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Review

Feasibility of Accessing Safe Water in Developing Countries Using Photocatalytic Technology—A Review

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ABSTRACT: Access to clean drinking water is a global concern. Notably, over one billion people in developing countries out of a total global population of approximately eight billion encounter challenges in accessing safe water. Photocatalytic technology is a potential solution for providing safe drinking water to these communities. However, only a few photocatalytic technologies are currently available. Although the potentialities of the photocatalytic treatment of water pollutants can be demonstrated in the laboratory, several factors hinder its effectiveness in real environmental applications. Additionally, the development of maintenance-free photocatalytic systems that can operate continuously without requiring complex maintenance is limited. Developing countries are unlikely to implement a system if it cannot be used sustainably without complex and/or frequent adjustments, regardless of the advanced technology. This principle is the fundamental premise of this review. This review in which are discusses the conditions necessary for photocatalytic water purification systems to be accepted in developing countries and explores how these systems can be successfully implemented.

Keywords: Photocatalyst; Drinking water; Water purification; Developing country; Water Matrix; Photocatalytic system

1. Introduction

The global challenge of ensuring access to potable water has been a persistent topic of international discussion, with initiatives focused on addressing it in an expedient manner. Water-related challenges have been addressed in the Millennium Development Goals (MDGs) and remain a priority in the Sustainable Development Goals (SDGs). As a result, the number of people without access to safe water has gradually decreased [1,2]. However, according to UN reports and various other sources, although figures vary slightly, approximately one billion people worldwide still lack access to safe drinking water [3]. A notable concern is the provision of drinking water in rural areas, where >75% of the population lacks access to safe drinking water and basic sanitation, as reported by the World Health Organization (WHO) and other sources [3–6]. In contrast, access to safe water in urban areas is relatively better, primarily because of the wider availability of water supply infrastructure and the lower economic stress associated with purchasing purified water. In rural areas, however, access to safe water is expected to remain limited because of the high costs associated with building water supply infrastructure and the expenses involved in purifying and treating drinking water at the household level. An evident correlation exists between income level and access to safe water [7]. Because access to safe drinking water is closely linked to the prevalence of diseases [8–11], addressing water issues is a critical first step toward improving public health in both developed and developing countries.

Notably, developing countries facing significant water problems are concentrated in low-latitude regions, as presented in various UN reports. Low-latitude regions (often referred to as the Sun Belt [12]) are characterized by high solar intensity and naturally increased average annual temperatures. These environmental conditions are ideal for bacterial growth, which contributes to the presence of disease-causing bacteria in drinking water in these areas [4,13–26]. The ideal solution to the water problem is to eliminate these bacteria using sunlight, which is a readily available and representative renewable energy source.

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Several methods exist for utilizing solar energy in water treatment. 1. Solar thermal treatment: This method uses solar heat to increase the water temperature above sterilization levels or to vaporize and distill water, thereby producing purified water [27–36]: 2. Solar disinfection (SODIS): This approach relies on the direct use of ultraviolet (UV) light from sunlight to disinfect water [37–42]. 3. Secondary solar applications: Solar energy is converted into electricity via solar panels to power devices such as pumps, valves, or germicidal lights used in water treatment systems [30,34,36,41]. 4. Photocatalytic purification: Sunlight is used to activate the photocatalysts that degrade water contaminants. These include bacteria and viruses found in drinking water [43–72], waterborne pathogens [73–80], and chemical pollutants [81–86]. This review focuses on this form of water purification. These possibilities are not entirely independent; combinations of these technologies are frequently used.

Currently, several promising methods are available to ensure safe access to water in developing countries, particularly for addressing bacterial contamination. Table 1 outlines the typical water treatment methods (with a focus on disinfection), including photocatalysis, and presents the advantages and disadvantages of each technique.

Table 1. Passive means of drinking water purification that can be used in developing countries.

Method	**Details**	**Advantage**	**Disadvantage**	**References**
Sachet water	Purified or treated drinking water that's packaged in small (around 500 mL), sealed plastic bags	Affordability Convenience	Low quality Short shelf life Plastic waste (lack of recycling system)	[87–94]
Bottled Water	Typically, it is drinking water filled in PET bottles, but also includes that filled in returnable bottles.	Reliability for bottled water Convenience Long shelf life	Differences in quality control by operators Costly Resources-intensive Plastic waste	[95–100]
Sodium hypochlorite	Water disinfection with sodium hypochlorite	Strong bactericidal power Residual effect Fast-acting Cost performance	Disinfectant smell Taste Generation of byproducts Chemical handling risk	[101–108]
Rainwater	Collect rainwater and use it for drinking purposes	Easy and safe access to water in rainy regions	Weather-dependent Water quality instability Pollution risk during storage	[109–113]
Filtration (advanced)	Filter for settlement (Slow sand filter, *etc.*)	Continuous processing low operating costs High physical filtration capacity Low environmental impact	Initial cost Running cost Upkeep of maintenance	[114–116]
Filtration (simple)	Filter for personal use (Membrane filter (MF), ceramic, charcoal, & sand filter, *etc.*)	Simplicity	Initial cost (MF) Running cost (MF) Short lifetime (MF) Limitation of performance (ceramic, charcoal, & sand filter)	[117–122]
Boiling	Boiling	Simplicity (the most fundamental sterilization method)	Time-consuming (boiling and cooling) Troublesome Problem of fuel	[123–126]
Solar energy				
Thermal	Sterilization by solar thermal	Low running cost Durability	Weather-dependent Time-consuming Ineffective against chemical contamination Initial cost	[27–36]
SODIS	Sterilization by solar thermal & UV in sunlight	Simplicity Totally low cost	Weather-dependent Time-consuming	[37–42]

			Ineffective against chemical contamination	
Photocatalyst	Photocatalytic sterilization	Low running cost Durability	Weather-dependent Initial cost	[43–72]

The WHO Organization’s Evaluation of Household Water Treatment Options [127] provides a comprehensive description of the extent to which the treatment methods listed in Table 1 should achieve water purification. Notably, photocatalytic drinking water purification is excluded, as it remains in the research phase. A key advantage of solar energy technology over other methods is that it does not incur ongoing operating costs. In developing countries, this “no-cost” factor is particularly important for technologies that require continuous use, such as water purification, as well as for other essential services. When focusing on ensuring access to safe water, the introduction of such technologies is often based on public or private aid for economic reasons. However, in this case, users have little or no knowledge of the water purification technology being installed, and even if they do, subsequent maintenance is likely not to be performed for economic reasons. Numerous water purification projects have failed for these reasons [128–134]. Therefore, when introducing water purification technology to developing countries, particularly in rural areas, the key factors for ensuring the technology’s sustainability are, at a minimum, ease of maintenance by users and minimal or no economic burden. Photocatalytic drinking water purification can function continuously with sunlight, making it a viable technology for use in developing countries. For drinking water purification in developing countries, the combination of the SODIS method with photocatalysis may be the most feasible method when considering access to safe water [57,58,71,135–137]. However, the SODIS method has a non-technical problem; some individuals might refrain from using SODIS because its use would be perceived as a sign of poverty [138], and researchers and technicians may lack this perspective. Therefore, another factor to consider is that it allows users to purify water with a sense of superiority rather than inferiority. Therefore, recognizing the need for water purification methods that can be used by the poor while maintaining user pride is necessary.

