge monitoring parameter	Indicates filtration and pond polishing performance
11	Biochemical oxygen demand	mg/L	Wastewater organic pollution indicator	Shows biodegradable organic load before discharge or reuse
12	Chemical oxygen demand	mg/L	Wastewater organic pollution indicator	Shows total oxidizable pollution in wastewater polishing

6.6. Technology mismatch

Technology mismatch occurs when advanced treatment systems are deployed without adequate consideration of source-water quality, local technical capacity or long-term maintenance requirements. RO is appropriate for dissolved contaminants such as salinity, fluoride and nitrate but may be unnecessarily costly where microbial contamination is the principal risk. UV can provide effective pathogen inactivation but performs poorly when turbidity is high and provides no residual protection during storage. Photocatalysis has potential for degrading dyes, organic pollutants and emerging contaminants, but catalyst recovery, reactor scale-up, by-product verification and long-term field performance remain important challenges. Technology selection should therefore begin with source-water characterization, followed by treatment selection based on measured risks, local pilot testing, operator training and confirmation that spare parts and monitoring tools are available before wider deployment (Loeb et al., 2018; Moore et al., 2026; Okamoto & Lienhard, 2019; Paiu et al., 2025).

7. Recommended Technology Combinations

International experience indicates that an effective PV-powered water-purification system is usually a treatment train rather than a single technology. The appropriate sequence depends on the dominant contaminant, available energy, operator capability and post-treatment storage conditions. Filtration commonly provides the first barrier because it reduces turbidity, protects downstream processes and improves the performance of UV, chlorination, reverse osmosis and photocatalytic treatment (Maiyo et al., 2023; Zewdie et al., 2021). Recommended combinations should therefore be prioritized according to reliability, maintainability and verifiable treatment performance rather than laboratory efficiency alone.

The first recommended pathway is PV-powered filtration followed by chlorination. Filtration reduces suspended matter and chlorine demand, while chlorination provides residual protection during storage and distribution. International evidence shows that low-energy chlorination can improve drinking-water safety

when dosing is controlled, residual chlorine is monitored, user acceptance is considered and local management is maintained (García-López et al., 2024; Otter et al., 2019; Pickering et al., 2019). In Tanzania, this pathway is suitable for community storage tanks, schools, clinics, village water points and small piped systems where treated water may be stored or transported.

The second recommended pathway is PV-powered filtration followed by UV disinfection. International case studies from Tanzania, Kenya, Rwanda, India, the Philippines, and Mexico show that decentralized UV systems can improve microbial water quality in schools, households, health facilities, and community schemes, particularly when turbidity is controlled through sedimentation, sand filtration, biosand filtration, biochar filtration, cartridge filtration, or roughing filtration (Beck et al., 2017; Moore et al., 2026; Song et al., 2016). This pathway is most appropriate where treated water is consumed close to the treatment point. Where water is transported, stored for extended periods, or distributed through pipelines, safe-storage measures or low-dose chlorination should be incorporated to reduce the risk of recontamination.

The third recommended pathway combines PV-powered pretreatment, RO or NF, and post-disinfection. This configuration should be reserved for locations where water-quality testing confirms dissolved contaminants such as fluoride, salinity, nitrate, heavy metals, or other chemical pollutants. Evidence from Tanzania and international desalination studies shows that renewable-energy-powered membrane systems can produce high-quality water but require effective pretreatment, pressure control, membrane cleaning, cartridge replacement, trained operators, and appropriate brine management (Okamoto & Lienhard, 2019; Prado de Nicolás et al., 2023; Schäfer et al., 2018; Shen et al., 2016). RO or NF should therefore not be adopted as a default treatment option where the principal risk is microbial contamination.

The fourth recommended pathway is PV-powered filtration followed by photocatalytic polishing. International studies demonstrate the potential of photocatalysis for degrading dyes, organic pollutants, and emerging contaminants, but field deployment remains constrained by catalyst recovery, limited light penetration, reactor scale-up, by-product verification, and the need for long-term performance monitoring (Loeb et al., 2018; Oyetade et al., 2022; Paiu et al., 2025). At the Kalobe Waste Stabilization Ponds, this pathway is most appropriately considered as a pilot polishing step after settling and filtration, while final pathogen control should continue to rely on validated UV treatment or chlorination supported by routine monitoring.

