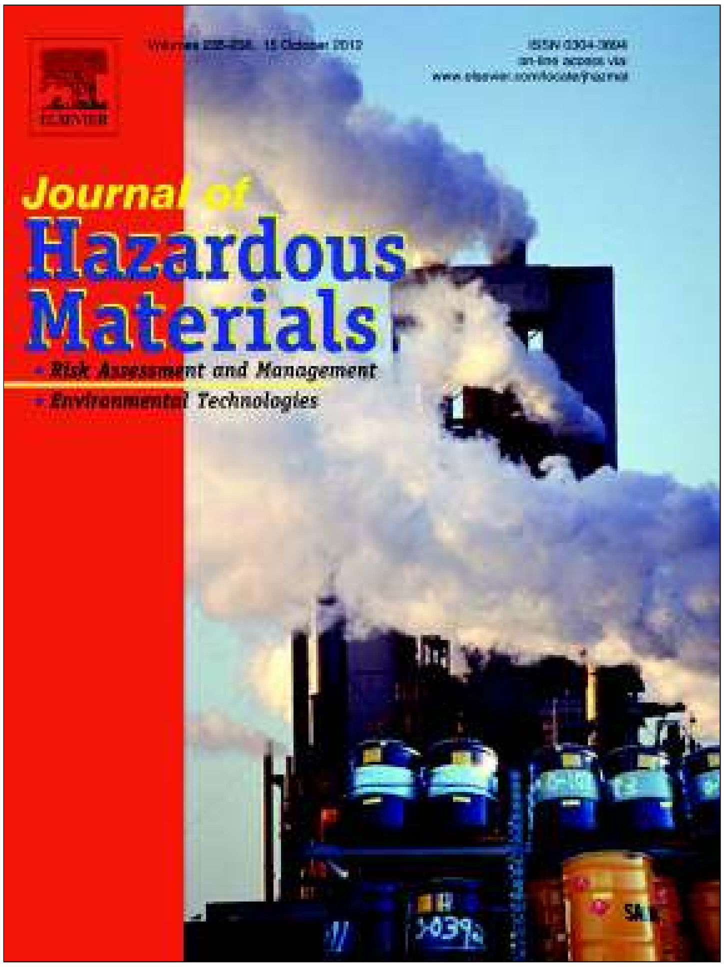
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Review

Solar water disinfection (SODIS): A review from bench-top to roof-top

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HIGHLIGHTS

- ► A thorough review of current state of play of solar water disinfection.
- ► An examination of both laboratory and field studies.
- ► Description of the economic and behaviour change aspects of this technology.

GRAPHICAL ABSTRACT

. Water being treated by solar disinfection outside a primary school classroom in Southern Uganda. Students fill their bottles at home and expose them to the sun while they are at school.

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ABSTRACT

Solar water disinfection (SODIS) has been known for more than 30 years. The technique consists of placing water into transparent plastic or glass containers (normally 2 L PET beverage bottles) which are then exposed to the sun. Exposure times vary from 6 to 48 h depending on the intensity of sunlight and sensitivity of the pathogens. Its germicidal effect is based on the combined effect of thermal heating of solar light and UV radiation. It has been repeatedly shown to be effective for eliminating microbial pathogens and reduce diarrhoeal morbidity including cholera. Since 1980 much research has been carried out to investigate the mechanisms of solar radiation induced cell death in water and possible enhancement technologies to make it faster and safer. Since SODIS is simple to use and inexpensive, the method has spread throughout the developing world and is in daily use in more than 50 countries in Asia, Latin America, and Africa. More than 5 million people disinfect their drinking water with the solar disinfection (SODIS) technique. This review attempts to revise all relevant knowledge about solar disinfection from microbiological issues, laboratory research, solar testing, up to and including real application studies, limitations, factors influencing adoption of the technique and health impact.

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1. Introduction

Despite progress towards the Millennium Development Goals, in June 2012 the United Nations reported that, 11% of the global population (approx. 783 million people) remains without access to an improved source of drinking water and, at the current pace, 605 million people will still lack coverage in 2015 [1]. It is likely that many hundreds of millions more will still lack sustainable access to safe drinking water. Even when municipally treated water is available in urban areas, access is often restricted by landlords who place locks on standpipes and charge tenants a fee for access to it. Often in such cases the municipal supply is illegally tapped into which poses a risk of recontamination both at the collection point (in Fig. 1 such a collection point in the Nakuru slums in Kenya is directly above an open sewer) and further down the supply line. The burden of waterborne disease falls disproportionately on communities in the developing world. Tragically, more than 90% of diarrhoeal cases are preventable through modifications to the environment, including interventions to increase the availability of clean water [2]. While interventions at the distribution source have been shown to reduce diarrhoea [3,4] more recent research has demonstrated that point-of-use interventions within the household can be even more effective [5,6]. Appropriate household water treatment and storage (HWTS) interventions must satisfy certain criteria in order to be accepted by a community. They should be:

Fig. 1. A child collects drinking water from a cracked municipal supply pipe directly above an open sewer in the Nakuru slum district of Kenya. In order to collect the treated water from the pipe, her container is partially immersed in raw sewage.