In this review, we highlight some of the challenges associated with photocatalytic water purification, particularly in the treatment of bacterial contamination, and explore potential solutions for these issues. This review aims to contribute to the development of sustainable water purification technologies for communities facing difficulties in accessing safe water.

2. What Are the Reasons for the Lack of Practical Implementation of Photocatalytic Water Purification?

Photocatalysis began with the discovery of the photocatalytic water-splitting reaction by Honda and Fujishima at the University of Tokyo in 1971. Environmental purification using photocatalysts is generally considered an advanced oxidation technology (AOT), and the reaction process is referred to as the accelerated oxidation process (AOP). This process decomposes organic pollutants through oxidation (the reaction mechanism of photocatalysis has been extensively detailed in numerous literature and books). Photocatalytic materials based on this reaction have transitioned from research to commercialization in fields such as air purification and self-cleaning technologies [139–143]. Photocatalytic water purification technologies have been investigated since the inception of photocatalytic reactions. However, despite the substantial body of academic research on this topic, the practical applications of photocatalytic water purification are limited compared with those of the other two technologies.

Industrialized countries encounter a considerable demand for sewage treatment, which has led to extensive research on the photocatalytic treatment of sewage since the inception of photocatalytic water purification research. However, considering material balance, treating sewage with high pollutant concentrations requires large amounts of energy, which is difficult to achieve with the low excitation light intensity provided by sunlight. Additionally, although photocatalysis is an AOP, the amount of dissolved oxygen in water is extremely limited (approximately 10 mg-O_2/L) at room temperature [144]. To treat sewage, aeration is required to compensate for the oxygen deficit, which requires electricity to power the aeration system.

Moreover, unlike air, water contains various dissolved substances that can inhibit photocatalytic activity. Notably, only approximately 0.2% of AOP wastewater treatment studies have examined the effect of the water matrix on treatment efficacy [145]. Even fewer studies have investigated how the composition of the water matrix affects the photocatalytic performance. Some studies have addressed the difference in photocatalytic activity between ultrapure and environmental water (including tap water), but very few have focused specifically on the ions that influence photocatalytic activity.

Additionally, studies on photocatalytic materials that can maintain their effectiveness in water for extended periods are limited. These unfavorable conditions explain why photocatalytic water purification is not widely applicable, particularly for drinking water.

Groundwater can contain several harmful substances, including inorganic compounds such as heavy metal ions, organic compounds such as pesticides, and various bacteria and viruses. Photocatalysis primarily targets organic substances, such as pesticides, bacteria, and viruses, as photocatalytic water treatment is an AOP, as described above [139,146–149]. Groundwater is often in reducing environments, and arsenic (a well-known contaminant in groundwater) typically exists in a highly toxic trivalent (As^{3+}) state [150]. Although As^{3+} can be oxidized to its less toxic pentavalent (As^{5+}) form through photocatalysis [151–155]. However, this process only changes the valence state of arsenic and does not remove it from the water matrix. Therefore, this review does not discuss the treatment of inorganic substances.

Photocatalysis may also be a solution to the contamination of drinking water by pesticides. Most pesticides used in agriculture permeate the soil and enter groundwater or can contaminate drinking water tanks through aerosols [156–159] (Figure 1 shows an example of a receiving water tank for drinking water installed adjacent to a farm). However, high pesticide concentrations are rare in water sources. Therefore, unlike the treatment of highly concentrated contaminants, such as sewage, it is feasible to treat trace amounts of pesticides in drinking water using photocatalysis, even with challenges related to dissolved oxygen and sunlight intensity, from a material balance perspective.

Figure 1. An example of a common water tank observed in many regions worldwide (a receiving water tank installed adjacent to a sugarcane farm (**Left**) and a rice field (**Right**) in Hòa-Binh Province, Vietnam) (Photo: Negishi).

3. Water Matrix Problem

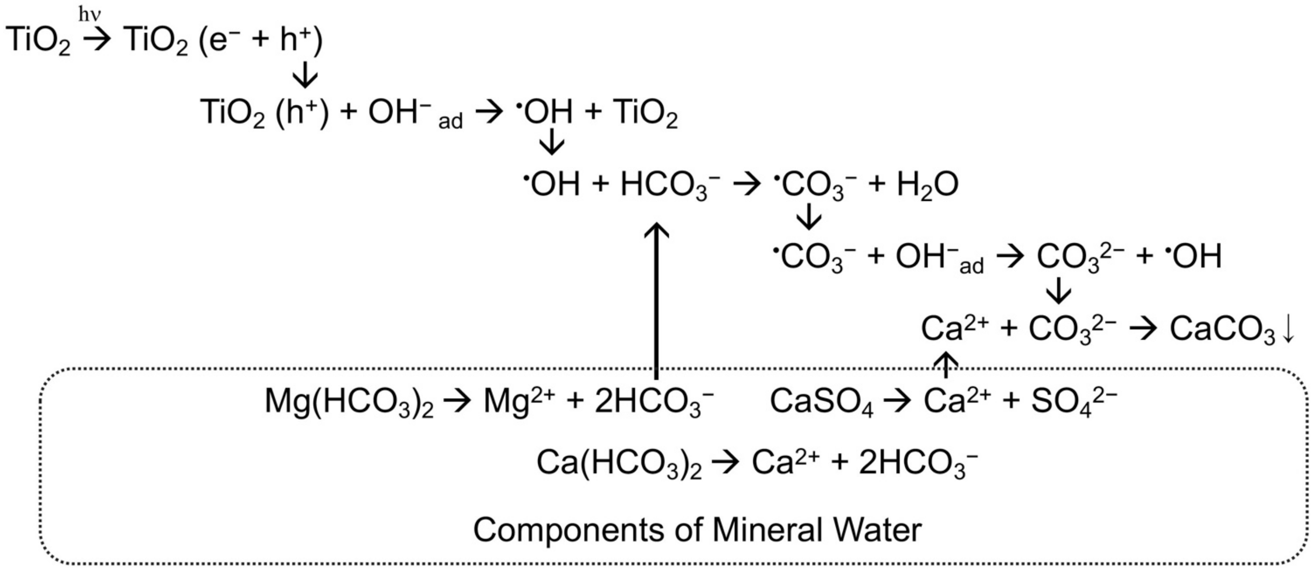
The problem of the water matrix is an inherent challenge in water purification using photocatalysis. When focusing on drinking water purification, we should mind the effect of the water matrix on the photocatalytic performance, particularly when the primary constituents of groundwater, such as well and spring water, are involved. In certain locations, the groundwater may contain high concentrations of dissolved substances.

