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Efficacy of solar water disinfection treatment system in improving rural and peri-urban household drinking water quality and reducing waterborne diarrhoeal diseases

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ABSTRACT

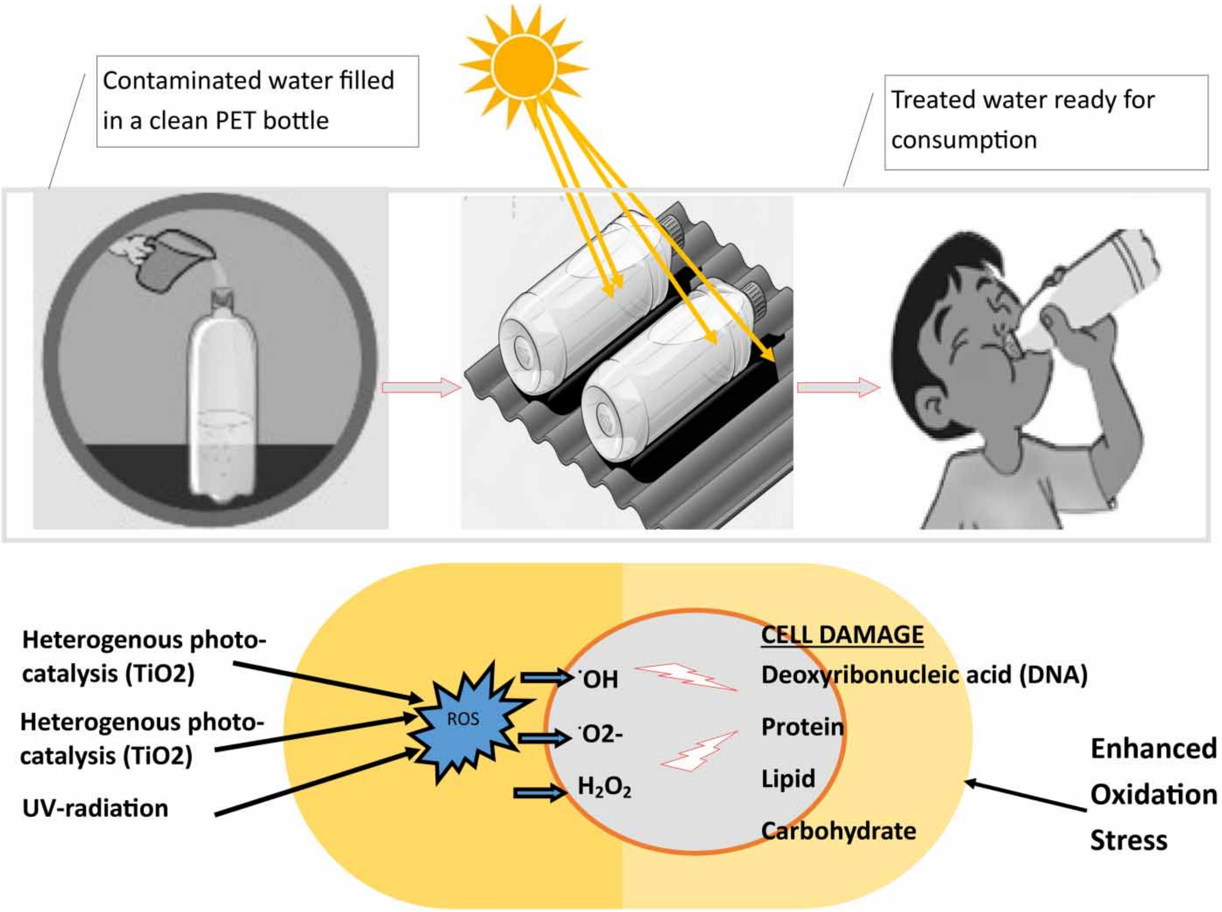
Consumption of untreated microbiologically contaminated water, prevalent in many developing countries, exposes the vulnerable population to inordinate health risks including most life-threatening diarrhoeal diseases like cholera and other illnesses. In response, innovative techniques for treating water at the household level, known as household water treatment (HWT), have emerged as practical and cost-effective solutions. Solar water disinfection (SODIS) has gained recognition as one such method that utilizes sunlight to inactivate harmful micro-organisms in water. This review examines the effectiveness of SODIS as an HWT technique by analysing scientifically robust evidence documenting its microbiological efficacy and the positive health gains among SODIS users. It explores the challenges and limitations that impact its inactivation efficiency and sustainability. Its novelty lies in its expanded exploration of the available strategies and techniques for enhancing the effectiveness of SODIS to address its associated limitations and challenges. By providing a comprehensive analysis of the scientific evidence, this review presents compelling reasons for the implementation and scalability of SODIS in the developing world. This novel perspective contributes to the existing literature on improving access to safe drinking water in underserved communities, offering valuable insights into the advancement of SODIS as a practical and sustainable HWT solution.

Key words: household water treatment (HWT), microbiological effectiveness, pathogens, scalability, solar disinfection (SODIS)

HIGHLIGHTS

- Efficacy of SODIS in inactivating enteric pathogens and reducing diarrhoeal diseases was reviewed.
- Scientific evidence of SODIS effectiveness was presented.
- Sustained health benefits are subject to correct, consistent, and long-term use.
- Opportunities and challenges to SODIS sustainability and scalability were discussed.
- Education, sensitization, and promotions campaigns are key to SODIS social acceptability.

GRAPHICAL ABSTRACT



1. INTRODUCTION

In the natural environment, sources of contamination that end up in drinking water are ubiquitous (Lawrence *et al.* 2001). The leading and widely recognized health risk associated with drinking water is contamination with pathogenic micro-organisms (bacteria, viruses, protozoa, and helminths) transmitted through faeces (WHO *et al.* 2022). The drinking of untreated faeces-contaminated water leads to transfer of these pathogenic micro-organisms from the environment into humans (Gwenzi *et al.* 2017). Once ingested, these pathogens can lead to outbreaks of waterborne diseases such as cholera, giardia, dysentery, and typhoid fever. The alarming reality is that 25% of the global population lacks access to safely managed drinking water at home (WHO & UNICEF 2021), and approximately 2 billion individuals depend on water sources contaminated with faecal matter (WHO *et al.* 2022). This means that the world is still off track to meet the first target of sustainable development goal number 6, which aims to ensure universal and equitable access to safe and affordable drinking water for all by 2030. Deplorably, least developed nations have the furthest to go, and it will be especially challenging for them to accelerate progress especially in fragile contexts (WHO & UNICEF 2021). For example, at current rates, it is projected that just 37% of the population of Sub-Saharan Africa will be using safely managed drinking water by 2030.

Many homes in rural areas of the developing world are too few and/or highly dispersed to justify the cost of installing reticulated systems from a high-quality water supply source or a centralized drinking water treatment facility (REAL-Water 2022). As a result, the majority resorts unsafe drinking water sources. Besides concerns of contamination at source, subsequent microbiological contamination of previously safe water also occurs due to unhygienic handling of water during collection, transportation, and storage within the home (Sobsey 2002; World Health Organization 2007; Yefanova *et al.* 2022). Several studies have observed significant deterioration in microbiological quality of drinking water between water source and point-of-use (POU) (Lindskog & Lindskog 1988; Mølbak *et al.* 1989; Roberts *et al.* 2001; Moyo *et al.* 2004;

Wright *et al.* 2004; Cronin *et al.* 2006; Gundry *et al.* 2006; Psutka *et al.* 2011; Kanyerere *et al.* 2012). To protect the vulnerable population from consuming microbiologically contaminated water, innovative household water treatment (HWT) techniques have emerged as practical and cost-effective solutions. These techniques specifically target and enhance the microbiological quality of drinking water at the point of use, thereby providing immediate relief in areas lacking centralized water treatment infrastructure (Clasen 2009). The combination of these HWT interventions together with safe storage, collectively called household water treatment and storage, provides interim measures to communities to take charge of improving their own microbiological water quality at homes until they can be reached with safe, reliable, household piped-water connections (Sobsey 2002; Clasen 2009; Clasen *et al.* 2015).

Solar water disinfection (SODIS) is one such HWT method that has gained recognition and popularity over the years. The method utilizes sunlight to inactivate microbial pathogens in water, offering a simple, cost-effective, and environmentally friendly water treatment solution that does not produce toxic disinfection by-products. Its effectiveness and potential have earned it official recognition and recommendation by the World Health Organization (WHO). By exposing transparent containers containing contaminated water to sunlight for a specific duration, the method harnesses ultraviolet (UV) radiation and increases temperature to kill or inactivate a wide range of pathogens in drinking water. Pioneering research conducted in the Maasai community in Kenya by Conroy *et al.* (1996, 1999, 2001) validated the effectiveness of SODIS in enhancing water quality and reducing waterborne illnesses. Subsequent studies and field trials in different parts of the world have consistently shown significant reductions in microbial contamination and improvements in health outcomes through SODIS implementation.

Despite its beneficial features, the SODIS method has limitations that impede its effectiveness under certain circumstances. Conventional SODIS often requires prolonged exposure times ranging from 6 to 48 hours to achieve effective disinfection. This limitation is attributed to the reliance on sunlight availability and the requirement for water temperatures of 50 °C or higher (Wegelin *et al.* 1994; Sommer *et al.* 1997). Insufficient sunlight or cloudy weather can impede the disinfection process, while the need for high temperatures restricts the treatment volume to small quantities, limiting its scalability and practicality (Pulgarin 2015; Luzi *et al.* 2016). Extended exposure times and inadequate disinfection may lead to bacterial re-growth in treated water. Various factors including water turbidity and climatic conditions can influence the disinfection process and heighten the risk of bacterial re-growth, compromising the safety of the water. In addition, challenges such as limited volume, the unavailability of PET bottles, and user behaviour contribute to the social acceptance of SODIS.

This review critically examines the effectiveness of SODIS as an HWT technique by analysing scientifically robust evidence documenting its microbiological efficacy and the positive health impacts reported among SODIS users. It investigates the limitations that affect its pathogen inactivation efficiency and the challenges that influence its scalability and sustainability in real-life applications. The review also highlights the importance of behaviour change interventions to ensure consistent and correct application of SODIS. The novelty of this review lies in its expanded exploration of available strategies and innovative approaches to overcome the issues associated with SODIS disinfection efficiency and implementation. By providing a comprehensive analysis of the existing scientific evidence, this review presents compelling reasons for the implementation and scalability of SODIS in the developing world. The novel perspective presented here contributes to the existing literature on improving access to safe drinking water in underserved communities, offering valuable insights into the advancement of SODIS as a practical and sustainable HWT solution.

2. BACKGROUND AND THEORY OF SODIS

SODIS is the water disinfection method that relies on effects of solar radiation to destroy or inactivate pathogenic microorganisms in microbiologically contaminated drinking water. The method was endorsed by WHO in 2001 and has been recommended for low-income countries and in the aftermath of natural disasters or humanitarian crises to improve access to safe water (Rainey & Harding 2005; Meierhofer 2006). Since then, the method is being promoted in developing countries through information and awareness campaigns, training and advising of the public sector (government institutions), networking activities, as well as user training at the grassroot level (Meierhofer & Landolt 2009). Being a fundamentally behaviour change strategy than a product, its adoption by the corporate world remains unattractive and many are reluctant to support its promotion campaigns (Lantagne *et al.* 2006; Clasen 2009; McGuigan *et al.* 2012). Nevertheless, the technology has gained the largest traction and acceptability among low-income populations, with more than 2.1 million reported users by the end of 2007 (Clasen 2009). For the past years, the method has achieved some coverage in areas where it has been promoted, although the coverage figures varied widely among settings (between 9 and 66%, although persistent use is less clear)

(Schmidt & Cairncross 2009). However, there is limited information regarding recent practical application of SODIS, including its application scale and geographical coverage. As noted by Ballesteros *et al.* (2021), there is limited attention given to the real-world application of solar-driven methods, as well as other crucial aspects such as testing of regulated microbial indicators and emerging pathogens. By 2012, it was estimated that more than 5 million people in more than 50 countries across the developing world (Latin America, Asia, and Africa) were regular users of SODIS at that time (McGuigan *et al.* 2012).

A detailed conventional SODIS application procedure is described in the SODIS manual by Luzi *et al.* (2016). In short, it involves filling potentially microbiologically contaminated water into transparent PET bottles of up to 2L volume (or smaller) and exposes it to full sunlight for at least 6 h on a sunny day or for 2 consecutive days (48 h) if cloudiness is greater than 50% (McGuigan *et al.* 2012; Luzi *et al.* 2016). The treated water is then stored in the bottles until consumption in order to avoid re-contamination. It is also recommended to not drink within 24 hours to avoid the possibility of post-exposure re-growth (McGuigan *et al.* 2012).