- Low cost, since usually only the poorest communities tend to be affected.
- Easy to use. Compliance will suffer if the protocol is overly complicated.
- Sustainable. The technique must not require consumables that are difficult or too expensive to obtain.

In addition to boiling, chlorination and filtration another household water treatment which has gained popularity over the past 10 years is that of solar disinfection (SODIS) [7].

The basic SODIS technique is demonstrated in Fig. 2. Transparent containers are filled with contaminated water and placed in direct sunlight for at least 6 h, after which time it is safe to drink. Solar disinfection containers (reactors) can be glass or plastic (usually polyethylene-terephthalate – P.E.T.) – even plastic bags have been used [8,9]. Plastic bottles are more robust than glass bottles since few glass bottles survive an off-road journey in the back of a four-wheel drive vehicle or a fall from a roof. It is recommended that solar disinfected water should be consumed within 24 h to avoid the possibility of post-exposure re-growth. The efficiency of the basic protocol can be enhanced by adding a number of additional steps such as:

- Placing filled bottles on reflective surfaces to boost the amount of sunlight absorbed by the reactor [10,11].
- Painting the underside of the SODIS reactor black to enhance solar heating [12].
- 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 [13,14].
- Filtering the water before filling the reactor [13].

Solar disinfection is not a recent technology. Descriptions exist of communities on the Indian sub-continent nearly 2000 years ago who placed drinking water outside in open trays to be “blessed” by the sun [15]. Although the bactericidal effect of sunlight was rigorously investigated by Downes and Blunt in 1877 [16], it was not until 1984 that Aftim Acra and co-workers in the University of Beirut [17,18] published their seminal work on using sunlight to disinfect contaminated water for use in oral rehydration solutions. Since then the full potential of SODIS to inactivate a wide range of waterborne pathogens has been investigated by several groups [12,13,19–22].

Despite a large canon of work describing the efficacy of SODIS as a low cost HWTS treatment, it remains one of the least