The major constituents in groundwater include anions such as Cl^-, SO_4^{2-}, HCO_3^-, and silicate ions (sometimes considered as water-soluble silica), as well as cations such as Na^+, Mg^{2+}, and Ca^{2+} [160]. Although these ionic species can occasionally enhance the photocatalytic degradation of certain contaminants [161,162], they generally tend to reduce the photocatalytic activity [163–171]. Several studies have explored the effects of extreme ion concentrations on the photocatalytic performance. However, it is reasonable to assume that drinking water rarely contains high concentrations of these major groundwater constituents.

However, attention must focus on exceptional components that, despite being present in high concentrations, do not affect the taste of water. For example, HCO_3^-, which typically reduces photocatalytic activity [167–171], is often found in high concentrations in groundwater without affecting taste. Rincón et al. reported that the presence of HCO_3^- significantly decreases the efficiency of photocatalytic disinfection [163]. Therefore, the HCO_3^- concentration in raw water should be a key consideration when applying photocatalytic treatments to bacteria. Silicate ions, which can also be present in relatively high concentrations without affecting taste, may inhibit photocatalytic activity in proportion to their concentration [172].

Although it is rational that these ionic species should be removed by ion exchange to enhance photocatalytic efficiency, such advanced water treatment methods are not economically viable in developing countries. Therefore, if the reaction rate in ultrapure water is halved owing to the presence of these ionic species, the length of the photocatalytic reaction path would need to be doubled to maintain the same treatment volume per unit time. This effectively implies doubling the amount of catalyst, which increases the initial cost but does not affect the ongoing operational costs; that is, it is economically advantageous over time.

It is believed that Ca^{2+} can potentially exert both immediate and long-term effects on photocatalytic activity. This phenomenon is associated with calcium carbonate scale precipitation, which is not unique to photocatalysis but is also a common problem in general water supply systems. There is a concern that long-term photocatalytic treatment of groundwater may lead to the accumulation of calcium carbonate on the photocatalyst surface, ultimately resulting in a loss of catalytic activity. Serrà et al. reported that inorganic scaling can block catalytic sites, thereby inhibiting photocatalytic reactivity [173]. Although a limited number of studies have investigated the long-term effects of photocatalytic groundwater treatment, several studies have confirmed the accumulation of scale on photocatalyst surfaces during extended use [174,175]. Negishi et al. demonstrated that calcium carbonate scale precipitation occurs when formic acid is added to groundwater, such as Contrex and Evian, and subjected to repeated photocatalytic degradation reactions (Scheme 1). On the other hand, they observed no significant decline in the photocatalytic activity, even when the catalyst surface was entirely covered by the precipitated scale.



Scheme 1. Photocatalytic reaction scheme of groundwater matrix components.

Scale formation requires the presence of both Ca^{2+} and HCO_3^- in the water, which combine to form $CaCO_3$ through a photocatalytic process. Although Mg^{2+} is also a major component of groundwater, dolomite ($CaMg[CO_3]_2$) does not form, even at high Mg^{2+} concentrations, and only $CaCO_3$ was observed to precipitate [176]. Furthermore, in the presence of Mg^{2+}, $CaCO_3$ tends to precipitate as aragonite [177–179]. In contrast, the absence of Mg^{2+} increases the likelihood of calcite precipitation [175]. The mechanism behind the exclusive precipitation of $CaCO_3$ is notably straightforward. Although Na^+, K^+, and Mg^{2+} in water can theoretically react with carbonate ions to form their respective carbonates, these do not precipitate in practice because Na_2CO_3, K_2CO_3, and $MgCO_3$ are all highly soluble in water. In contrast, $CaCO_3$ precipitates readily because of its exceptionally low solubility [180]. Calcium carbonate exists in three main polymorphic crystal forms: calcite, which is the most stable at room temperature and pressure (trigonal-rhombohedral); aragonite, a metastable phase (orthorhombic); and vaterite, an unstable phase with a hexagonal structure [181–185]. Aragonite exhibits a characteristic needle-like crystal habit that tends to grow radially when it precipitates on photocatalyst surfaces [175]. These needle-like structures have diameters in the order of several tens of nanometers, and numerous microscopic gaps exist between the needle crystals. Here, $CaCO_3$ does not absorb light in the UV-A region (approximately $\lambda = 365$ nm), which is required to excite TiO_2. Consequently, TiO_2 can still generate reactive species, such as hydroxyl radicals (${}^{\bullet}OH$), through photoexcitation. These reactive species can diffuse through the gaps between the needle-like aragonite crystals, allowing the photocatalytic reaction to continue despite the surface coverage by scale. This mechanism may explain why the photocatalytic activity is maintained even when the surface of the photocatalyst appears to be completely covered with $CaCO_3$. Figure 2 shows the SEM images and specific surface areas of calcite and aragonite precipitated on the TiO_2 ceramic. The specific surface area of the TiO_2 ceramic decreased by approximately 20% with aragonite precipitation and by approximately 70% with calcite precipitation. This reduction indicates the extent to which the photocatalyst surface was covered with $CaCO_3$. The decrease in the specific surface area indicates the degree of active site coverage on the TiO_2 surface, which can explain why the decrease in photocatalytic activity was smaller for TiO_2 with aragonite precipitation and more significant for TiO_2 with calcite precipitation.

Aragonite nanoneedles deposited on TiO_2 mechanically destroy bacteria in water, a phenomenon known as the mechano-bactericidal effect [186]. In typical mechano-bactericidal processes, bacterial residues often remain attached to the needle-like structures. However, these bacterial remnants are subsequently decomposed and removed by reactive species, such as hydroxyl radicals ($^{\bullet}OH$), generated from the underlying TiO_2, potentially enabling a self-cleaning effect on the nanostructured surface through the combination of TiO_2 and aragonite. Moreover, aragonite nanoneedles can regenerate from the bacterial residues, suggesting the possibility of self-regeneration for the nanoneedles damaged during the mechano-bactericidal reaction. Although it is possible that the nanoneedles could be damaged during use and subsequently spilled into water, aragonite, despite its needle-like structure, is not particularly irritating to living organisms [187]. Therefore, even if nanoneedles are introduced into drinking water, they do not pose any safety risks. The immobilization of nanoneedles on photocatalysts is expected to result in a synergistic effect between mechano-bactericidal and photocatalytic sterilization (Figure 3) [186].