2.1. Basic principles of SODIS

SODIS operates based on two fundamental principles: utilizing sunlight for water disinfection and adhering to recommended exposure times. When water is exposed to sunlight, it undergoes two simultaneous processes that contribute to its safety for consumption. The first process involves solar ultraviolet (UV) radiation, specifically UV-A light, which exhibits germicidal properties. This radiation penetrates the water, causing disruption of the DNA of pathogens. The second process involves the infrared heat from the sunlight, which raises the temperature of the water inside the bottles. This elevated temperature further enhances the inactivation of micro-organisms, complementing the UV disinfection process. The combined effect of both stresses produces synergistic action that makes SODIS an effective and accessible method for treating household water in resource-constrained settings (Meierhofer & Wegelin 2002; Borde *et al.* 2016).

2.1.1. Germicidal effects of UV-A radiation

Optical radiation within the electromagnetic spectrum includes ultraviolet radiation, visible light, and infrared radiation (IR) (Gallagher *et al.* 2010). According to WHO, ultraviolet (UV) radiation is the radiation energy that comes naturally from the sun as a major source, and it covers the wavelength range of 100–400 nm, which is a higher frequency and lower wavelength than visible light (WHO 1994). It is divided into three bands, namely, UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm) (WHO 1994). Solar UV radiation causes various biological impacts such as changes in the composition of proteins, DNA, and other important biological compounds. It also has long-term effects on vital physiological processes, resulting in decreased growth and cell division, loss of pigmentation, and hindered energy production, and induces acute physiological stress in different organisms (Rastogi *et al.* 2010). The main mechanism of pathogen inactivation during solar disinfection is direct or mediated damage to proteins and the DNA of the organisms, induced by radiation in the UV-B, UV-A, and possibly the lower visible range (Luzi *et al.* 2016). When the pathogens are exposed to sunlight, UV-A radiation directly interacts with the DNA, nucleic acids, and enzymes of their living cells, changes the molecular structure and eventually leads to cell death (Meierhofer & Wegelin 2002). However, UV-B plays a minor role in SODIS inactivation of micro-organisms because most (95%) of it (and also UV-C) is absorbed by the stratospheric ozone (O_3) layer which protects the earth from radiation coming from space, water vapour, oxygen, and carbon dioxide (WHO 1994; Meierhofer & Wegelin 2002; Luzi *et al.* 2016). In addition, materials of the vessels used (PET) absorb most of the UV-B radiation (Luzi *et al.* 2016).

Only a higher fraction of UV-A radiation, in the wavelength range of 320 nm to 400 nm, near the visible violet light, reaches the surface of the earth (Meierhofer & Wegelin 2002). Therefore, the UV-A portion of sunlight is the main inactivation factor of SODIS (Moreno-SanSegundo *et al.* 2021). When water is exposed to UV-A light, the combined effects of UV-A absorption and photochemical reactions contribute to the inactivation of pathogens during solar disinfection. Clear plastic or glass bottles used in SODIS allow UV-A radiation to pass through and be absorbed by the water. This absorbed UV-A radiation interacts with the micro-organisms present in the water, damaging their DNA, nucleic acids, and enzymes present in their cells. This interaction alters the molecular structure, eventually causing the cells to die (Meierhofer & Wegelin 2002). However, according to Luzi *et al.* (2016), the absorbed UV-A radiation does not directly harm the genetic material of pathogens. Instead, it triggers photochemical reactions within the micro-organisms. During these reactions, the UV-A radiation interacts with oxygen molecules in the water, resulting in the generation of highly reactive oxygen species (ROS) such as singlet oxygen, superoxide, hydrogen peroxide, and hydroxyl radical. These ROS subsequently interact with and damage DNA or proteins (and other cellular components), impeding the pathogens' ability to reproduce and survive (García-Gil *et al.* 2021). It is worth noting that the ROS can be mediated by organic photosensitizers dissolved in the water, such as organic molecules or iron (exogenous mechanism), or by molecules of the pathogenic organisms themselves (endogenic mechanism) (Luzi *et al.* 2016).

2.2. IR (increased temperature)

In addition to UV-A radiation, sunlight also contains IR, which contributes to the heating of the water in SODIS bottles. The IR absorbed by the water is responsible for heating it up. Elevated temperatures can enhance the inactivation of pathogens through thermal effects, as many micro-organisms are sensitive to higher temperatures. Higher temperatures can also accelerate the biochemical reactions occurring within the micro-organisms, further compromising their viability (Meierhofer & Wegelin 2002; Luzi *et al.* 2016). In actual fact, heat damages the molecular structure of pathogenic organisms, a mechanism known as thermal inactivation or pasteurization when the water temperature is raised to 70 °C–75 °C (Meierhofer & Wegelin 2002; Luzi *et al.* 2016). During solar exposure, the water is typically heated up by solar IR depending on the irradiation intensity, ambient temperature, and location (wind cooling, heat absorbing background) (Luzi *et al.* 2016). As the water is heating up, bottle water temperatures rise above the metabolism temperatures of the micro-organisms (Luzi *et al.* 2016).

In this case, water does not have to be boiled to kill 99.9% of the micro-organisms. For instance, in their experiment to investigate efficacy of SODIS for enteric pathogens and to test applicability of the reciprocity law, Berney *et al.* (2006) found out that *Vibrio cholerae* was more susceptible to mild heat at temperatures as low as 40 °C and *Escherichia coli*, *Salmonella typhimurium*, and *Shigella flexneri* were sensitive at temperature above 45 °C. Previously, World Health Organization (2015) presented results of various investigations which have shown that waterborne pathogens are sensitive to heat and are killed or inactivated even at temperatures below boiling (less than 100 °C). According to Clasen (2009), heating water to even 55 °C has been shown to kill or inactivate most enteric pathogens. As Table 1 shows, heating the water to 50–60 °C for 1 h has the same effect as boiling (Meierhofer & Wegelin 2002). However, it is still argued that bringing water to a rolling boil is the only way to ensure high enough temperatures to eliminate the risk of pathogenic bacteria, viruses, and protozoa (Sobsey 2002; Clasen 2009; Rosa *et al.* 2010; Juran & MacDonald 2014).

Table 1 shows temperatures and exposure times required to eliminate micro-organisms.

2.3. Synergetic effect of UV-A radiation and temperature

It has been established in the scientific literature that combined exposure to the sun's heat and the UV light in the SODIS process has a lethal synergistic effect that produces enhanced inactivation efficiency far greater than the cumulative effect that a single agent can produce when used individually (Wegelin *et al.* 1994; McGuigan *et al.* 1998; Meierhofer & Wegelin

Table 1 | Thermo-resistance of micro-organisms (Sommer *et al.* 1997)

	Time and temperature for 100% destruction		
Micro-organisms	**1 min**	**6 min**	**60 min**
Enteroviruses			62 °C
Rotaviruses		63 °C for 30 min	
Faecal coliforms	complete destruction at 80 °C		
Salmonella		62 °C	
Shigella		61 °C	54 °C
Vibrio cholera			45 °C
Entamoeba histolytica cysts	57 °C	54 °C	50 °C
Giardia cysts	57 °C	54 °C	50 °C
Hookworm eggs and larvae		62 °C	51 °C
Ascaris eggs	68 °C	62 °C	57 °C
Schistosoma eggs	60 °C	55 °C	50 °C
Taenia eggs	65 °C	57 °C	51 °C

2002; Sobsey 2002; Mtapuri-Zinyowera *et al.* 2009; Graf *et al.* 2010; Castro-Alférez *et al.* 2017). At temperatures above 45–50 °C, a synergistic effect of thermal inactivation and UV-A radiation occurs which strongly enhances the inactivation efficiency of SODIS (Luzi *et al.* 2016). According to Sobsey (2002), combined effects of UV radiation in the UV-A ranging from 320 to 400 nm and heating to temperature of 50–60 °C, respectively, have germicidal effects and are high enough to extensively (99.9%) inactivate many enteric micro-organisms. This same synergistic effect was also observed in a study by Mtapuri-Zinyowera *et al.* (2009) where cysts of *Giardia duodenalis* and *Entamoeba histolytica* or *Entamoeba dispar* were destroyed when temperatures increased above 50 °C, with complete death at 56 °C.

The synergetic effect of UV-A radiation and temperature leads to an increased production of ROS within the micro-organisms. The central hypothesis is that UV-A light generates ROS, which has the potential to harm nucleic acids, proteins, and other essential cellular components that support cell life (Berney *et al.* 2006). These ROS, including singlet oxygen and hydroxyl radicals, are highly reactive molecules that can cause oxidative damage to various cellular components such as lipids, proteins, and DNA (Berney *et al.* 2006; Huang *et al.* 2017). The DNA damage, disruption of cellular structures, and oxidative stress as a result of these intracellular mechanisms collectively contribute to the effective elimination of micro-organisms and the improvement of water quality during solar water disinfection using SODIS (Figure 1).

2.4. Limitations of SODIS

2.4.1. Prolonged exposure time

One of the primary limitations of the conventional SODIS method is the prolonged exposure time required to achieve effective disinfection. Exposure times typically range from 6 to 48 hours, depending on factors such as sunlight intensity and water turbidity. Insufficient sunlight or cloudy weather conditions can significantly impede the disinfection process, prolonging the time required to treat water effectively. This limitation poses challenges in regions with inconsistent sunlight patterns, particularly during certain seasons or in areas with high cloud cover.

2.4.2. Dependency on weather and climatic conditions

SODIS relies on the energy from sunlight to inactivate pathogens in water. Therefore, factors such as cloud cover, rainfall, and seasonal variations in sunlight intensity can affect the efficiency of the process. The process requires favourable climatic conditions, i.e., sunlight radiation and ambient temperatures preferably not under 500 W/m^2 and 20 °C, respectively (EAWAG/SANDEC 1991). The amount of solar irradiation can significantly fluctuate throughout the day due to factors like cloud cover (Berney *et al.* 2006). An increase in cloud cover leads to reduced sunlight and lower temperatures, which logically means a slower rate of inactivation (Sommer *et al.* 1997). During periods of cloudy weather or continuous rainfall, it is advisable to increase the exposure time of SODIS by keeping the bottles exposed for two consecutive days. However, in cases of prolonged cloudiness or persistent rainfall, it is recommended to consume boiled water or previously treated SODIS water that has been stored (Wegelin *et al.* 1994; Meierhofer 2006; Luzi *et al.* 2016).

2.4.3. Inability to treat water with high turbidity

SODIS is associated with potential difficulties in treating highly turbid water (Sobsey 2002). This is because high turbidity hinders penetration of sunlight into the water, reducing its effectiveness as a disinfection method (Borde *et al.* 2016). To yield more effective results, it is recommended that SODIS should be applied to relatively clear water, < 30 NTU

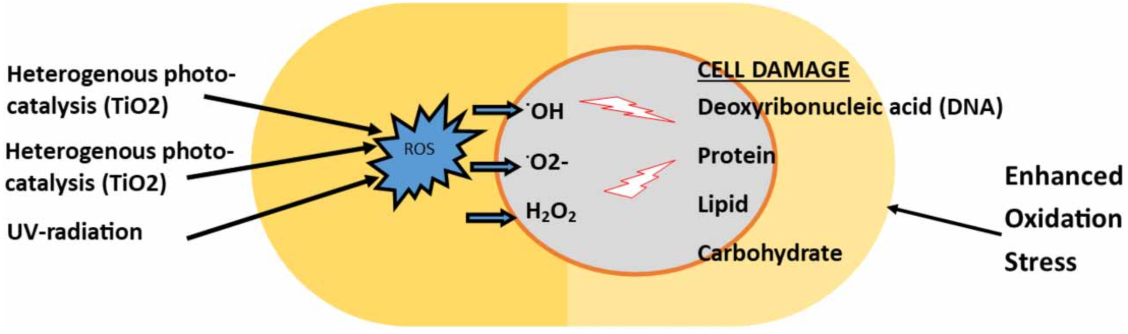


Figure 1 | The depiction of the intricate process by which pathogenic organisms suffer cellular damage caused by ROS.

(World Health Organization 2007). This means that other simple methods for reducing the turbidity of water before solar treatment should be applied. While the importance of low-turbidity water has been emphasized (Wegelin *et al.* 1994; Meierhofer & Wegelin 2002; Meierhofer 2006; Dessie *et al.* 2014), studies conducted by McGuigan *et al.* (1998) and Joyce *et al.* (1996) demonstrated that SODIS can effectively inactivate certain pathogenic bacteria even in highly turbid water (200 NTU), provided that the water temperature exceeds 55 °C.