Overall, rural PV-water systems should follow a stepwise decision process: characterize the raw water, reduce turbidity where necessary, select treatment according to the measured contaminant risk, provide residual protection where storage or distribution creates a recontamination risk, and budget for monitoring, spare parts, and maintenance before installation. For Tanzania, the most practical near-term pathways are PV-powered monitoring, filtration, and chlorination; PV-powered filtration and UV for point-of-use or controlled-storage applications; PV-powered RO or NF for confirmed dissolved contaminants; and PV-powered photocatalysis primarily for research and advanced wastewater polishing. This sequence is formalized in Figure 9 as a decision framework that explicitly includes the deployment critical variables of source-water type, energy/SEC, grid and solar reliability, operator availability, supply-chain access and lifecycle maintenance. In the framework, installed PV capacity is expressed in kilowatt-peak (kWp), while capital expenditure (CAPEX) and operating expenditure (OPEX) denote lifecycle cost components.

7.1. Limitations of the review

This review has several limitations. First, Scopus and Web of Science were evaluated as potential additional sources, but full document-level institutional access and reproducible export were unavailable to the authors during the literature search; consequently, the reproducible search was limited to ScienceDirect and Google Scholar, supplemented by cross-publisher discovery, backward citation searching, publisher-site verification and Tanzanian institutional sources. Some indexed studies may therefore have been missed. Second, Google Scholar reports approximate relevance-ranked hit counts, and the original search log did not preserve a fully exportable record-level Google Scholar dataset or prospectively recorded intermediate screening counts. For

transparent reporting, the archived ScienceDirect and Google Scholar search material was reconciled retrospectively at title and bibliographic-record level to reconstruct the PRISMA sequence. The intermediate PRISMA counts should therefore be interpreted as a retrospective audit reconstruction rather than prospectively logged screening statistics. Third, the reviewed studies are heterogeneous in source-water quality, treatment capacity, PV configuration, climate, operating pressure and energy-accounting boundaries, which limits direct comparison of SEC values. Fourth, long-term field evidence from rural Tanzania is limited relative to laboratory, pilot and international studies. Finally, rainfall, source-water quality and solar resource vary spatially and seasonally across Tanzania, so the proposed technology-selection framework requires site-specific validation before deployment.

7.2. Proposed decision framework for PV-powered water-treatment selection in rural Tanzania

Figure 9 presents a seven-stage decision framework for selecting solar photovoltaic (PV)-powered water-treatment systems suited to rural Tanzania. First, source water is characterized to identify microbial contamination, turbidity, dissolved constituents and organic pollutants. Second, appropriate treatment barriers are selected: filtration for particle removal and pretreatment, chlorination or ultraviolet disinfection for microbial control, reverse osmosis or nanofiltration for dissolved contaminants, and photocatalysis for advanced polishing. Third, daily water demand, treatment flow, specific energy consumption (SEC, kWh/m³) and peak electrical load are estimated to define operational requirements. Fourth, these requirements are matched with site-specific solar resources, including wet-season availability, PV capacity, water or battery storage, and backup supply where needed.

The fifth stage assesses grid reliability, operator skills, monitoring capacity and institutional responsibility. The sixth evaluates access to consumables, replacement components, maintenance services and lifecycle costs. Finally, the lowest-complexity configuration capable of meeting water-quality targets is selected, piloted and rigorously verified before expansion. This integrated approach avoids selecting technologies solely on treatment efficiency and instead considers energy reliability, affordability and long-term sustainable operation. For the Kalobe Waste Stabilization Ponds in Mbeya, the framework offers a basis for assessing PV-supported monitoring, filtration and final disinfection; site-specific testing and validation remain essential before implementation.

8. Conclusions

This review demonstrates that integrating solar PV with water-treatment processes can provide a practical decentralized option for rural Tanzanian communities affected by unsafe water and unreliable electricity supply. PV electricity can support pumps, filters, UV systems, dosing devices, membrane processes and water-quality monitoring equipment. However, successful implementation depends on selecting treatment stages according to the measured source-water problem and local operational capacity rather than on technological novelty alone.

The main finding is that PV-powered filtration combined with chlorination is the most scalable near-term option for many rural communities because of its low energy demand, manageable operation, local adaptability, and residual protection during storage and distribution. PV-powered filtration combined with UV is also suitable for schools, clinics, kiosks, and point-of-use systems where turbidity is controlled and treated water is consumed close to the treatment point. PV-powered RO or NF is technically effective for fluoride, salinity, nitrate, and heavy metals, but requires pretreatment, skilled operation, membrane replacement, and brine management. PV-assisted photocatalysis is promising for wastewater polishing, particularly for dyes and organic pollutants, but should initially be implemented through carefully monitored pilot systems.