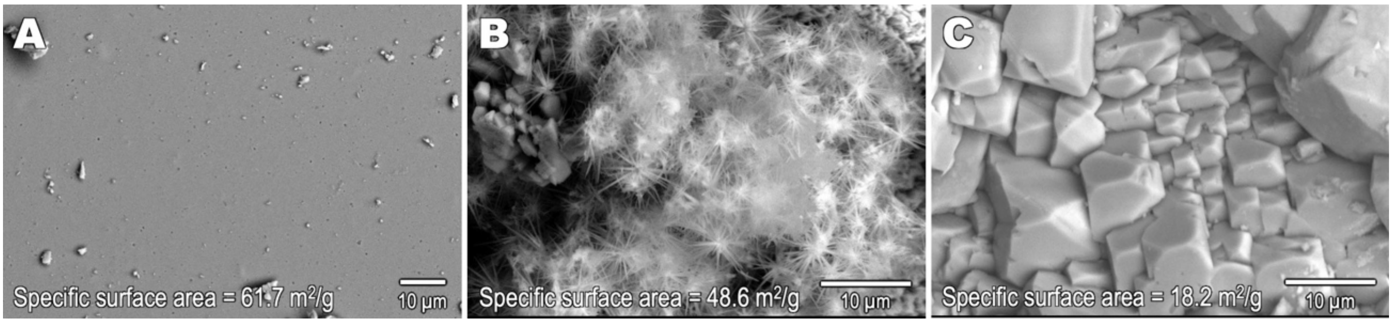


Figure 2. Surface conditions and specific surface areas of $CaCO_3$ precipitated on TiO_2 ceramic; (**A**) bare TiO_2 ceramic (specific surface area = 61.7 m^2/g), (**B**) TiO_2 ceramic with aragonite precipitated (specific surface area = 48.6 m^2/g), (**C**) TiO_2 ceramic with calcite precipitated (specific surface area = 18.2 m^2/g).

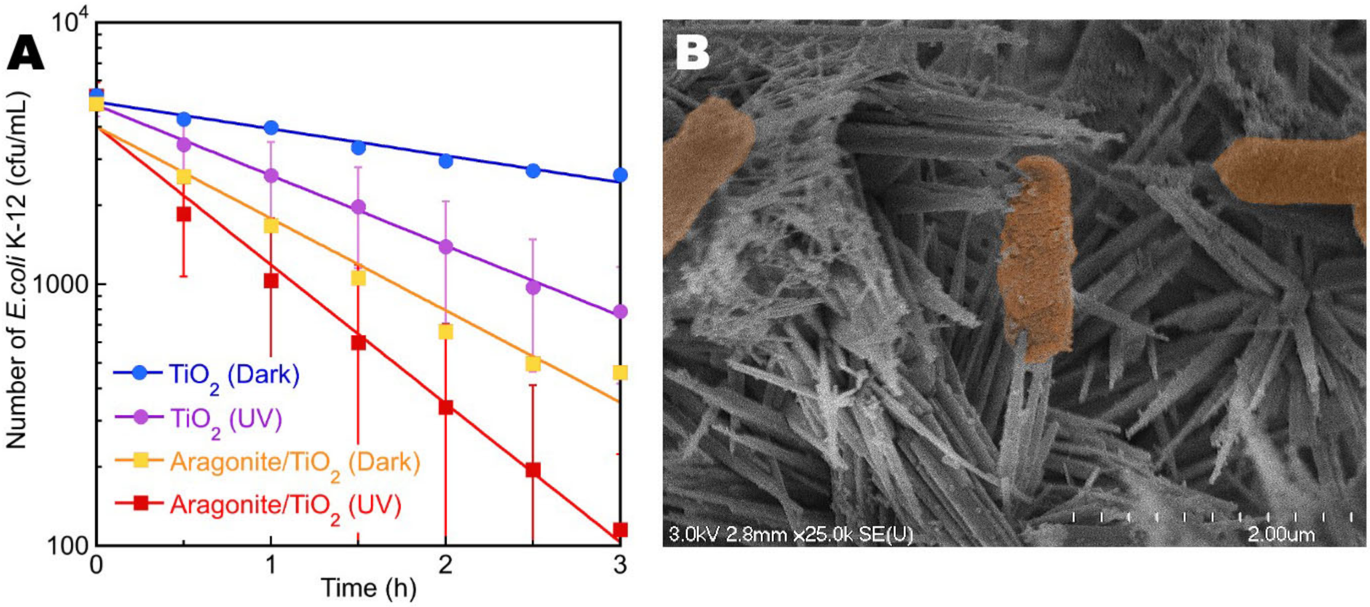


Figure 3. (**A**): Changes in the number of *E. coli* K-12 over time in circulation systems featuring TiO_2 ceramic. Aragonite-immobilized TiO_2 ceramic under dark (D) and UV light (UV) conditions. For the photocatalyst alone, *E. coli* showed little reduction over time under dark conditions. However, under UV irradiation, the rate of reduction increased owing to the photocatalytic bactericidal effect. In the sample with aragonite nanoneedles immobilized on the TiO_2 ceramic, a greater reduction in *E. coli* was observed even under dark conditions compared to the TiO_2 ceramic alone, indicating a significant bactericidal effect (mechano-bactericidal effect) independent of light. Under UV irradiation, this sample exhibited a synergistic effect, combining the photocatalytic sterilization effect of the TiO_2 ceramic substrate with the mechano-bactericidal action of the aragonite nanoneedles. (**B**) FE-SEM image of *E. coli* on the aragonite-nanoneedle immobilized on TiO_2 ceramic photocatalyst. The aragonite nanoneedles are stabbing the *E. coli* cells, and perforations have formed on the bacterial membranes.

As mentioned above, the precipitated scale was composed almost exclusively of one form of calcium carbonate, regardless of the variations in groundwater composition. Although this calcium carbonate precipitation does not significantly reduce the catalytic activity, continued accumulation may eventually cause issues such as blockage of flow paths. To address this issue, excess calcium carbonate scales can be removed using citric acid or similar substances, which are relatively available even in rural markets in developing countries. In conclusion, by understanding how the water matrix affects photocatalytic performance, the purification of drinking water through photocatalysis is expected to become a feasible and promising solution.