2.4.4. Pathogen re-growth

Microorganisms, including pathogenic ones, have evolved mechanisms to repair DNA damage caused by heat and other stressors. This allows them to regain their infectivity and survive adverse conditions (Linden *et al.* 2002). One important repair mechanism in various organisms is photoreactivation, which involves the enzyme photolyase. Photolyase uses light energy to repair UV-induced DNA lesion (Sinha & Häder, 2002). This repair process is crucial for maintaining DNA integrity and preventing the accumulation of genetic damage. In addition to photoreactivation, excision repair is another significant mechanism for DNA repair. Excision repair, categorized as base excision repair (BER) and nucleotide excision repair (NER), also plays a significant role in DNA repair. BER involves glycosylases, while NER involves polymerases (Sinha & Häder, 2002). Due to some limitations, SODIS may not completely inactivate all pathogens in water. Due to their self-repair abilities, the pathogens may re-emerge in SODIS-treated water. Understanding the repair mechanisms employed by micro-organisms and the limitations of SODIS in completely eliminating all pathogens can guide the development of more effective water treatment strategies. In addition, unhygienic handling and poor storage practices can introduce new contaminants, including pathogenic micro-organisms, into the treated water. This highlights the importance of proper water storage and handling procedures to minimize the risk of re-contamination and ensure the safety of SODIS-treated water. It is recommended to consume the treated water directly from the original small, narrow-necked bottles with caps within a 24-h period (Lantagne *et al.* 2006).

2.4.5. Pathogen resistance to SODIS

Different micro-organisms have varying levels of heat resistance, and while technologies like SODIS primarily target the vegetative forms of micro-organisms, certain pathogens can exist in more resilient stages such as cysts or spores, which are not effectively deactivated by solar radiation (Den Besten *et al.* 2018). SODIS has been successful in eliminating common waterborne pathogenic bacteria after a 6-h exposure under suitable conditions. However, there are cases where faecal coliforms show slower rates of inactivation, and certain subpopulations of *E. coli* have been found to be more resistant to light and show reduced rates of inactivation (Wegelin *et al.* 1994). This highlights the diverse responses of bacterial strains to solar disinfection, suggesting the presence of factors that influence their susceptibility. While spore-forming bacteria like *Bacillus cereus* and *Clostridium perfringens* can withstand SODIS, they are not typically associated with waterborne transmission or considered pathogens, but studying their behaviour provides insights into the effectiveness of SODIS against more complex micro-organisms (McGuigan *et al.* 2012).

Protozoan pathogens, such as *Giardia lamblia* and *Cryptosporidium* spp, exhibit resistance to SODIS due to their infective stages being enclosed in protective structures, such as cysts or oocysts (McGuigan *et al.* 2012). These structures make them more resilient to environmental stress, including solar UV radiation, making it more difficult to efficiently remove or inactivate them using SODIS (Luzi *et al.* 2016). Even other disinfection methods like boiling and chlorination struggle to fully inactivate cysts, requiring higher heat intensity and longer exposure durations (Den Besten *et al.* 2018). Studies have shown that SODIS can effectively inactivate poliovirus but may not significantly reduce the viability of *Acanthamoeba polyphaga* cysts at lower temperatures (Heaselgrave *et al.* 2006). Similarly, SODIS and other disinfection methods have limited effectiveness against the cyst stage of *A. polyphaga* (Lonnen *et al.* 2005). These findings emphasize the challenge of dealing with the resistant stages of protozoan pathogens in the context of SODIS, necessitating alternative approaches or higher UV doses for effective inactivation.

On the other hand, different viral species exhibit varying degrees of resistance to solar disinfection. Some viruses such as somatic phage, bacteriophage f2, bovine rotavirus, and polio virus have been completely inactivated within a few hours of exposure to sunlight. However, picornavirus (encephalomyocarditis) required a longer exposure time of 12.5 h for complete inactivation (Wegelin *et al.* 1994). In a study conducted by Harding & Schwab (2012), it was found that MNV (murine norovirus) displayed exceptional resistance to SODIS. Despite a 6-h exposure, SODIS only achieved a 1.4 log reduction in MNV. This raises concerns about the efficacy of SODIS in preventing viral gastroenteritis caused by human norovirus. Further investigation is needed to gain a deeper understanding of this issue. Parsa *et al.* 2021 contend that SODIS has limited effectiveness in eradicating the SARS-CoV-2 virus. The reason for this lies in the specific requirements of the virus, which necessitates higher temperatures (>56 °C) and UV-C wavelengths (100–280 nm) for successful inactivation. In contrast, conventional SODIS systems typically operate at lower temperatures (<45 °C) and utilize UV-A radiation (315–400 nm). As a result, relying solely on SODIS as a method for wastewater treatment or ensuring the safety of drinking water during the pandemic may not be a dependable approach.

2.5. Enhancing pathogen removal in SODIS treatment

Disinfection efficacy of the SODIS method depends on a number of parameters including type of pathogenic organism, irradiation intensity, material and size of bottles, place and position of bottle exposure, turbidity and dissolved organic matter, oxygen content, water temperature, and re-growth of pathogens after treatment. Each of them affects pathogen removal in one way or another. A detailed discourse of each of these factors is discussed in the SODIS manual (Luzi *et al.* 2016).

To address some of the limitations of the conventional SODIS method, some innovative strategies aimed to enhance the disinfection process and maximize the benefits of SODIS have been explored. They include approaches such as painting the bottom of plastic bottles black to enhance thermal disinfection (Wegelin & Sommer 1998), using solar concentrators/reflectors to amplify radiation exposure, and incorporating chemical additives like citric acid or riboflavin that can be activated by sunlight (McGuigan *et al.* 2012; Cowie *et al.* 2020). Chemical additives like citrus-based compounds (Harding & Schwab 2012) and riboflavin (Heaselgrave & Kilvington 2010) are also known to enhance solar disinfection. For instance, lime juice/pulp reduced *E. coli* levels within a short duration of 30 min in a study by Harding & Schwab (2012). Heaselgrave & Kilvington (2010) used riboflavin (vitamin B2) in combination with UV-A radiation as a potential therapeutic application for treating ocular bacterial and fungal pathogen. The results demonstrate that the inclusion of riboflavin in SODIS (SODIS-R) significantly improved the eradication of micro-organisms compared to SODIS alone. The addition of riboflavin reduced the time needed for complete inactivation, allowing SODIS-R to achieve a faster and more effective elimination of organisms than SODIS alone. However, the highly resistant *A. polyphaga* cysts and *Bacillus subtilis* spores were unaffected by both SODIS and SODIS-R at an optical irradiance of 150 $W\ m^{-2}$.

Further, a study by Rodríguez-Chueca *et al.* (2019) shows the feasibility of enhancing solar disinfection (SODIS) treatment by incorporating chemical additives such as peroxymonosulfate (PMS) and peroxydisulfate (PDS) to generate sulphate and hydroxyl radicals through various activation routes. The study examined the efficacy of using different promoters, including sunlight irradiation, mild heat (40 °C), and micromolar amounts of Fe^{2+} (iron) as activation factors. The results showed that PMS had higher efficiency compared to PDS in removing *E. coli*, requiring lower concentrations and shorter reaction times for complete bacterial inactivation. When all the promoters were combined (oxidant/Fe2 + /sunlight/40 °C), total bacterial inactivation was achieved within 30 min using PMS, whereas it took twice as long with PDS. Moreover, the addition of hydroxyl radicals alongside PMS further enhances the disinfection process, achieving complete bacterial removal in just 20 min. In addition, the combined processes were effective in eliminating contaminants of emerging concern, such as drugs and pesticides.

Efforts have also been made to concentrate solar radiation inside SODIS bottles by using solar mirrors. For instance, *E. coli* inactivation efficiency was significantly improved in aluminium foil backed bottles in a study by Kehoe *et al.* (2001). Bacterial populations in bottles with foil backing exhibited a mean decay constant that was 1.85 times higher than those without foil backing, indicating a more rapid inactivation. According to McGuigan *et al.* (2012), several flow reactor designs have been investigated to improve solar disinfection. Some designs concentrate on increasing optical inactivation by utilizing solar collectors and reflectors, while others aim to enhance thermal inactivation by incorporating black plates or TiO_2 photocatalyst.

The integration of SODIS with more advanced approaches such as heterogeneous photocatalysis and solar photothermal disinfection systems holds promise in addressing limitations of traditional SODIS methods. These methods have been suggested to be more efficient, and their integration with SODIS has been reported to yield improved outcomes. For instance, according to Cowie *et al.* (2020), incorporating a highly efficient photocatalyst has the capacity to enhance SODIS to a much greater extent compared to other enhancement approaches. However, their costs are prohibitively high to be considered as a part of the SODIS system for use in the developing world where the majority are poor and vulnerable (McGuigan *et al.* 2012). Other affordable techniques to enhance the treatment efficiency of the standard procedure include the placing of filled plastic bottles on sunlight-reflective surfaces such as aluminium or corrugated iron sheets to boost the amount of sunlight absorbed by the bottle, shaking a two-thirds filled bottle vigorously for 30 s before topping up and sealing, to increase initial levels of dissolved oxygen for solar induced oxidative inactivation processes, and filtering the water before filling (McGuigan *et al.* 2012).

2.5.1. Titanium dioxide photocatalysis

Photocatalysis has emerged as a promising method for water treatment, offering a solution to the limitations of traditional SODIS disinfection approaches. It involves using light energy to facilitate a chemical reaction between a photocatalyst and contaminated water. Typically, a semiconductor material like titanium dioxide (TiO_2) is used as the photocatalyst. When exposed to light, TiO_2 generates ROS that can inactivate micro-organisms. This photocatalytic process has shown remarkable efficacy, stability, affordability, and safety. TiO_2 is a widely studied photocatalyst for water treatment applications, particularly for pathogen inactivation (Butterfield *et al.* 1997; Caballero *et al.* 2009; Guo *et al.* 2019; Bono *et al.* 2021). When TiO_2 is exposed to light energy above its band gap, it generates electron (e^-) and hole (h^+) pairs that participate in redox reactions, leading to the production of ROS (Huang *et al.* 2017). These ROS possess strong oxidation potential, enabling them to penetrate the cell walls of micro-organisms and disrupt their cellular structures (Foster *et al.* 2011; McGuigan *et al.* 2012). The attack on the cell membrane releases intracellular organic matters which are then oxidized by the ROS, causing further damage to the microorganism's vital components and processes (Huang *et al.* 2017). This ultimately results in the inactivation of the microorganism. The photocatalytic mechanism of TiO_2 involving ROS has been extensively studied (Malato *et al.* 2009; Chong *et al.* 2010; Schneider *et al.* 2014) and relies on the unique electron characteristics of TiO_2 as a semiconductor (Chong *et al.* 2010). Under sufficient photon energy (hv), e^- and h^+ pairs are formed, initiating a series of reductive and oxidative reactions on the surface of TiO_2. The interfacial redox reactions between electrons and holes serve as the primary reactions underlying the photocatalytic process (Bono *et al.* 2021). Figure 2 illustrates the formation of electron–hole pairs when TiO_2 particles are irradiated with sufficient photon energy.