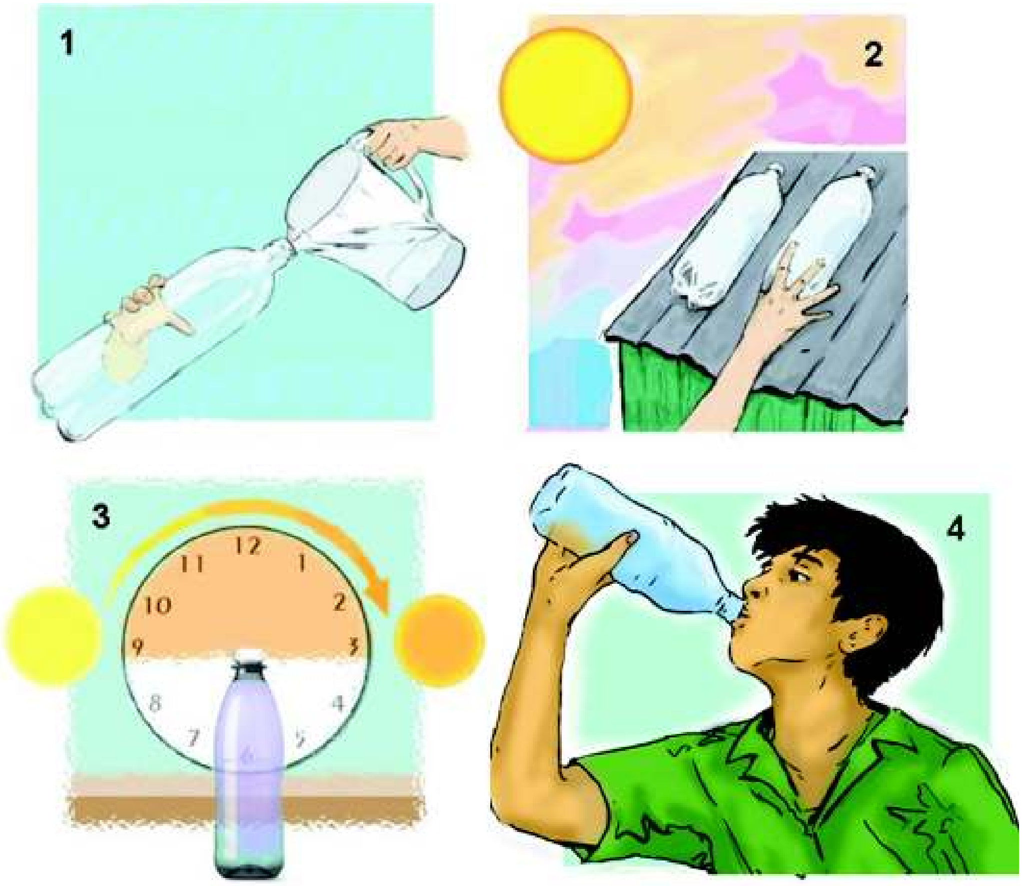

Fig. 2. A graphical description on the solar disinfection (SODIS) household water treatment technique.

frequently used point-of-use interventions. Consequently a review of all aspects of solar disinfection of drinking water describing laboratory and field studies and including both physical and social science considerations, might be useful and appropriate at this time.

2. Solar radiation and cellular damage

The solar irradiance incident on the outer Earth atmosphere is approximately 1360 W m^{-2} – this value varies with position within the elliptical sidereal orbit of the Earth as it orbits the Sun. Water vapour, CO_2, ozone and oxygen, in addition to pollutants in the atmosphere, scatter and absorb various portions of this such that for a typical cloudless atmosphere in summer at the equator, the received irradiance on a horizontal surface at ground level on the equator is reduced to roughly 1120 W m^{-2}. Thus we have 1.12 kJ m^{-2} of optical energy available in each second to inactivate whatever microbial pathogens are present in water exposed to sunlight. This value reduces in a cosine fashion as latitude increases away from the equator.

The wavelength ranges of UV are: 400–315 nm for UV-A; 315–280 nm for UV-B; and 280–100 nm for UV-C. When DNA is irradiated with UV light, some of that light is absorbed by the pyrimidine rings of thymine and cytosine bases in the DNA. This energy can lead to the formation of new bonds between adjacent pyrimidine bases, forming pyrimidine dimers (pairs connected by covalent bonds) [23]. These dimers include cyclobutane pyrimidine dimers (CPDs) and 6–4 photoproducts, of which the latter can further photoisomerize to form Dewar isomers [24]. Pyrimidine dimers are problematic for several reasons. They prevent base-pairing with the complementary purines on the other strand of DNA, which changes the shape of the DNA molecule in the area of the dimer. This in turn, makes it difficult for polymerase enzymes copying the DNA to move through the region of the dimer. In addition, since the dimer is not making base pairs, the polymerase does not know what nucleotide to add to the new DNA strand when it encounters the dimer. In some cases, the polymerase skips over the dimer, resulting in the deletion of two bases from the DNA strand. Sometimes the polymerase "guesses" what base belongs in that position, and incorporates something at random.

Cells have a number of DNA repair mechanisms at their disposal. Many bacteria contain CPD photolyase enzymes, which can repair CPD dimers in the presence of blue light. Cells can also remove the affected bases (base excision repair) followed by removal of the apyrimidinic site, or remove the damaged nucleotides (nucleotide excision repair), allowing the gap to be filled in either case by a DNA polymerase [24]. If the DNA contains a large number of pyrimidine dimers a so-called "SOS" response can be invoked in which the DNA repair systems may make too many cuts on both strands of DNA [25].

Although the UV-A wavelengths bordering on visible light are not sufficiently energetic to directly modify DNA bases, they play an important role in formation of reactive oxygen species (ROS) in water such as singlet oxygen, superoxide, hydrogen peroxide, and hydroxyl radical. Excitation of endogenous photosensitizers within cells such as porphyrins, flavins, and quinones, NADH/NADPH, and others [26–31] are believed to contribute to the formation of intracellular ROS. Once formed, these ROS can cause damage to DNA; oxidations of amino acids in proteins; oxidations of polyunsaturated fatty acids in lipids [32]. Additionally, sunlight can be absorbed by natural exogenous photosensitizers present in surface waters (humic acids and chlorophyls), which in turn can react with oxygen to produce ROS [33–35], which can exert a disinfecting effect [36]. A strong synergistic effect has been observed between optical and thermal inactivation processes for water temperatures exceeding 45 °C [21]. One explanation suggested by McGuigan et al. (1988) [21] for this synergistic response is that in addition to a slow pasteurizing effect, elevated water temperatures inhibit the DNA repair mechanisms.