4. Photocatalytic Materials for Water Treatment

The most critical issue in drinking water purification in developing countries is whether the system can be used continuously with minimal maintenance. Many studies on photocatalytic treatment have focused on the high concentrations of contaminants found in sewage, often utilizing suspension reactors with powdered photocatalysts, which are known for their high reaction efficiencies [188–195]. However, these suspension-type systems are typically closed-loop systems and require pumps for continuous operation. In addition, membranes are necessary to separate the treated water from the photocatalyst after the reaction. Consequently, these systems require electricity and feature complex structures requiring regular maintenance.

One such alternative method is the use of fixed-bed photocatalytic systems. These systems eliminate the need for post-reaction separation of the catalyst. They can be designed as simple one-pass systems that operate without electricity using a gravity-fed flow or other low-energy methods. Most fixed-bed designs involve photocatalyst coatings applied to the substrate, and numerous studies have explored this approach [74,196–227]. However, as mentioned previously, long-term maintenance-free operation is essential for practical use in developing countries. Despite this, very few studies have investigated the long-term durability of photocatalytic coating materials, and several studies have expressed concerns about their stability over time [228–230]. In particular, if frequent catalyst replacement is required owing to degradation, the system cannot be considered maintenance-free.

As a photocatalytic material preparation method other than coatings, TiO_2-SiO_2 gradient composites have also been proposed as a promising approach for durable photocatalytic materials. In these materials, the possibility of catalyst detachment from the substrate is extremely low, suggesting their excellent potential for long-term operational stability. Ishikawa et al. synthesized photocatalytic ceramic fibers using this gradient structure [231], which were subsequently commercialized. Although the material demonstrated outstanding long-term durability, it was ultimately discontinued in 2013 because of limited commercial success. As another example of a durable photocatalytic material, Chandra et al. reported a Si-fixed TiO_2 photocatalyst that maintained consistent activity over 30 consecutive days of photocatalytic operation without any observable degradation [232].

These cases highlight the importance of material design in ensuring the stability and longevity of photocatalytic systems, particularly in applications where maintenance must be minimized [233–236]. TiO_2 itself can be fabricated into a ceramic composed of a single component, and even if the material breaks, the newly exposed surfaces (cross-sections) are expected to show photocatalytic functionality. Kato et al. synthesized monolithic photocatalytic ceramics using a sol-gel method and demonstrated their notable durability (Figure 4). They reported no decline in photocatalytic activity after repeated water treatment cycles in a closed-circulation system for over 8 h. Furthermore, weight loss was not observed after continuous exposure to a one-pass flow of tap water at a rate of 200 mL/min over three months [228]. As expected, the material also exhibited high photocatalytic performance [237,238]. This ceramic photocatalyst is mechanically robust, exhibiting high hardness and excellent resistance to friction. Moreover, because it is composed entirely of TiO_2, it contains no additives or components harmful or potentially harmful to human health. Therefore, if any damage causes some catalytic material to leach into the treated water, there is no risk of introducing toxic substances into the water. For these reasons, TiO_2 ceramic is considered one of the most suitable photocatalytic materials for drinking water purification owing to its safety, durability, and low maintenance, making it suitable for developing countries.

Figure 4. Monolithic TiO_2 ceramic photocatalyst.

The TiO_2 ceramic is prepared by dispersing a TiO_2 sol, made from titanium alkoxide as a precursor, into a mold and then firing it at a specified temperature, which transforms the dried gel into a porous TiO_2 ceramic. For this TiO_2 ceramic, the hardness of the ceramic is inversely proportional to its specific surface area, and the catalytic activity is proportional to its specific surface area. A correlation exists between the hardness of the ceramic and the crystalline phase transition of TiO_2. The rapid increase in hardness with firing approximately coincides with the crystalline transition from the anatase to the rutile phase. In particular, the photocatalytic activity of the rutile phase is generally lower than that of the anatase phase, and firing at a temperature slightly lower than the crystal transition temperature is necessary to obtain ceramic photocatalysts with relatively high hardness [228].

5. System Configuration of the Photocatalytic Reactor

As mentioned previously, the fixed-bed type is the most suitable choice for drinking water purification in developing countries. Among these fixed-bed photocatalytic reactors, the parabolic trough reactor is the most promising system that meets all these requirements, including the use of sunlight, simple structure, relatively low cost, and long-term durability of the system. The trough photocatalytic reactor has an economic advantage because it can use commercially available, inexpensive borosilicate glass tubes (which have excellent permeability at approximately λ = 365 nm, the optimum excitation wavelength for TiO_2 photocatalyst). The parabolic trough reactor can be broadly classified into two types: parabolic trough reactor (PTR) and compound parabolic collecting reactor (CPC) (Figure 5) [43,54,191,193,195,197,214,239–249]; the CPC reactor by Alrousan et al. examined the processing efficiency as a system with a TiO_2 coating on the inner wall of the glass tube placed in the center and with a TiO_2-coated inner tube in the center of the tube (Figure 6) [43]. Coating the inner wall of the glass tube with TiO_2 did not provide sufficient photocatalytic efficiency because the UV light that reached the TiO_2 surface was absorbed by the TiO_2 layer. The absolute photocatalytic area of TiO_2 as a system was smaller when the TiO_2-coated tube was placed at the center of the glass tube; however, the treatment efficiency of the system reached its maximum. For PTR or CPC reactors, the photocatalytic material is expected to show the maximum catalyst activity when packed in the glass capillary. In particular, TiO_2 ceramic photocatalysts can be molded into virtually any shape by designing an appropriate mold frame, enabling exceptionally high photocatalytic activity. Specifically, if a photocatalytic reaction tube packed with a shape-controlled TiO_2 ceramic, designed such that the ceramic inside the glass tube casts no shadows under omnidirectional light irradiation, is positioned at the center of a trough mirror, the photocatalytic activity is expected to be maximized (Figure 7).