Studies have shown that incorporating TiO_2 into SODIS significantly enhances its effectiveness compared to traditional SODIS alone. Duffy *et al.* (2004) demonstrated that the inclusion of flexible plastic inserts coated with TiO_2 powder in PET plastic SODIS reactors resulted in an improvement of 25% in their effectiveness compared to standard SODIS reactors, in terms of inactivating *E. coli* K12. In another study, TiO_2-equipped SODIS reactors achieved faster inactivation

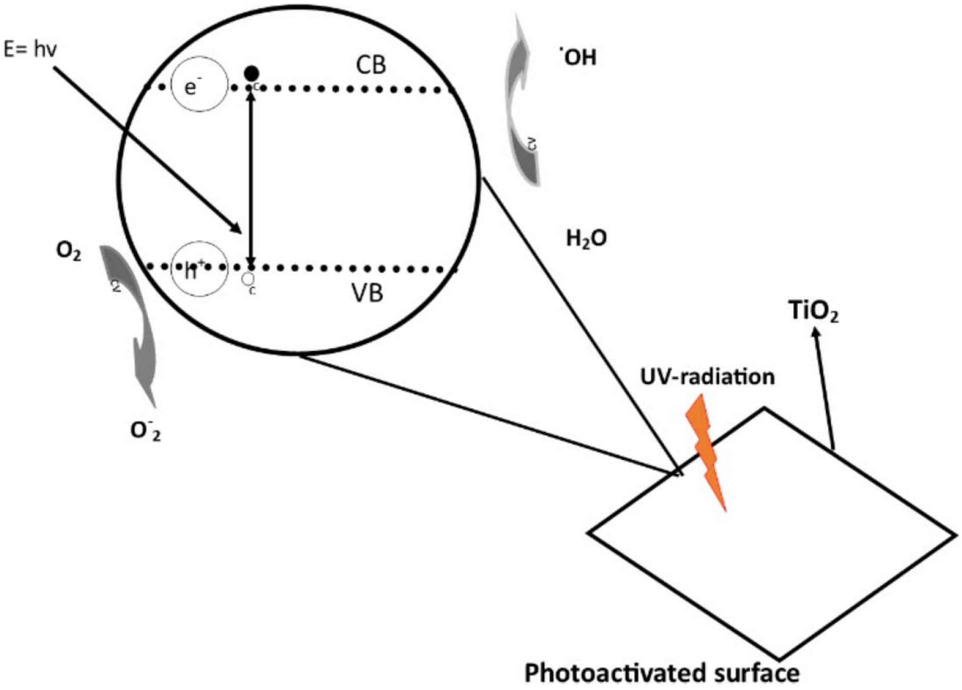


Figure 2 | Illustration of how electron–hole pairs are formed in a TiO_2 semiconductor particle when it is exposed to light in the presence of a water pollutant.

of micro-organisms compared to the standard SODIS, even under partial cloud cover (Lonnen *et al.* 2005). The presence of TiO_2 in SODIS treatments led to faster and more efficient disinfection, achieving non-detectable levels of coliform bacteria within a shorter exposure time. In a study by (Gelover *et al.* 2006), a minimum average global radiation of 800 W/m^2 was found to be necessary for effective disinfection, and TiO_2 photocatalysis prevented bacterial re-growth observed in standard SODIS treatments. The photocatalytic properties of TiO_2 facilitated irreversible damage to bacterial cells, even in UV-resistant micro-organisms, preventing re-growth after disinfection.

2.5.2. Nanomaterial-enhanced solar photothermal disinfection

Solar photothermal disinfection systems utilize solar energy to generate heat, which is crucial for killing pathogens. Noble metal-based plasmonic nanoparticles like gold, silver, and platinum have been extensively studied for their photothermal properties. However, their practical use is limited due to high costs and potential toxicity (Tang *et al.* 2022). To overcome these challenges, researchers have focused on developing alternative and cost-effective photothermal catalysts using carbon-based and phosphorus-based nanoparticles derived from readily available resources. Incorporating light-harvesting materials such as carbon nanotubes (CNTs) or metallic nanoparticles into photothermal disinfection systems enhances heat absorption and water temperature, leading to pathogen inactivation (Loeb *et al.* 2018). Solar photothermal disinfection combines thermal effects with other mechanisms to destroy pathogens by disrupting cellular processes, damaging cell structures, denaturing proteins, and disrupting cell membranes. Studies have demonstrated that solar radiation increases water temperature, accelerating bacterial inactivation. Advanced SODIS systems with photothermal conversion materials achieve even higher temperatures. The synergy between solar radiation and photo-induced heat results in the accumulation of ROS, further enhancing bacterial inactivation (Hong *et al.* 2022).

The recent study by Hong *et al.* (2022) investigated the use of a photothermal film reactor made of CNTs, which efficiently transferred heat to water, and rapidly heated it to temperatures above 45 °C, leading to significant bacterial inactivation within just 20 min. The accumulated ROS played a crucial role in destroying bacterial cell membranes and RNA, ultimately leading to bacterial cell death. Transcriptomic analysis revealed changes in gene expression during solar photothermal disinfection, with specific genes showing heightened activity under heat and photothermal stress. SafA, for example, played a role in suppressing ROS accumulation and oxidative stress. Solar photothermal disinfection also affected metabolic pathways, ribosome-related pathways, and nucleic acid synthesis, contributing to bacterial deactivation.

To overcome the limitations of bulk water boiling for water sterilization, Loeb *et al.* (2018) explored nanomaterials capable of converting solar energy into heat for direct bacterial and viral inactivation. To facilitate practical implementation, Loeb *et al.* developed a method to immobilize these light-absorbing nanomaterials onto films, creating functional devices for water treatment. Through their experiments, they demonstrated that these specially designed films, when exposed to simulated solar light, possessed the capability to thermally deactivate bacteria and viruses. The efficacy of the approach was verified through successful inactivation of surrogate organisms, including *E. coli* K-12, as well as bacteriophages MS2 and PR772. In a subsequent study (Loeb *et al.* 2019), it was reported that using light-harvesting nanoparticles in the form of photothermal films allowed for the achievement of functional disinfection temperatures using unconcentrated sunlight. The films containing nanoparticles, carbon black, and gold nanorods in a polymer, inactivated pathogens even at higher flow rates. Lower light intensity reduced inactivation, but Sun still achieved significant reduction. Carbon black alone showed similar efficacy to composite films with gold nanorods. Simulations indicated a compact reactor footprint (45 cm × 45 cm) could produce 8 l of safe water per day with 8 h of sunlight exposure, highlighting scalability for community needs.

3. EFFECTIVINESS OF SODIS

3.1. Microbiological efficacy

SODIS has been subject to rigorous testing, both in the laboratory and under field conditions, and has been proven to improve microbial quality of drinking water due to its biocidal effects against all waterborne pathogenic micro-organisms (Sommer *et al.* 1997; Wegelin & Sommer 1998; Sobsey *et al.* 2008; Clasen 2009). Results by McGuigan *et al.* (2006) have shown that cysts of *Giardia muris* and oocysts of *Cryptosporidium parvum* are rendered completely non-infective after batch SODIS exposures of 4 and 10 h, respectively. Likewise Joyce *et al.* (1996) reported complete disinfection of heavily contaminated water with a wild-type strain of *E. coli* within 7 h. There were no viable *E. coli* organisms detected either at the end of the experiment or 12 h later, indicating that no bacterial recovery occurred after disinfection. A study by Dessie *et al.* (2014) in Ethiopia also demonstrated complete and irreversible faecal coliform inactivation within 4 h of exposure in areas with ample sunshine (solar irradiance of about 3.99 kW/m^2 and above). Several other laboratory experiments and field studies have demonstrated solar disinfection efficacy in destroying diarrhoea-causing enteric pathogens (Wegelin *et al.* 1994; McGuigan *et al.* 1998, 2006; Smith *et al.* 2000; Kehoe *et al.* 2004; Lonnen *et al.* 2005; Berney *et al.* 2006; Méndez-Hermida *et al.* 2007; Boyle *et al.* 2008; Mtapuri-Zinyowera *et al.* 2009; Beattie *et al.* 2019; Chidya *et al.* 2021; Karim *et al.* 2021). Table 2 presents some of enteric pathogens commonly known to be inactivated by SODIS.

3.2. SODIS health impacts

SODIS has proven to be a highly efficient approach for enhancing public health in areas where access to clean drinking water is limited. Various research and field trials have consistently confirmed the effectiveness of SODIS in enhancing water quality and reducing the occurrence of waterborne illnesses. Implementation of SODIS in various communities has resulted in substantial decreases in microbial contamination and notable improvements in health outcomes.

3.3. Randomized trials in Kenya's Maasai community

The pioneering research conducted in Kenya's Maasai community demonstrated the significant impact of SODIS on water disinfection and health outcomes (Conroy *et al.* 1996, 1999, 2001). In the initial trial, children who consumed water exposed to sunlight had a significantly lower risk of diarrhoeal episodes compared to a control group. A subsequent trial specifically targeting children younger than 6 years showed a sustained 16.0% risk reduction in diarrhoeal illness through SODIS. Finally, during a cholera outbreak, children younger than 6 years in households using solar disinfection had significantly lower cholera incidence compared to the control group. Although detailed information about the water quality in the control groups is not available, the results strongly indicate that SODIS played a crucial role in lowering illness rates within the community.

3.4. Success stories in Bolivia, Pakistan, Uzbekistan, Nepal, and India

SODIS has achieved remarkable success globally, demonstrating its effectiveness in reducing diarrhoea and improving community health. These success stories, documented by Meierhofer (2006) and Meierhofer & Landolt (2009), provide compelling evidence of the positive impact of SODIS. For instance, in Bolivia, SODIS reduced diarrhoea incidence by over 35% among more than 200 children under 5 years old. Similarly, Uzbekistan saw a remarkable 53% reduction in diarrhoea cases among children younger than 5 years. These examples highlight the transformative power of SODIS in promoting the well-being of young children and securing a healthier future for them. In Pakistan's Rajoa and Chiniot, diarrhoea rates decreased from 26 to 13% and from 39 to 19% respectively, thanks to SODIS. In Nepal, East Lombok, and Assam, India, SODIS proved effective in reducing diarrhoea rates, benefiting over 970,000 users and preventing an estimated 2.4 million

Table 2 | Waterborne microbial species that are now known to be inactivated by SODIS (McGuigan *et al.* 2012)

Microbe	Species	Microbe	Species
Bacteria	*Campylobacter jejuni* *Enterococcus* sp. Enteropathogenic *Escherichia coli* *Mycobacterium avium* *Mycobacterium intracellulare* *Pseudomonas aeruginosa* *Salmonella typhi* *Salmonella typhimurium* *Shigella dysenteriae* Type I *Shigella flexneri* *Streptococcus faecalis* *Staphylococcus epidermidis* *Vibrio cholerae* *Yersinia enterocolitica*	Viruses	Bacteriophage f2 Encephalomyocarditis virus Polio virus Rotavirus Norovirus
Fungi	*Fusarium* sp. *Candida albicans*	Protozoa	*Acanthamoeba polyphaga* (cyst) *Cryptosporidium parvum* (oocyst) *Entamoeba* sp. (cysts)
Helminth	*Ascaris* sp. (ova)		*Giardia* sp (cysts)

cases of diarrhoea annually in the project areas. The widespread adoption of this accessible and sustainable solution has positively impacted the lives of numerous individuals.

These findings are supported by several other successful controlled randomized trials under typical environmental and cultural conditions in different countries including Kenya, South African, Cameroon, India, and Cambodia (Table 3). As can be seen from Table 3, SODIS reduced diarrhoeal diseases by 36–75% in these countries. Apart from SODIS, other POU treatment techniques, such as chlorination, have shown almost similar diarrhoea reduction results, mostly in the range of 30–40% (Quick *et al.* 2002; Mengistie *et al.* 2013; Pickering *et al.* 2019; Solomon *et al.* 2020). However, the efficacy of boiling in reducing diarrhoea when applied in households has been poorly documented despite compelling evidence that it can completely eliminate all pathogens in drinking water. Nevertheless, according to a 2014 WHO report, effective household water treatment (taken as boiling or filtration and safe storage) has shown the greatest disease reduction of 45% (World Health Organization 2014).

4. OPPORTUNITIES AND CHALLENGES TO SODIS SUSTAINED USE AND SCALABILITY

While the efficacy of the SODIS method in reducing exposure to enteric pathogens and improving microbiological water quality has been manifested, the realization of the corresponding health benefits (diarrhoea reduction) can be possible only if considerable number of users accept (adopt) the technology and continue to use it correctly and consistently over long periods. Sustainability entails that people remain sufficiently motivated and committed to integrate the technique into their daily lives even long after intensive study interventions have ended (Sobsey *et al.* 2008). In this case, SODIS-treated water has to constitute a significantly large percentage of drinking water consumed by the people in the targeted community, and it should be consumed constantly, habitually, and without interruption to supply (McGuigan *et al.* 2012). Scalability is attained when the initial small-scale pilots that reached a small number of beneficiaries translate to widespread adoption of the intervention, eventually reaching millions, after implementation (World Health Organization 2007).

Usually, it is challenging to achieve continued high acceptance and long-term use for innovations that are associated with a higher user burden, high or recurrent costs, or those that demand significant behaviour change from users (Brown & Clasen 2012). In the following sections, we look at opportunities and challenges to widespread and sustained use of SODIS.