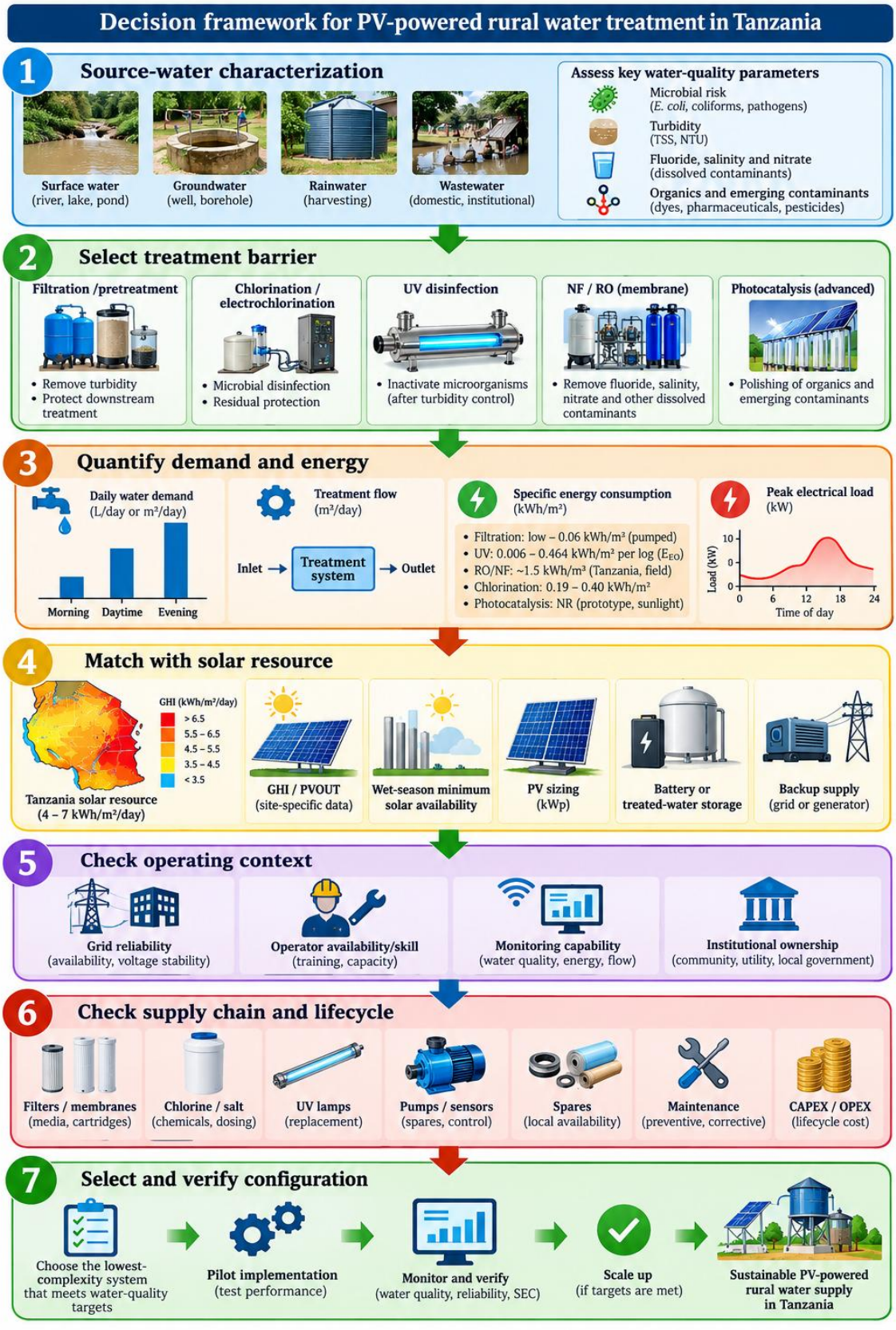


Figure 9 Decision framework for selecting PV-powered water-treatment configurations for rural Tanzania. Source: Authors' original synthesis based on the reviewed evidence.