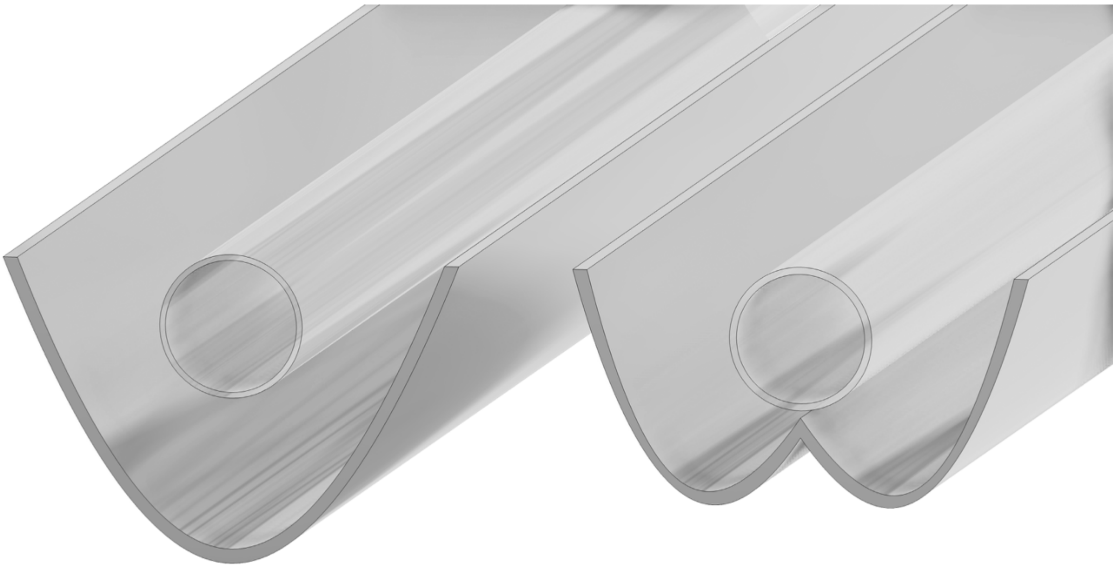


Figure 5. Cross-section image of the parabolic trough reactor (PTR: Left) and compound parabolic collecting reactor (CPC: Right).

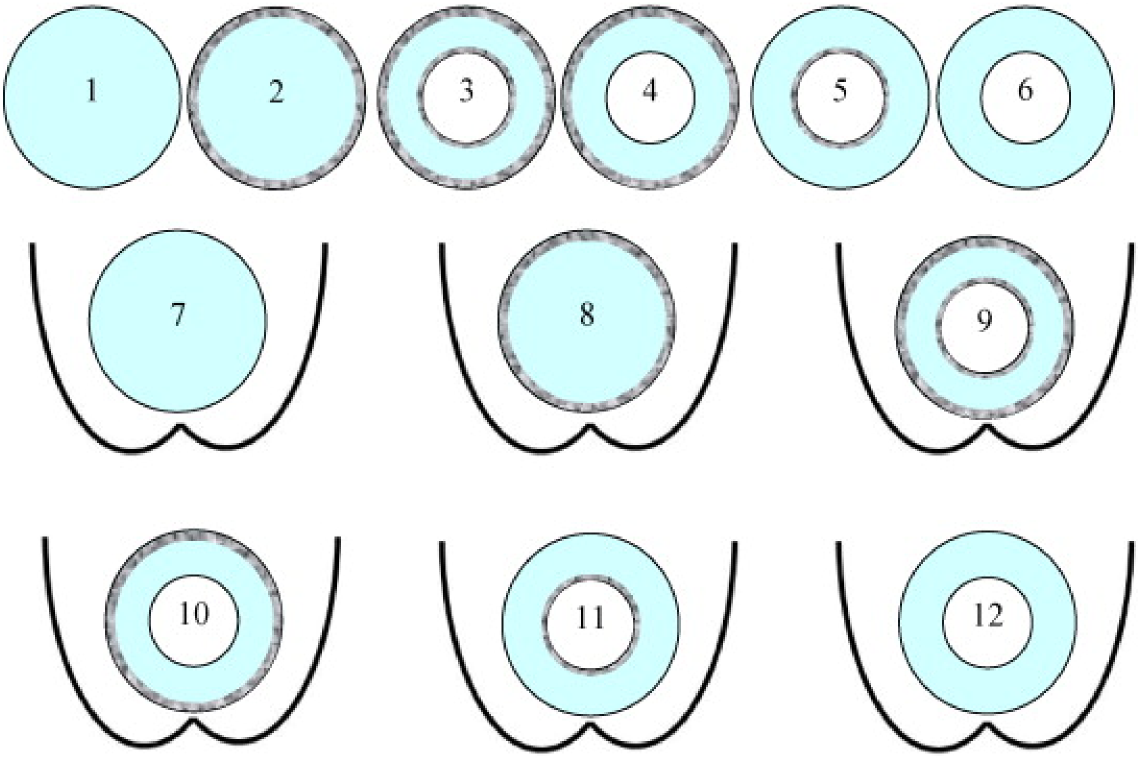


Figure 6. Schematic cross-section representation of the different reactor configurations tested in the solar reactor, (**1**)/(**7**) uncoated single tube without/with CPC; (**2**)/(**8**) coated single tube without/with CPC; (**3**)/(**9**) coated double tube without/with CPC; (**4**)/(**10**) coated external–uncoated internal without/with CPC; (**5**)/(**11**) coated internal–uncoated external without/with CPC; (**6**)/(**12**) uncoated double tube without/with CPC. Reprinted with permission from Ref. [43]. Copyright 2012, Elsevier.