4.1. Opportunities

4.1.1. Cost-effectiveness

The cost and willingness to pay for HWT technologies are important considerations for their implementation (Sobsey 2002). High price is one of the most significant barriers to the adoption of any POU treatment option, and willingness to pay studies reveal that the demand for a POU system begins to decline when the expense reaches 0.3–0.4% of annual household income (Deng 2021). For instance, McGuigan *et al.* (2012) reported that the frequently cited reason for continued use of SODIS has been based on economic benefit first rather than improvement of health. With an estimated cost of only $0.63 per person per year (Clasen *et al.* 2007a; Clasen 2009), SODIS is one of the cheapest household-based interventions against waterborne disease when compared with other methods like boiling, chlorination, filtration, and flocculation, which have estimated costs of $10.56, $0.66, $3.03, and $4.95 per person per year, respectively (García-Gil *et al.* 2021, 2022). The method relies mainly on locally available resources (PET bottles and sunlight) and is replicable with low investment costs (Meierhofer & Wegelin

Table 3 | Diarrhoeal disease reduction by SODIS in controlled studies

Location	Reduction in diarrhoeal disease (%)	References
Dabat district, northwest Ethiopia	40	Bitew *et al.* (2018)
Nakuru, Kenya	44	du Preez *et al.* (2011)
South African	36	du Preez *et al.* (2010)
Slum areas of Yaoundé́, Cameroon	42.5	Graf *et al.* (2010)
Urban slum in Vellore, Tamil Nadu, India	40	Rose *et al.* (2006)
Rural Cambodia	50	McGuigan *et al.* (2011)
Sikkim, India	75.83	Rai *et al.* (2010)

2002). Despite these low costs, the method has been demonstrated to have inactivation efficiency for bacteria in real field applications comparable to that of high-priced interventions such as chlorination and ceramic filtration (Luzi *et al.* 2016).

4.1.2. User friendliness

Besides being cost-effective, the application procedure of SODIS is very simple. This is important for sustainability as it is argued that people are more willing to modify their behaviours towards a technology when its application is easy to perform and materials are locally sourced (Juran & MacDonald 2014). However, this simplicity may also present a disadvantage. The effectiveness of SODIS as a treatment method is frequently questioned and met with scepticism due to its simple procedure. As a result, it is often overshadowed by well-established methods such as chlorination (Morse *et al.* 2020). For instance, in their study to establish factors influencing the sustained use of SODIS from a global promotion and dissemination programme, Meierhofer & Landolt (2009) reported that educated people were more difficult to being convinced that SODIS can efficiently treat drinking water. Likewise, Rai *et al.* (2010) faced tough opposition to convince healthy people in the urban slum regarding the effectiveness of this simple cost-effective method.

4.1.3. Environmental friendliness

SODIS is an environmentally sound technology that does not require the use of traditional energy sources such as firewood, charcoal, and kerosene/gas (EAWAG/SANDEC 1991; Davarcioglu 2015). Consequently, deforestation, which is a major environmental problem in most developing countries, and air pollution, created by burning conventional energy sources, are reduced (Davarcioglu 2015). For instance, it is estimated that 1 kg of wood is needed to boil 1 l of water (Clasen 2009). This is not only too far beyond the reach of most poor households but also contributes to deforestation. By using SODIS, it is speculated that a household can save approximately 3,650 kg of wood per year (Dessie *et al.* 2014). Besides, the time and energy that would have been otherwise spent on sourcing firewood, primarily for women and girls, is committed to other productive activities (Clasen 2009). Furthermore, the use of empty plastic bottles promotes the recycling of solid waste. However, frequent replacement of plastic bottles may lead to environmental issues (EAWAG/SANDEC 1991).

4.1.4. No changes in the taste of water

SODIS is independent of additional of chemicals. As a result, it is associated with minimal change in water taste and does not introduce chemicals or cause the production of harmful disinfection by-products in the drinking water (EAWAG/SANDEC 1991; Sobsey 2002). Besides, re-contamination is very unlikely if water is consumed directly from the small, narrow-necked bottles with caps in which it was treated (Lantagne *et al.* 2006).

4.2. Challenges

4.2.1. The need for user's behaviour change

Implementing SODIS entails additional efforts, such as proper water treatment, regular bottle cleaning and replacement to prevent biofilm growth, daily management of multiple bottles, post-treatment hygiene practices, and other activities that necessitate changes in both behaviour and lifestyle for SODIS users (Sobsey 2002; Clasen *et al.* 2007b; McGuigan *et al.* 2012). In this case, the target population is expected to be more willing to modify their routine behaviours and adopt new ones as demanded by the technology. Unfortunately, people seldom change and sustain new behaviours as intended (Figueroa & Kincaid 2010). This, coupled with factors such as cultural beliefs, lack of awareness, and competing priorities, contributes to inconsistent adherence and compliance among users. For example, individuals may be reluctant to adopt SODIS due to scepticism or cultural practices that favour alternative water treatment methods. In other cases, people may forget or neglect to expose the bottles to sunlight for the recommended time, compromising the effectiveness of the disinfection process. In addition, Figueroa & Kincaid (2010) pointed out the lack of clear and compelling benefits to convince the users to continue with the new behaviour. For example, McGuigan *et al.* (2012) noted the difficulties in persuading individuals who have grown accustomed to strong sunlight throughout their lives and have never considered the possibility that sunshine could disinfect water. To enhance the effectiveness of SODIS, it is suggested that the fundamental technical component be complemented with intensified efforts to promote behaviour change and motivation (Sobsey 2002). Meierhofer (2006) asserts that comprehensive community education, sensitization, and advocacy campaigns play a vital role in establishing SODIS at the grassroots level.

4.2.2. Quantity of water produced and time to treat

While the operation of SODIS requires simple steps, the system is suitable for treating small volumes of water and exposure to sunlight is typically carried out in small-volume plastic beverage bottles (Borde *et al.* 2016). Consequently, the safe drinking water demand is not always met unless a number of bottles are put to use at the same time. This can create a labour-intensive process, especially considering the considerable time required for water treatment, leading to decreased user acceptability (Meierhofer & Wegelin 2002; Lantagne *et al.* 2006; Borde *et al.* 2016). Nevertheless, as earlier discussed, some enhancements may be used to reduce treatment time. Besides, other studies have demonstrated the feasibility of increasing the volume PET containers. An experiment conducted in Spain by Keogh et al. (2015) confirmed that under conditions of strong sunlight and mild temperature, 19-l water dispenser containers provide bacterial inactivation similar to 2-l PET bottles. Results of a recent study conducted in four rural communities in the Tigray Region in Northern Ethiopia reported a similar decrease in cases of diarrhoeal diseases in children in the implementation (25 l PET TJC) and control (2 l PET bottles) groups (García-Gil *et al.* 2022). In another study, Polo-López et al. (2019) observed similar inactivation kinetics for *E. coli*, MS2-phage, and *C. parvum* using 5- and 20-l transparent polypropylene buckets fabricated locally at a low cost in Malawi. The larger 20-l bucket size resulted in a 10-fold expansion of the treatment batch volume, making it simpler to fulfil the drinking water needs of most households. These findings indicate that alternative container sizes and materials can offer potential solutions to the limitations of small bottle-based SODIS systems. Implementing larger containers or buckets may increase the water treatment capacity and efficiency, potentially enhancing the practicality and acceptability of SODIS in various settings.

The study further reported that UV transmission of the 20-l buckets remained stable and with physical integrity even after the longest ageing periods (9 months or 900 h of natural or artificial solar UV exposure, respectively). They also observed that the lesser thickness of the 5-l bucket resulted in easy physical degradation and loss of significant UV transmission than the 20-l bucket. However, the reason behind the 5-l bucket's greater loss of UV transmission compared to the thicker 20-l one is not clearly understood. This is surprising because thicker materials generally have a higher probability of scattering light compared to thinner materials. The increased thickness provides more opportunities for light to interact with the particles or structures within the material, increasing the likelihood of scattering events as the light passes through. Therefore, further investigation is needed to understand why the thinner bucket exhibited a higher loss of UV transmission despite the expected scattering behaviour associated with thicker materials.

4.2.3. Unavailability of PET bottles

Local availability of the sufficient number of the required bottles is crucial for consistent and widespread long-term use of SODIS application (Meierhofer 2006). In many areas, inaccessibility of PET bottles happens to be the limiting factor for the continued SODIS use. For instance, Murinda & Kraemer (2008) found out that unavailability of plastic PET bottles was the most important potential hindrance to the successful implementation of SODIS in Zimbabwe. In areas where plastic bottles are not easily accessible, it becomes necessary to establish a supply system to acquire and transport used plastic bottles from urban areas to rural communities (Meierhofer 2006). To address the scarcity of PET bottles in certain areas, Meierhofer & Landolt (2009) suggested the establishment of micro-enterprises. They highlighted the successful implementation of a bottle supply system in East Lombok, where the local health system initiated a program to purchase empty bottles from a PET-bottle producer for distribution to users through health posts. Currently, commercially produced PET bottles specifically designed for water disinfection purposes are scarce, prompting the use of standard PET bottles originally intended for other applications.

4.2.4. Limited knowledge on germ disease theory

The inability of poorly educated villagers to comprehend the germ theory of disease also makes it difficult for them to appreciate the need to adopt water treatment practices (Gilman & Skillicorn 1985). As pointed out by Meierhofer (2006), it is difficult to create an understanding among illiterate people on the relation between the consumption of contaminated drinking water, hygiene practices, and the dangers of invisible pathogens on human health. The concept of invisible microorganisms causing diseases is abstract and difficult to grasp without basic education on germ theory. According to Figueroa & Kincaid (2010), water treatment is not always perceived to have health benefits by many people, and diarrhoea is not always seen as a significant health threat. Rather, it is widely viewed as part of growing up and may even be seen as beneficial for children (Figueroa & Kincaid 2010). The observations made by Murinda & Kraemer (2008) in Zimbabwe further support the notion of limited knowledge about bacterial contamination of water as a major challenge for the implementation of

SODIS. In their study, they reported that limited knowledge about bacterial contamination of water was one of the major challenges to the implementation of SODIS in the country.

Generally, the lack of awareness about the presence of harmful bacteria in water hinders the recognition of the need for water treatment methods like SODIS. Without a clear understanding of the risks associated with bacterial contamination, it becomes difficult to motivate individuals to adopt and sustain water treatment practices. Addressing this issue requires comprehensive education and awareness campaigns. These campaigns should aim to bridge the knowledge gap by providing accessible information about the connection between contaminated water, hygiene practices, and the impact of invisible pathogens on human health. By promoting understanding and raising awareness, it may become possible to overcome the barriers posed by limited knowledge on the germ theory of disease and foster the adoption of effective water treatment practices like SODIS.

4.2.5. Concerns for possible chemical leaching

While reusing plastic bottles over time makes SODIS cost-effective and a plus in solid waste recycling, a review in literature by Borde *et al.* (2016) revealed concerns about leaching of chemicals such as antimony and phthalates from plastic containers (with PET) into the food or water they contain. It is argued that exposing plastics made from PET to high temperatures results in leaching of some toxic additives such as acetaldehyde, antimony, and phthalates (Alabi *et al.* 2019). However, contrary to these fears, conclusions from studies by Wegelin *et al.* (2001); Schmid *et al.* (2008) and Ubomba-Jaswa *et al.* (2010) have refuted the migration of hazardous chemicals in critical levels into SODIS water.

Nevertheless, there are alternatives to plastic bottles for SODIS applications. For example, transparent pouches or bags made of UV-transmitting materials have been explored as alternative reactors. The study by Gutiérrez-Alfaro *et al.* (2017) revealed that certain types of transparent plastic bags, such as those made from polyethylene (PE), can yield better results compared to PET bottles traditionally used in SODIS. It was further found that PE bags demonstrated faster disinfection, achieving a 6-log reduction within 60 min. Other types of bags like bio-oriented polypropylene, polyamide, and PET also outperformed PET bottles in terms of disinfection efficacy. The orientation of the bags or bottles (vertical or horizontal) did not significantly impact the disinfection results. In addition, according to Wegelin & Sommer (1998), the use of flat plastic bags with a volume ranging from 2 to 6 cm was found to offer an improved area-to-volume ratio and higher water temperatures compared to traditional round bottles. Furthermore, glass reactors equipped with compound parabolic collectors have also been found to be effective and can accommodate larger volumes (García-Gil *et al.* 2019). Transparent 20L PE containers can also serve as durable and long-lasting alternatives to standard plastic bottles, reducing the need for frequent replacements (Polo-López *et al.* 2019).

5. CONCLUSIONS AND PERSPECTIVES

A general overview of the effectiveness of the SODIS technique in both improving microbiological water quality and reduction of infectious diarrhoeal diseases was examined. The efficacy of SODIS in inactivating enteric pathogens and improving microbial water quality and reducing diarrhoeal disease incidences has been demonstrated in various laboratory works and field trials. Capitalizing mainly on locally available resources, it has been shown that SODIS has managed to reduce diarrhoeal disease incidences, as much as above 75%, in some developing countries. The synergistic effect that results as a consequence of the combined effect of UV light and rise in water temperature has been demonstrated to eliminate 99.9% of many enteric micro-organisms.