The principal contribution of this review is a decision framework for matching PV-powered treatment technologies with contaminant type, energy demand, operating complexity, maintenance capacity, and rural deployment conditions. By linking international evidence with the Kalobe Waste Stabilization Ponds context in Mbeya, the review illustrates how Tanzania could progress from isolated technology demonstrations toward sustainable water-service delivery. For Kalobe and similar systems, a realistic pathway is incremental improvement through PV-powered monitoring, filtration, UV disinfection or chlorination, and safe reuse or controlled discharge. Long-term effectiveness will depend on life-cycle financing, reliable spare-part supply chains, trained operators, routine water-quality verification, clear institutional ownership, and community acceptance.

9. Recommendations

For deployment of PV-powered water purification in rural Tanzania, site-specific water-quality characterization should be the first step. Each community should identify the dominant risk, whether microbial contamination, turbidity, salinity, fluoride, nitrate, metals, organic pollutants or wastewater-derived contamination. This assessment enables selection of a treatment pathway that is technically appropriate, economically justified, and maintainable over the intended service life.

For many rural applications, PV-powered filtration followed by chlorination represents the most immediately deployable option. Filtration removes suspended particles and reduces disinfectant demand, while chlorination provides residual protection during storage and distribution. This combination is particularly suitable for villages, schools, health facilities and small water-supply schemes because it has relatively low energy requirements, is operationally straightforward and can provide continuing microbial protection when properly managed.

Where non-chemical disinfection is preferred, PV-powered filtration combined with ultraviolet disinfection should be applied only when turbidity is adequately controlled and treated water is consumed close to the treatment point. UV systems should include pretreatment, protected electrical components, lamp-status indicators, routine cleaning, spare lamps, and trained operators. Where treated water is stored for extended periods, low-dose chlorination or rigorous safe-storage practices should be added. Reverse osmosis should be reserved for sites with confirmed dissolved contaminants such as fluoride, salinity, nitrate, arsenic, or heavy metals. It should not be installed where microbial contamination is the principal problem because RO is comparatively energy-intensive, costly, and maintenance-demanding. Any RO project should include pretreatment, membrane-replacement planning, pressure control, trained operators, and safe concentrate disposal.

For the Kalobe Waste Stabilization Ponds, improvement should proceed incrementally rather than through complete replacement of the existing treatment system. Priority measures include PV-powered water-quality monitoring, low-energy filtration, final disinfection, and controlled reuse where applicable. PV-powered photocatalysis should be evaluated only as a pilot polishing process after filtration to determine its effectiveness for color, organic pollutants, and emerging contaminants under local operating conditions.

Every PV-powered water project should include a long-term sustainability plan covering financing, spare-part procurement, operator training, routine water-quality monitoring, tariff or service-fee collection, community engagement, and institutional responsibility. Without these supporting arrangements, technically effective treatment units may become unreliable or non-functional after installation.

Declaration of Ethical Standards

This review involved no human participants, animals, biological samples, personal data, or field interventions. The analysis was based exclusively on published literature, standards, reports, and other secondary sources; therefore, ethical approval was not required. All sources used in the review are appropriately cited.

Credit Authorship Contribution Statement

Gerald Kasase Rukanda contributed to conceptualization, literature review, analysis, drafting, tables, figures and manuscript revision.

Arthur Mngoma Omari contributed to supervision, technical guidance, validation, critical review and final editing. Both authors approved the final manuscript.

Declaration of Competing Interest

The authors declared that they have no conflict of interest.

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Data Availability

No new data were generated. All information used in this review was obtained from published articles, standards, reports and cited sources. The schematic block diagrams developed for this manuscript were prepared by the authors from the described working principles; where a figure is based on a published source, the source is acknowledged in the corresponding caption.

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Appendix

Table 9 Results of search terms from the databases of ScienceDirect and Google Scholar

Search string	**All access**	
	ScienceDirect	**Google scholar**
("solar photovoltaic" OR "solar PV" OR "PV-powered") AND ("water purification" OR "water treatment") AND (rural OR Tanzania)	735	959
("solar-powered" OR "PV-powered") AND ("UV disinfection" OR chlorination OR electrochlorination) AND ("drinking water" OR rural)	380	650
("solar photovoltaic" OR "solar-powered") AND ("reverse osmosis" OR nanofiltration OR "membrane filtration") AND (rural OR Tanzania)	943	796
("solar-powered" OR "PV-powered") AND (filtration OR photocatalysis) AND ("water treatment" OR wastewater) AND (rural OR Tanzania)	536	995
Total	2594	3400
Total of both	5994	