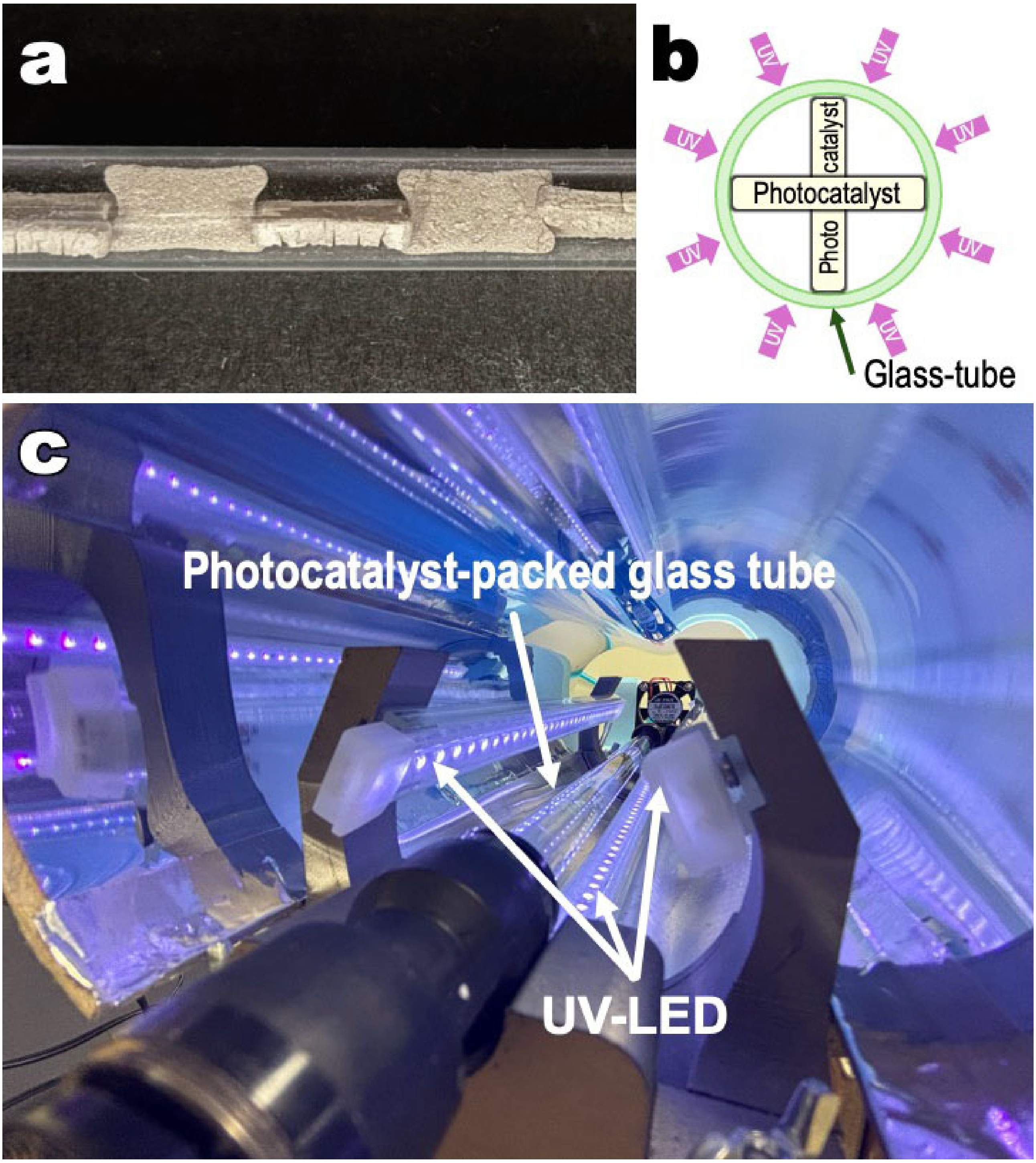


Figure 7. TiO_2 ceramic photocatalyst packed reactor tube. (**a**) TiO_2 ceramic photocatalyst packed vertically and horizontally in a glass tube, (**b**) The alternating vertical and horizontal arrangement of TiO_2 ceramic photocatalysts prevents the formation of shadow areas that do not contribute to the reaction due to UV irradiation from all directions, (**c**) UV-LED omnidirectional irradiation device for photocatalytic packing reaction tubes.

A crucial consideration in a packed-bed reactor system is that the ratio of photocatalyst surface area to the water volume in the reactor tube should be carefully optimized. The lifetime of hydroxyl radicals ($^{\bullet}OH$) generated through photoexcitation on the photocatalyst surface is extremely short (ranging from nanoseconds to microseconds) [250–252]. Therefore, if the water volume is too large relative to the effective photocatalytic area (the light-exposed surface area, not the specific surface area of the catalyst itself), the reactive species may not effectively interact with the contaminants in the water. This is because of the increased diffusion distance of the active species, which lowers the probability that these short-lived radicals will reach and react with the target molecules in time.

Another point to keep in mind, it is necessary to adjust the length of the photocatalytic reaction tube to suit the water matrix described in Section 3. Among the various constituents of groundwater, hydrogen carbonate ions have the most significant impact on photocatalytic activity. According to Negishi et al. [175], regardless of the accompanying counterion, a hydrogen carbonate ion concentration of approximately 100 mg/L reduces photocatalytic activity to one-tenth of that observed in pure water without hydrogen carbonate. In practical uses, this means that while a 1-m reaction tube may suffice in pure water, a 10-m tube would be required when the hydrogen carbonate concentration reaches 100 mg/L. However, the relationship between hydrogen carbonate ion concentration and photocatalytic reaction rate follows a logarithmic trend; beyond 100 mg/L, the decline in reaction rate becomes small. Therefore, a concentration of 100 mg/L is the goal when designing water purification systems. In cases where groundwater exhibits particularly extreme matrix compositions, it is not practical to extend the reaction tube indefinitely. Instead, the residence time can be increased by reducing the flow rate, thereby compensating for decreased reaction efficiency without modifying the tube length.

Based on these observations, in both the PTR and CPC configurations, the ceramic photocatalyst discussed in Section 4 is expected to demonstrate optimal performance when packed inside a glass tube, making it a compelling choice for practical deployment.

6. Considerations for Designing Photocatalytic Water Treatment Systems for Real Environments

We discuss drinking water purification systems for developing countries based on photocatalysts, and the main factors influencing the operation of these systems are as follows.

(1) Cost and Economics: Rural communities often have limited financial resources, making it essential to implement systems that are affordable for installation and maintenance. The use of inexpensive and locally available materials and technologies that operate with minimal energy consumption is ideal.
(2) Local Availability and Ease of Maintenance: Even if the system has advanced technologies, it should be designed to enable community members to operate and maintain it efficiently. For example, pre-filters that remove macroscopic impurities such as sand particles should be cleanable and replaceable through simple procedures that do not require specialized tools or expertise.
(3) Sustainability and Durability: The system must be capable of long-term stable operation with minimal need for repair or component replacement. Utilizing renewable energy sources such as solar irradiation is critical for sustainability, particularly in regions with unreliable electricity supplies.
(4) Purification Performance and Safety: The system should effectively address local water quality challenges, including pathogens (bacteria, protozoa, and viruses), heavy metals, arsenic, and chemical pollutants (such as pesticides and wastewater infiltrates). Ideally, treated water should meet or exceed the WHO drinking water quality standards.
(5) Cultural and Social Acceptability: Regardless of the technical performance, a system will not be adopted unless it aligns with local cultural practices and social norms. Design and operational simplicity that fit the daily lives of the local population are essential for community acceptance and continued use.
(6) Education and Training: Integrating educational initiatives that focus on basic water quality principles and system usage will foster community ownership and enable sustainable, long-term maintenance by the local population.