However, certain pathogens, particularly those with protective structures such as cysts, may be less susceptible to solar disinfection, requiring alternative approaches or higher UV doses for effective inactivation. Moreover, it is essential to carefully consider issues such as extended exposure time, pathogen re-growth, and resistance during the application of SODIS. To overcome these limitations, several innovative approaches have been proposed to enhance the effectiveness of SODIS and reduce the required exposure time. Technologies like TiO_2 photocatalysis and nanomaterial-enabled solar photothermal disinfection have shown promising results in terms of improved inactivation efficiency and prevention of pathogen re-growth. However, integrating these technologies with SODIS requires specialized equipment and materials, which negates the original concept of SODIS as a low-cost and simple water disinfection method. Utilizing inexpensive and sustainable materials would be a desirable option for scalability and sustainability. Besides, research efforts should focus on developing cost-effective and scalable production methods for catalysts and nanomaterials, making them more accessible to communities with limited resources. This may involve investigating alternative materials or modifying existing ones to enhance affordability and availability.

Comprehensive studies should also be conducted to assess the performance and limitations of the integrated system under different environmental conditions and water sources. Establishing practical guidelines for users is crucial to ensure optimal operation and reliable disinfection outcomes. Collaboration among researchers, engineers, and policymakers is vital to gather data, exchange knowledge, and develop standardized protocols for implementing the integrated approach. Moreover, raising public awareness and providing education about the integrated approach is essential. Communities should be informed about the advantages, limitations, and proper usage of the technology. Training programs and educational materials should be provided to empower individuals and communities to effectively adopt and utilize the integrated system, maximizing its benefits and ensuring long-term sustainability.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Alabi, O. A., Ologbonjaye, K. I., Awosolu, O. & Alalade, O. E. 2019 Public and environmental health effects of plastic wastes disposal: a review. *J Toxicol Risk Assess* **5** (021), 1–13. https://doi.org/10.23937/2572-4061.1510021.

Ballesteros, M., Brindley, C., Sánchez-Pérez, J. A. & Fernández-Ibañez, P. 2021 Worldwide research trends on solar-driven water disinfection. *International Journal of Environmental Research and Public Health* **18** (17), 9396. https://doi.org/10.3390/ijerph18179396.

Beattie, A., Dillon, H., Poor, C. & Kenton, R. 2019 Solar water disinfection with parabolic and flat reflectors. *Journal of Water and Health* **17** (6), 921–929. https://doi.org/10.2166/wh.2019.174.

Berney, M., Weilenmann, H. U., Simonetti, A. & Egli, T. 2006 Efficacy of solar disinfection of *Escherichia coli*, *Shigella flexneri*, *Salmonella typhimurium* and *Vibrio cholerae*. *Journal of Applied Microbiology* **101** (4), 828–836. https://doi.org/10.1111/j.1365-2672.2006.02983.x.

Bitew, B. D., Gete, Y. K., Biks, G. A. & Adafrie, T. T. 2018 The effect of SODIS water treatment intervention at the household level in reducing diarrheal incidence among children under 5 years of age: a cluster randomized controlled trial in Dabat district, northwest Ethiopia. *Trials* **19** (1), 1–15. https://doi.org/10.1186/s13063-018-2797-y.

Bono, N., Ponti, F., Punta, C. & Candiani, G. 2021 Effect of UV irradiation and TiO_2-photocatalysis on airborne bacteria and viruses: an overview. *Materials* **14** (5), 1075. https://doi.org/10.3390/ma14051075.

Borde, P., Elmusharaf, K., McGuigan, K. G. & Keogh, M. B. 2016 Community challenges when using large plastic bottles for solar energy disinfection of water (SODIS). *BMC Public Health* **16** (1), 1–8. https://doi.org/0.1186/s12889-016-3535-6.

Boyle, M., Sichel, C., Fernández-Ibáñez, P., Arias-Quiroz, G., Iriarte-Puná, M., Mercado, A., Ubomba-Jaswa, E. & McGuigan, K. 2008 Bactericidal effect of solar water disinfection under real sunlight conditions. *Applied and Environmental Microbiology* **74** (10), 2997–3001. https://doi.org/10.1128/AEM.02415-07.

Brown, J. & Clasen, T. 2012 High adherence is necessary to realize health gains from water quality interventions. *PloS one* **7** (5), e36735. https://doi.org/10.1371/journal.pone.0036735.

Butterfield, I., Christensen, P., Curtis, T. & Gunlazuardi, J. 1997 Water disinfection using an immobilised titanium dioxide film in a photochemical reactor with electric field enhancement. *Water Research* **31** (3), 675–677. https://doi.org/10.1016/S0043-1354(96)00391-0.

Caballero, L., Whitehead, K., Allen, N. & Verran, J. 2009 Inactivation of *Escherichia coli* on immobilized TiO_2 using fluorescent light. *Journal of Photochemistry and Photobiology A: Chemistry* **202** (2–3), 92–98. https://doi.org/10.1016/j.jphotochem.2008.11.005.

Castro-Alférez, M., Polo-López, M. I., Marugán, J. & Fernandez-Ibanez, P. 2017 Mechanistic modeling of UV and mild-heat synergistic effect on solar water disinfection. *Chemical Engineering Journal* **316**, 111–120. https://doi.org/10.1016/j.cej.2017.01.026.

Chidya, R. C., Munthali, A. K., Chitedze, I. & Chitawo, M. L. 2021 Design and efficacy of solar disinfection system for improved rural household water treatment. *Journal of Sustainable Development of Energy, Water and Environment Systems* **9** (4), 1–16. https://doi.org/10.13044/j.sdewes.d8.0369.

Chong, M. N., Jin, B., Chow, C. W. & Saint, C. 2010 Recent developments in photocatalytic water treatment technology: a review. *Water Research* **44** (10), 2997–3027. https://doi.org/10.1016/j.watres.2010.02.039.

Clasen, T. 2009 *Scaling up Household Water Treatment among low-Income Populations*. World Health Organization, Geneva. Available from: https://apps.who.int/iris/bitstream/handle/10665/70049/WHO_HSE_WSH_09.02_eng.pdf.

Clasen, T., Haller, L., Walker, D., Bartram, J. & Cairncross, S. 2007a Cost-effectiveness of water quality interventions for preventing diarrhoeal disease in developing countries. *Journal of Water and Health* **5** (4), 599–608. https://doi.org/10.2166/wh.2007.010.

Clasen, T., Schmidt, W.-P., Rabie, T., Roberts, I. & Cairncross, S. 2007b Interventions to improve water quality for preventing diarrhoea: systematic review and meta-analysis. *BMJ* **334** (7597), 782. https://doi.org/10.1136/bmj.39118.489931.BE.

Clasen, T. F., Alexander, K. T., Sinclair, D., Boisson, S., Peletz, R., Chang, H. H., Majorin, F. & Cairncross, S. 2015 Interventions to improve water quality for preventing diarrhoea. *Cochrane Database of Systematic Reviews* **2015** (10), CD004794. https://www.cochranelibrary.com/cdsr/doi/10.1002/14651858.CD004794.pub3/full.

Conroy, R. M., Elmore-Meegan, M., Joyce, T., McGuigan, K. G. & Barnes, J. 1996 Solar disinfection of drinking water and diarrhoea in Maasai children: a controlled field trial. *The Lancet* **348** (9043), 1695–1697. https://doi.org/10.1016/S0140-6736(96)02309-4.

Conroy, R. M., Meegan, M. E., Joyce, T., McGuigan, K. & Barnes, J. 1999 Solar disinfection of water reduces diarrhoeal disease: an update. *Archives of Disease in Childhood* **81** (4), 337–338. https://doi.org/10.1136/adc.81.4.337.

Conroy, R. M., Meegan, M., Joyce, T., McGuigan, K. & Barnes, J. 2001 Solar disinfection of drinking water protects against cholera in children under 6 years of age. *Archives of Disease in Childhood* **85** (4), 293–295. https://doi.org/10.1136/adc.85.4.293.

Cowie, B. E., Porley, V. & Robertson, N. 2020 Solar disinfection (SODIS) provides a much underexploited opportunity for researchers in photocatalytic water treatment (PWT). *ACS Catalysis* **10** (20), 11779–11782. https://doi.org/10.1021/acscatal.0c03325.

Cronin, A. A., Breslin, N., Gibson, J. & Pedley, S. 2006 Monitoring source and domestic water quality in parallel with sanitary risk identification in Northern Mozambique to prioritise protection interventions. *Journal of Water and Health* **4** (3), 333–345. https://doi.org/10.2166/wh.2006.029.

Davarcioglu, B. 2015 Solar water disinfection considerations: using ultraviolet light methods to make water safe to drink. *International Journal of Innovative Science, Engineering and Technology* **2**, 253–264. Available from: https://ijiset.com/vol2/v2s8/IJISET_V2_I8_35.pdf.

Den Besten, H. M., Wells-Bennik, M. H. & Zwietering, M. H. 2018 Natural diversity in heat resistance of bacteria and bacterial spores: impact on food safety and quality. *Annual Review of Food Science and Technology* **9**, 383–410. https://doi.org/10.1146/annurev-food-030117-012808.

Deng, Y. 2021 Making waves: principles for the design of sustainable household water treatment. *Water Research* **198**, 117151. https://doi.org/10.1016/j.watres.2021.117151.

Dessie, A., Alemayehu, E., Mekonen, S., Legesse, W., Kloos, H. & Ambelu, A. 2014 Solar disinfection: an approach for low-cost household water treatment technology in Southwestern Ethiopia. *Journal of Environmental Health Science and Engineering* **12**, 1–6. https://doi.org/10.1186/2052-336X-12-25.

Duffy, E., Al Touati, F., Kehoe, S., McLoughlin, O., Gill, L., Gernjak, W., Oller, I., Maldonado, M., Malato, S. & Cassidy, J. 2004 A novel TiO_2-assisted solar photocatalytic batch-process disinfection reactor for the treatment of biological and chemical contaminants in domestic drinking water in developing countries. *Solar Energy* **77** (5), 649–655. https://doi.org/10.1016/j.solener.2004.05.006.

Du Preez, M., McGuigan, K. G. & Conroy, R. M. 2010 Solar disinfection of drinking water in the prevention of dysentery in South African children aged under 5 years: the role of participant motivation. *Environmental Science & Technology* **44** (22), 8744–8749. https://doi.org/10.1021/es103328j.

du Preez, M., Conroy, R. M., Ligondo, S., Hennessy, J., Elmore-Meegan, M., Soita, A. & McGuigan, K. G. 2011 Randomized intervention study of solar disinfection of drinking water in the prevention of dysentery in Kenyan children aged under 5 years. *Environmental Science & Technology* **45** (21), 9315–9323. https://doi.org/10.1021/es2018835.

EAWAG/SANDEC 1991 *SODIS News* (4 May 1999). EAWAG/SANDEC. Available from: https://www.ircwash.org/sites/default/files/EAWAG-1999-Sodis.pdf.

Figueroa, M. E. & Kincaid, D. L. 2010 *Social, Cultural and Behavioral Correlates of Household Water Treatment and Storage*. Johns Hopkins Bloomberg School of Public Health, Center for Communication Programs. Available from: https://ccp.jhu.edu/wp-content/uploads/2014/11/Household-Water-Treatment-and-Storage-2010.pdf.

Foster, H. A., Ditta, I. B., Varghese, S. & Steele, A. 2011 Photocatalytic disinfection using titanium dioxide: spectrum and mechanism of antimicrobial activity. *Applied Microbiology and Biotechnology* **90**, 1847–1868. https://doi.org/10.1007/s00253-011-3213-7.

Gallagher, R. P., Lee, T. K., Bajdik, C. D. & Borugian, M. 2010 Ultraviolet radiation. *Chronic Diseases and Injuries in Canada* **29**, 51–68. https://doi.org/10.24095/hpcdp.29.S1.04

García-Gil, Á., Casado, C., Pablos, C. & Marugán, J. 2019 Novel procedure for the numerical simulation of solar water disinfection processes in flow reactors. *Chemical Engineering Journal* **376**, 120194. https://doi.org/10.1016/j.cej.2018.10.131.

García-Gil, Á., García-Muñoz, R. A., McGuigan, K. G. & Marugán, J. 2021 Solar water disinfection to produce safe drinking water: a review of parameters, enhancements, and modelling approaches to make SODIS faster and safer. *Molecules* **26** (11), 3431. https://doi.org/10.3390/molecules26113431.