By applying these factors to photocatalytic water purification systems, they can be interpreted as follows:

(1) Cost and Economics: Photocatalytic materials with high durability show no degradation, even after extended use [228]. These materials will eliminate running costs associated with other water treatment methods, such as the periodic replacement of adsorbents or the continual purchase of chemicals. However, it is important to acknowledge that photocatalytic systems are unlikely to match the extremely low cost of the SODIS method, such as using PET bottles. The initial cost of photocatalytic systems will exceed the financial costs for residents in rural communities. In reality, numerous programs are already in place, led by central and local governments, NGOs, and international volunteer organizations, which provide water purification systems as donations. Therefore, we will be required to research and develop affordable photocatalytic water purification systems that can be distributed to each household by these organizations. Achieving this goal requires minimizing the system's size and complexity. That is to say, by reducing the system's size to the scale of each household, it is possible to avoid the risk of inconveniencing all residents if the system stops owing to a breakdown, as is the case with a large system serving a village.
(2) Local availability and ease of maintenance. The environmental conditions under which a photocatalytic water treatment system may be deployed vary significantly depending on the location. For example, access to electricity is not guaranteed in many rural areas. For such off-grid settings, a trough-type reactor is particularly suitable

because it can operate entirely by gravity flow, eliminating the need for powered pumps or complex infrastructure. One critical consideration is the quality of the input water. Directly introducing untreated source water, particularly water containing macro-contaminants, such as suspended solids or turbidity-causing materials, can foul the photocatalyst surface, considerably reducing its efficiency. Therefore, prefiltration is essential. However, highly sophisticated filtration systems are not required. Simple and low-tech filters made from readily available materials such as charcoal, sand, or cloth can be effectively used for this purpose [253–255]. These materials are widely accessible in nearly every region and can be easily assembled, cleaned, and replaced by local users without specialized knowledge or equipment. This ensures that the system remains practical and can be maintained at the community level.

(3) Sustainability and durability: Theoretically, photocatalysts are semi-permanent, meaning that their functionality does not degrade over time under normal operation. However, as mentioned in Section 2, activity degradation can occur if the catalyst surface is contaminated. Therefore, the use of pre-filters is essential. If basic maintenance, such as periodic cleaning or replacement of the pre-filter, is performed, the photocatalytic system provides greater sustainability than other water purification methods, which often require regular chemical replenishment or component replacement. From the durability perspective, the design of a photocatalytic purification system without electrical or mechanical components eliminates the most common causes of failure. The remaining concerns are primarily related to the physical lifespan of individual parts, which should be easily replaced when needed. Among all components, the glass reactor is the most vulnerable. As glass can break under impact, it is particularly susceptible to damage in rural environments where physical hazards are more common. For example, while operating a photocatalytic purification system in a village in a developing country [256], we observed residents using slingshots to capture free-range chicken. Children playing by throwing stones is also common. If struck, the glass reactor will undoubtedly be damaged. Therefore, to address both direct impacts and flying debris, protective measures such as covering the reactor system with a metal mesh or cage are essential to ensure long-term durability in such environments.

(4) Purification performance and safety: There are no major concerns regarding the purification performance of photocatalytic systems because numerous studies and field demonstrations have validated their effectiveness. As mentioned earlier, photocatalytic activity can be influenced by the composition of the water matrix, and this can be addressed by adjusting the size or capacity of the system accordingly. Therefore, a preliminary analysis of the source water is essential before system installation to ensure optimal performance. Regarding safety, TiO_2-based photocatalysts pose no health risks, making them suitable for drinking water applications. Additionally, because suspension systems using TiO_2 powder are not considered feasible in developing countries owing to maintenance and separation problems, on the contrary, the potential risks associated with nanoparticle exposure (nano-risks) can be effectively avoided.

(5) Cultural and social acceptability: One of the challenges observed with the SODIS method, which utilizes plastic bottles for solar sterilization, is the anxiety about hurting residents' pride. In contrast, a photocatalytic water purification system with its prominent structure may promote a sense of pride among users. As the system must be installed in a sunlit and conspicuous location, it becomes a visible symbol of sustainable innovation within the community (Figure 8). This visibility is likely to attract interest and encourage adoption among neighboring households, potentially increasing community-wide acceptance and use of the system.

(6) Education and training: This focuses on informing users about the importance of water purification. In many communities, even where waterborne diseases are prevalent, such issues may be normalized as a part of daily life. Therefore, educating users about the direct link between water purification and reduced disease incidence is crucial [7,257–261]. Additionally, promoting the broader benefits of improved water quality, such as enhanced productivity and increased household income owing to better health, can strengthen public motivation for system adoption. Although photocatalytic systems meet criteria 1–5, including cost, availability, sustainability, safety, and cultural compatibility, they are not entirely maintenance-free. It is important to communicate that a minimal level of care is required, such as cleaning or replacing pre-filters and checking for leaks; however, this effort ensures long-term access to safe drinking water. Therefore, community-based training should be provided on how to manage the routine upkeep of the system, focusing on tasks that can be easily performed by users themselves without the need for specialists or complex tools.

Figure 8. The trial of the solar water purification system in Chiang Rai Province, Thailand (Length of photocatalyst tube = 13 m) (Photo: Negishi).

7. Conclusions

Drinking water in developing countries, particularly in rural areas, can be purified using photocatalysis activated by sunlight. To achieve this, developing sustainable and appropriate photocatalytic materials and water treatment systems is essential. Among the available materials, TiO_2 ceramic photocatalysts are the most suitable because of their high durability and minimal degradation over time. Technologies such as through-type reactors that enable natural single-pass water treatment using gravity flow are available and provide promising solutions.

However, the composition of the source water (the water matrix) varies widely in real-world environments, and its impact on the photocatalytic performance must be thoroughly evaluated before installation. Accordingly, treatment systems should be appropriately sized based on the local water quality. Equally important is the requirement that these systems be long-term and have a low maintenance load. The prefiltration step is crucial in preventing macro-contaminants from fouling the photocatalyst surface, thereby preserving its activity. These filters should be made from simple, locally available materials, such as sand, charcoal, and cloth, and easily assembled and maintained by the users themselves.

Widespread photocatalytic water purification systems have the potential to reduce the incidence of waterborne diseases in developing countries significantly. Consequently, this can lead to improved health, increased labor productivity, and household income, creating a positive feedback loop that enables communities to access more advanced water treatment technologies gradually.

Research on solar photocatalytic water purification has attracted attention for decades, dating back to the study by Ollis [262], which suggested its feasibility via solar irradiation. Despite this early interest, progress in the practical application of this technology has been slow owing to a range of technical challenges. However, recent studies suggest that breakthroughs may be on the horizon. With continued innovation and by addressing the remaining technical and social hurdles, the use of photocatalytic technology for water purification in developing regions is expected to become a viable and impactful solution, ensuring safe and sustainable access to clean water.

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Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data is available on request.

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Declaration of Competing Interest

The author declares that they have no competing financial interests or personal relationships that may have influenced the work reported in this study.

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