García-Gil, Á., García-Muñoz, R. A., Martínez-García, A., Polo-López, M. I., Wasihun, A. G., Teferi, M., Asmelash, T., Conroy, R., McGuigan, K. G. & Marugán, J. 2022 Solar water disinfection in large-volume containers: from the laboratory to the field. A case study in Tigray, Ethiopia. *Scientific Reports* **12** (1), 1–9. https://doi.org/10.1038/s41598-022-23709-5.

Gelover, S., Gómez, L. A., Reyes, K. & Leal, M. T. 2006 A practical demonstration of water disinfection using TiO_2 films and sunlight. *Water Research* **40** (17), 3274–3280. https://doi.org/10.1016/j.watres.2006.07.006.

Gilman, R. H. & Skillicorn, P. 1985 Boiling of drinking-water: can a fuel-scarce community afford it? *Bulletin of the World Health Organization* **63** (1), 157. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2536343/pdf/bullwho00084-0165.pdf.

Graf, J., Zebaze Togouet, S., Kemka, N., Niyitegeka, D., Meierhofer, R. & Gangoue Pieboji, J. 2010 Health gains from solar water disinfection (SODIS): evaluation of a water quality intervention in Yaounde, Cameroon. *Journal of Water and Health* **8** (4), 779–796. https://doi.org/10.2166/wh.2010.003.

Gundry, S. W., Wright, J. A., Conroy, R., Du Preez, M., Genthe, B., Moyo, S., Mutisi, C., Ndamba, J. & Potgieter, N. 2006 Contamination of drinking water between source and point-of-use in rural households of South Africa and Zimbabwe: implications for monitoring the Millennium Development Goal for water. *Water Practice and Technology* **1** (2), 1–10. https://doi.org/10.2166/wpt.2006.032.

Guo, Q., Zhou, C., Ma, Z. & Yang, X. 2019 Fundamentals of TiO_2 photocatalysis: concepts, mechanisms, and challenges. *Advanced Materials* **31** (50), 1901997. https://doi.org/10.1002/adma.201901997.

Gutiérrez-Alfaro, S., Acevedo, A., Figueredo, M., Saladin, M. & Manzano, M. A. 2017 Accelerating the process of solar disinfection (SODIS) by using polymer bags. *Journal of Chemical Technology & Biotechnology* **92** (2), 298–304. https://doi.org/10.1002/jctb.5005.

Gwenzi, W., Chaukura, N., Noubactep, C. & Mukome, F. N. 2017 Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision. *Journal of Environmental Management* **197**, 732–749. https://doi.org/10.1016/j.jenvman.2017.03.087.

Harding, A. S. & Schwab, K. J. 2012 Using limes and synthetic psoralens to enhance solar disinfection of water (SODIS): a laboratory evaluation with norovirus, Escherichia coli, and MS2. *The American Journal of Tropical Medicine and Hygiene* **86** (4), 566. https://doi.org/10.4269/ajtmh.2012.11-0370.

Heaselgrave, W. & Kilvington, S. 2010 Antimicrobial activity of simulated solar disinfection against bacterial, fungal, and protozoan pathogens and its enhancement by riboflavin. *Applied and Environmental Microbiology* **76** (17), 6010–6012.

Heaselgrave, W., Patel, N., Kilvington, S., Kehoe, S. & McGuigan, K. 2006 Solar disinfection of poliovirus and *Acanthamoeba polyphaga* cysts in water – a laboratory study using simulated sunlight. *Letters in Applied Microbiology* **43** (2), 125–130. https://doi.org/10.1111/j.1472-765X.2006.01940.x.

Hong, Y., Shi, W., Wang, H., Ma, D., Ren, Y., Wang, Y., Li, Q. & Gao, B. 2022 Mechanisms of *Escherichia coli* inactivation during solar-driven photothermal disinfection. *Environmental Science: Nano* **9** (3), 1000–1010. https://doi.org/10.1039/d1en00999k.

Huang, G., Ng, T. W., An, T., Li, G., Xia, D., Yip, H. Y., Zhao, H. & Wong, P. K. 2017 Probing the intracellular organic matters released from the photocatalytic inactivation of bacteria using fractionation procedure and excitation-emission-matrix fluorescence. *Water Research* **110**, 270–280. https://doi.org/10.1016/j.watres.2016.12.032.

Joyce, T., McGuigan, K., Elmore-Meegan, M. & Conroy, R. 1996 Inactivation of fecal bacteria in drinking water by solar heating. *Applied and Environmental Microbiology* **62** (2), 399–402. https://doi.org/10.1128/aem.62.2.399-402.1996.

Juran, L. & MacDonald, M. C. 2014 An assessment of boiling as a method of household water treatment in south India. *Journal of Water and Health* **12** (4), 791–802.

Kanyerere, T., Levy, J., Xu, Y. & Saka, J. 2012 Assessment of microbial contamination of groundwater in upper Limphasa River catchment, located in a rural area of northern Malawi. *Water SA* **38** (4), 581–596. https://doi.org/10.4314/wsa.v38i4.14.

Karim, M., Khan, M., Bejoy, H. R., Akash, M. & Shams, S. 2021 Effectiveness of solar disinfection for household water treatment: an experimental and modeling study. *Journal of Water, Sanitation and Hygiene for Development* **11** (3), 374–385. https://doi.org/10.2166/washdev.2021.243.

Kehoe, S., Joyce, T., Ibrahim, P., Gillespie, J., Shahar, R. & McGuigan, K. 2001 Effect of agitation, turbidity, aluminium foil reflectors and container volume on the inactivation efficiency of batch-process solar disinfectors. *Water Research* **35** (4), 1061–1065. https://doi.org/10.1016/S0043-1354(00)00353-5.

Kehoe, S., Barer, M., Devlin, L. & McGuigan, K. 2004 Batch process solar disinfection is an efficient means of disinfecting drinking water contaminated with *Shigella dysenteriae* type I. *Letters in Applied Microbiology* **38** (5), 410–414. https://doi.org/10.1111/j.1472-765X.2004.01515.x.

Keogh, M. B., Castro-Alférez, M., Polo-López, M., Calderero, I. F., Al-Eryani, Y., Joseph-Titus, C., Sawant, B., Dhodapkar, R., Mathur, C. & McGuigan, K. G. 2015 Capability of 19-L polycarbonate plastic water cooler containers for efficient solar water disinfection (SODIS): field case studies in India, Bahrain and Spain. *Solar Energy* **116**, 1–11. https://doi.org/10.1016/j.solener.2015.03.035.

Lantagne, D. S., Quick, R. & Mintz, E. D. 2006 Household water treatment and safe: storage options in developing countries. *Navig* **99**, 17–38. Available from: https://sswm.info/sites/default/files/reference_attachments/LANTAGNE%202006%20Household%20Water%20Treatment%20and%20Safe%20Storage%20in%20Developing%20Countries_0.pdf.

Lawrence, A., Macdonald, D., Howard, A., Barrett, M., Pedley, S., Ahmed, K. & Nalubega, M. 2001 *Guidelines for Assessing the Risk to Groundwater From on-Site Sanitation (CR/01/142)*. B. G. Survey. Available from: https://nora.nerc.ac.uk/id/eprint/20757.

Linden, K. G., Shin, G.-A., Faubert, G., Cairns, W. & Sobsey, M. D. 2002 UV disinfection of *Giardia lamblia* cysts in water. *Environmental Science & Technology* **36** (11), 2519–2522. https://doi.org/10.1021/es0113403.

Lindskog, R. & Lindskog, P. 1988 Bacteriological contamination of water in rural areas: an intervention study from Malawi. *Tropical Medicine & International Health* **91** (1), 1–7. Available from: https://www.ircwash.org/sites/default/files/241.1-7221.pdf.

Loeb, S., Li, C. & Kim, J.-H. 2018 Solar photothermal disinfection using broadband-light absorbing gold nanoparticles and carbon black. *Environmental Science & Technology* **52** (1), 205–213. https://doi.org/10.1021/acs.est.7b04442.

Loeb, S. K., Kim, J., Jiang, C., Early, L. S., Wei, H., Li, Q. & Kim, J.-H. 2019 Nanoparticle enhanced interfacial solar photothermal water disinfection demonstrated in 3-D printed flow-through reactors. *Environmental Science & Technology* **53** (13), 7621–7631. https://doi.org/10.1021/acs.est.9b01142.

Lonnen, J., Kilvington, S., Kehoe, S., Al-Touati, F. & McGuigan, K. 2005 Solar and photocatalytic disinfection of protozoan, fungal and bacterial microbes in drinking water. *Water Research* **39** (5), 877–883. https://doi.org/10.1016/j.watres.2004.11.023.

Luzi, S., Tobler, M., Suter, F. & Meierhofer, R. 2016 *SODIS Manual: Guidance on Solar Water Disinfection*. SANDEC, Department of Sanitation, Water and Solid Waste for Development, Eawag, Switzerland. Available from: https://www.sodis.ch/methode/anwendung/ausbildungsmaterial/dokumente_material/sodismanual_2016_lr.pdfM.

Malato, S., Fernández-Ibáñez, P., Maldonado, M. I., Blanco, J. & Gernjak, W. 2009 Decontamination and disinfection of water by solar photocatalysis: recent overview and trends. *Catalysis Today* **147** (1), 1–59. https://doi.org/10.1016/j.cattod.2009.06.018.

McGuigan, M., Joyce, J., Conroy, C., Gillespie, G. & Elmore-Meegan, E. M. 1998 Solar disinfection of drinking water contained in transparent plastic bottles: characterizing the bacterial inactivation process. *Journal of Applied Microbiology* **84** (6), 1138–1148. https://doi.org/10.1046/j.1365-2672.1998.00455.x.

McGuigan, K., Méndez-Hermida, F., Castro-Hermida, J., Ares-Mazás, E., Kehoe, S., Boyle, M., Sichel, C., Fernández-Ibáñez, P., Meyer, B. & Ramalingham, S. 2006 Batch solar disinfection inactivates oocysts of *Cryptosporidium parvum* and cysts of *Giardia muris* in drinking water. *Journal of Applied Microbiology* **101** (2), 453–463. https://doi.org/10.1111/j.1365-2672.2006.02935.x.

McGuigan, K. G., Samaiyar, P., du Preez, M. & Conroy, R. M. 2011 High compliance randomized controlled field trial of solar disinfection of drinking water and its impact on childhood diarrhea in rural Cambodia. *Environmental Science & Technology* **45** (18), 7862–7867. https://doi.org/doi.org/10.1021/es201313x.

McGuigan, K. G., Conroy, R. M., Mosler, H.-J., du Preez, M., Ubomba-Jaswa, E. & Fernandez-Ibanez, P. 2012 Solar water disinfection (SODIS): a review from bench-top to roof-top. *Journal of Hazardous Materials* **235**, 29–46. https://doi.org/10.1016/j.jhazmat.2012.07.053.

Meierhofer, R. 2006 Establishing solar water disinfection as a water treatment method at household level. *Madagascar Conservation & Development* **1** (1). https://doi.org/10.4314/mcd.v1i1.44036.

Meierhofer, R. & Landolt, G. 2009 Factors supporting the sustained use of solar water disinfection – experiences from a global promotion and dissemination programme. *Desalination* **248** (1–3), 144–151. https://doi.org/10.1016/j.desal.2008.05.050.

Meierhofer, R. & Wegelin, M. 2002 *Solar Water Disinfection: A Guide for the Application of SODIS (Vol. 06/02)*. Water and Sanitation in Developing Countries (SANDEC). Available from: https://www.ircwash.org/sites/default/files/Meierhofer-2002-Solar.pdf.

Méndez-Hermida, F., Ares-Mazás, E., McGuigan, K. G., Boyle, M., Sichel, C. & Fernández-Ibáñez, P. 2007 Disinfection of drinking water contaminated with *Cryptosporidium parvum* oocysts under natural sunlight and using the photocatalyst TiO_2. *Journal of Photochemistry and Photobiology B: Biology* **88** (2–3), 105–111. https://doi.org/10.1016/j.jphotobiol.2007.05.004.

Mengistie, B., Berhane, Y. & Worku, A. 2013 Household water chlorination reduces incidence of diarrhea among under-five children in rural Ethiopia: a cluster randomized controlled trial. *PloS one* **8** (10), e77887. https://doi.org/10.1371/journal.pone.0077887.

Mølbak, K., Højlyng, N., Jepsen, S. & Gaarslev, K. 1989 Bacterial contamination of stored water and stored food: a potential source of diarrhoeal disease in West Africa. *Epidemiology & Infection* **102** (2), 309–316. https://doi.org/10.1017/S0950268800029988.

Moreno-SanSegundo, J., Giannakis, S., Samoili, S., Farinelli, G., McGuigan, K. G., Pulgarín, C. & Marugán, J. 2021 SODIS potential: a novel parameter to assess the suitability of solar water disinfection worldwide. *Chemical Engineering Journal* **419**, 129889. https://doi.org/10.1016/j.cej.2021.129889.

Morse, T., Luwe, K., Lungu, K., Chiwaula, L., Mulwafu, W., Buck, L., Harlow, R., Fagan, G. H. & McGuigan, K. 2020 A transdisciplinary methodology for introducing solar water disinfection to rural communities in Malawi – formative research findings. *Integrated Environmental Assessment and Management* **16** (6), 871–884. https://doi.org/10.1002/ieam.4249.

Moyo, S., Wright, J., Ndamba, J. & Gundry, S. 2004 Realising the maximum health benefits from water quality improvements in the home: a case from Zaka district, Zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C* **29** (15–18), 1295–1299. https://doi.org/10.1016/j.pce.2004.09.012.

Mtapuri-Zinyowera, S., Midzi, N., Muchaneta-Kubara, C., Simbini, T. & Mduluza, T. 2009 Impact of solar radiation in disinfecting drinking water contaminated with *Giardia duodenalis* and *Entamoeba histolytica/dispar* at a point-of-use water treatment. *Journal of Applied Microbiology* **106** (3), 847–852. https://doi.org/10.1111/j.1365-2672.2008.04054.x.

Murinda, S. & Kraemer, S. 2008 The potential of solar water disinfection as a household water treatment method in peri-urban Zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C* **33** (8–13), 829–832. https://doi.org/10.1016/j.pce.2008.06.025.

Parsa, S. M., Momeni, S., Hemmat, A. & Afrand, M. 2021 Effectiveness of solar water disinfection in the era of COVID-19 (SARS-CoV-2) pandemic for contaminated water/wastewater treatment considering UV effect and temperature. *Journal of Water Process Engineering* **43**, 102224. https://doi.org/10.1016/j.jwpe.2021.102224.

Pickering, A. J., Crider, Y., Sultana, S., Swarthout, J., Goddard, F. G., Islam, S. A., Sen, S., Ayyagari, R. & Luby, S. P. 2019 Effect of in-line drinking water chlorination at the point of collection on child diarrhoea in urban Bangladesh: a double-blind, cluster-randomised controlled trial. *The Lancet Global Health* **7** (9), e1247–e1256. https://doi.org/10.1016/S2214-109X(19)30315-8.

Polo-López, M. I., Martínez-García, A., Abeledo-Lameiro, M. J., Gómez-Couso, H., E, H., Ares-Mazás, E., Reboredo-Fernández, A., Morse, T. D., Buck, L., Lungu, K., McGuigan, K. G. & Fernández-Ibáñez, P. 2019 Microbiological evaluation of 5 L-and 20 L-transparent polypropylene buckets for solar water disinfection (SODIS). *Molecules* **24** (11), 2193. https://doi.org/10.3390/molecules24112193.

Psutka, R., Peletz, R., Michelo, S., Kelly, P. & Clasen, T. 2011 Assessing the microbiological performance and potential cost of boiling drinking water in urban Zambia. *Environmental Science & Technology* **45** (14), 6095–6101. https://doi.org/10.1021/es2004045.

Pulgarin, C. 2015 Fe vs. TiO2 photo-assisted processes for enhancing the solar inactivation of bacteria in water. *Chimia* **69** (1–2), 7–7. https://doi.org/10.2533/chimia.2015.7.

Quick, R. E., Kimura, A., Thevos, A., Tembo, M., Shamputa, I., Hutwagner, L. & Mintz, E. 2002 Diarrhea prevention through household-level water disinfection and safe storage in Zambia. *The American Journal of Tropical Medicine and Hygiene* **66** (5), 584–589. https://doi.org/10.4269/ajtmh.2002.66.584.

Rai, B., Pal, R., Kar, S. & Tsering, D. C. 2010 Solar disinfection improves drinking water quality to prevent diarrhea in under-five children in Sikkim, India. *Journal of Global Infectious Diseases* **2** (3), 221. https://doi.org/10.4103/0974-777X.68532.

Rainey, R. C. & Harding, A. K. 2005 Acceptability of solar disinfection of drinking water treatment in Kathmandu Valley, Nepal. *International Journal of Environmental Health Research* **15** (5), 361–372. https://doi.org/10.1080/09603120500289168.

Rastogi, R. P., Kumar, A., Tyagi, M. B. & Sinha, R. P. 2010 Molecular mechanisms of ultraviolet radiation-induced DNA damage and repair. *Journal of Nucleic Acids* **2010**. https://doi.org/10.4061/2010/592980.

REAL-Water. 2022 *Technological Innovations for Rural Water Supply in Low-Resource Settings*. Available from: https://www.globalwaters.org/sites/default/files/4dec_technological_innovations.pdf.

Roberts, L., Chartier, Y., Chartier, O., Malenga, G., Toole, M. & Rodka, H. 2001 Keeping clean water clean in a Malawi refugee camp: a randomized intervention trial. *Bulletin of the World Health Organization* **79**, 280–287. https://doi.org/10.1590/S0042-96862001000400003.

Rodríguez-Chueca, J., Giannakis, S., Marjanovic, M., Kohantorabi, M., Gholami, M. R., Grandjean, D., de Alencastro, L. F. & Pulgarín, C. 2019 Solar-assisted bacterial disinfection and removal of contaminants of emerging concern by Fe2+-activated HSO5-Vs. S2O82-in drinking water. *Applied Catalysis B: Environmental* **248**, 62–72. https://doi.org/10.1016/j.apcatb.2019.02.018.

Rosa, G., Miller, L. & Clasen, T. 2010 Microbiological effectiveness of disinfecting water by boiling in rural Guatemala. *The American Journal of Tropical Medicine and Hygiene* **82** (3), 473.

Rose, A., Roy, S., Abraham, V., Holmgren, G., George, K., Balraj, V., Abraham, S., Muliyil, J., Joseph, A. & Kang, G. 2006 Solar disinfection of water for diarrhoeal prevention in southern India. *Archives of Disease in Childhood* **91** (2), 139–141. https://doi.org/10.1136/adc.2005.077867.

Schmid, P., Kohler, M., Meierhofer, R., Luzi, S. & Wegelin, M. 2008 Does the reuse of PET bottles during solar water disinfection pose a health risk due to the migration of plasticisers and other chemicals into the water? *Water Research* **42** (20), 5054–5060. https://doi.org/10.1016/j.watres.2008.09.025.

Schmidt, W.-P. & Cairncross, S. 2009 Household water treatment in poor populations: is there enough evidence for scaling up now? *Environmental Science & Technology* **43** (4), 986–992. https://doi.org/10.1021/es802232w.

Schneider, J., Matsuoka, M., Takeuchi, M., Zhang, J., Horiuchi, Y., Anpo, M. & Bahnemann, D. W. 2014 Understanding TiO$_2$ photocatalysis: mechanisms and materials. *Chemical Reviews* **114** (19), 9919–9986. https://doi.org/10.1021/cr5001892.

Sinha, R. P. & Häder, D.-P. 2002 UV-induced DNA damage and repair: a review. *Photochemical & Photobiological Sciences* **1** (4), 225–236. https://doi.org/10.1039/b201230h.

Smith, R., Kehoe, S., McGuigan, K. & Barer, M. 2000 Effects of simulated solar disinfection of water on infectivity of *Salmonella typhimurium*. *Letters in Applied Microbiology* **31** (4), 284–288. https://doi.org/10.1046/j.1472-765x.2000.00815.x.

Sobsey, M. D. 2002 *Managing Water in the Home: Accelerated Health Gains From Improved Water Supply*. World Health Organization. Available from: https://apps.who.int/iris/bitstream/handle/10665/67319/?sequence=1.

Sobsey, M. D., Stauber, C. E., Casanova, L. M., Brown, J. M. & Elliott, M. A. 2008 Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environmental Science & Technology* **42** (12), 4261–4267. https://doi.org/10.1021/es702746n.

Solomon, E. T., Robele, S., Kloos, H. & Mengistie, B. 2020 Effect of household water treatment with chlorine on diarrhea among children under the age of five years in rural areas of Dire Dawa, eastern Ethiopia: a cluster randomized controlled trial. *Infectious Diseases of Poverty* **9**, 1–13. https://doi.org/10.1186/s40249-020-00680-9.

Sommer, B., Marino, A., Solarte, Y., Salas, M., Dierolf, C., Valiente, C., Mora, D., Rechsteiner, R., Setter, P. & Wirojanagud, W. (1997). SODIS – an emerging water treatment process. *AQUA(OXFORD)*, **46**(3), 127–137. Available from: https://www.researchgate.net/profile/Yezid-Solarte-2/publication/235803199_SODIS-An_emerging_water_treatment_process/links/543d17ba0cf24ef33b766ddc/SODIS-An-emerging-water-treatment-process.pdf.

Tang, Z., Ma, D., Chen, Q., Wang, Y., Sun, M., Lian, Q., Shang, J., Wong, P. K., He, C. & Xia, D. 2022 Nanomaterial-enabled photothermal-based solar water disinfection processes: fundamentals, recent advances, and mechanisms. *Journal of Hazardous Materials* **129373**. https://doi.org/10.1016/j.jhazmat.2022.129373.

Ubomba-Jaswa, E., Fernández-Ibáñez, P. & McGuigan, K. G. 2010 A preliminary Ames fluctuation assay assessment of the genotoxicity of drinking water that has been solar disinfected in polyethylene terephthalate (PET) bottles. *Journal of Water and Health* **8** (4), 712–719. https://doi.org/10.2166/wh.2010.136.

Wegelin, M. & Sommer, B. 1998 Solar water disinfection(SODIS) – destined for worldwide use? *Waterlines* **16** (3), 30–32. https://doi.org/10.3362/0262-8104.1998.013.

Wegelin, M., Canonica, S., Mechsner, K., Fleischmann, T., Pesaro, F. & Metzler, A. 1994 Solar water disinfection: scope of the process and analysis of radiation experiments. *Aqua* **43** (4), 154–169. Available from: https://www.sodis.ch/methode/forschung/publikationen/papers/wegelin_mikorbiologie_1994.pdf.

Wegelin, M., Canonica, S., Alder, C., Marazuela, D., Suter, M.-F., Bucheli, T. D., Haefliger, O., Zenobi, R., McGuigan, K. & Kelly, M. 2001 Does sunlight change the material and content of polyethylene terephthalate (PET) bottles? *Journal of Water Supply: Research and Technology – AQUA* **50** (3), 125–135. https://doi.org/10.2166/aqua.2001.0012.

WHO 1994 *Ultraviolet Radiation*. World Health Organization Geneva. Available from: https://www.who.int/health-topics/ultraviolet-radiation#tab=tab_1.

WHO and UNICEF 2021 *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2020: Five Years Into the SDGs*. Available from: https://apps.who.int/iris/bitstream/handle/10665/345081/9789240030848-eng.pdf?sequence=1.

WHO, UNICEF, & World Bank 2022 *State of the World's Drinking Water*. World Health Organization. Available from: https://apps.who.int/iris/rest/bitstreams/1474551/retrieve.

World Health Organization 2007 *Combating Waterborne Disease at the Household Level*. World Health Organization. Available from: https://apps.who.int/iris/bitstream/handle/10665/43621/9789241595223_eng.pdf?sequence=1&isAllowed=y.

World Health Organization 2014 *Preventing Diarrhoea Through Better Water, Sanitation and Hygiene: Exposures and Impacts in Low- and Middle-Income Countries*. World Health Organization, Geneva.

World Health Organization 2015 *Technical Brief. Boil, Water (WHO/FWC/WSH/15.02)*. Available from: https://apps.who.int/iris/bitstream/handle/10665/155821/WHO_FWC_WSH_15.02_eng.pdf?sequence=1&isAllowed=y.

Wright, J., Gundry, S. & Conroy, R. 2004 Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. *Tropical Medicine & International Health* **9** (1), 106–117. https://doi.org/10.1046/j.1365-3156.2003.01160.x.

Yefanova, S. L. N., Ouédraogo, J. C. W., Ouédraogo, B. & Bonzi-Coulibaly, Y. L. 2022 The Use of plants for drinking water disinfection: traditional knowledge, scientific validation, current challenges and prospects for the future. *From Traditional to Modern African Water Management* 115–133. https://doi.org/10.1007/978-3-031-09663-1_9.

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