The post-exposure effects and mechanisms acting on microbial pathogens is a matter of study since complete inactivation of microorganisms doesn't always happen for a variety of reasons, usually involving poor weather or poor turbidity conditions. According to several authors, the damage induced by sunlight continues even when the cells are taken out of the sun and are incubated in the dark [37,38]. The amount of post-treatment bacterial inactivation depends on the UV-A dose. Therefore, repair mechanisms for DNA probably come into action but are overwhelmed if the received UV-A dose is sufficiently high. This matter is particularly important for bacterial re-growth during storage.

Moreover, other microbiological parameters have been shown to have an important effect on the mechanism of action of UV light for bacterial cells. For example, their sensitivity to the solar treatment strongly depends on the growth rate and physiological stage [39]; this explain the wide variability of experimental results reported in the literature on solar disinfection. Recently, Berney (2006) [40] and Bosshard (2010) [41] studied damaging effects of sunlight on cell protein. They pointed out that solar photons attack proteins, directly or indirectly via ROS, and this could be the main mechanism of action during solar disinfection.

3. Inactivation of pathogens

3.1. Bacteria

Pathogenic waterborne bacteria and pathogen indicators formed the main focus of early laboratory based studies of SODIS efficacy. Due to the entirety of its genome mapping and its status as a faecal indicator organism [42], *Escherichia coli* is the most frequently studied species [10,21,22,43–49]. Flow cytometry studies by Berney et al. [40] have shown that inactivation of this species by solar disinfection is caused by disrupting a sequence of normal cellular functions. ATP synthesis and efflux pump activity both cease shortly after the start of exposure. These are followed by a gradual loss of membrane potential and a reduction in glucose uptake. Finally the cytoplasmic membrane of the bacterial cells becomes permeable, which comes later than loss of culturability.

DNA is a critical target of UV-A and UV-B wavelengths in *E. coli* [26]. Moreover, *E. coli* inactivation rates can be highly dependent on wavelength [22,31], dissolved oxygen concentration [13], salt concentration [50] and post-irradiation growth conditions [51]. It is likely that DNA damage dominates *E. coli* inactivation under some conditions, while membrane damage may be the dominant route to cell death under others. This seems particularly plausible since DNA damage capable of causing loss of culturability may not be detected by flow cytometric studies utilizing live–dead staining techniques.

To date, all of the classically defined waterborne pathogenic bacteria have been found to be readily amenable to solar disinfection following 6 h under suitable field conditions (See Fig. 3 and Table 1) [22,52]. However, naturally occurring fecal coliforms have shown much slower inactivation rates in some cases [12,53], while light-resistant sub-populations of cultured *E. coli* were found to be inactivated considerably more slowly than light-sensitive organisms in other trials [21]. *Bacillus subtilis* a gram positive, spore-forming bacterium, is neither waterborne nor a pathogen in the true sense of the word. However, it gives an indication of SODIS inactivation in more complex microorganisms. The maximum reduction

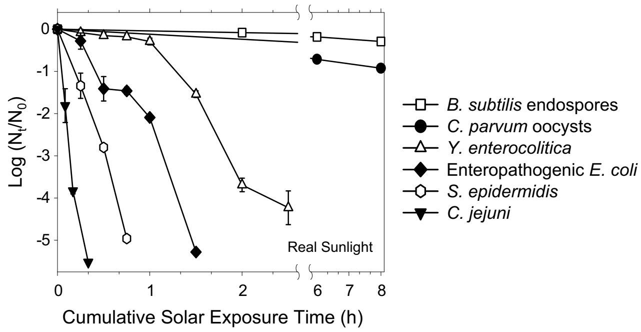

Fig. 3. Inactivation kinetics of microbial populations exposed to real sunlight conditions expressed in units of log reduction. Unless otherwise stated, stationary phase bacterial suspensions were used [54].

observed for *B. subtilis* endospores, after a cumulative exposure time of 16 h of strong natural sunlight was 96.3%, (std. err. = 3.0%) which only corresponds to a 1.3 log unit reduction for a total cumulative received global dose of 22.2 kWh m^{-2} (=79.9 MJ m^{-2}) [54].

3.2. Viruses

Studies evaluating the efficacy of SODIS against viral organisms are scarce. As one might expect, resistance to solar disinfection varies significantly from species to species. Somatic phage [55], bacteriophage f2 and bovine rotavirus [22] were all completely inactivated (3 log unit reduction) in less than 3 h of full sunshine. Polio virus has been inactivated under simulated SODIS laboratory conditions (850 W m^{-2}, water temp. = 25 °C) in under 6 h [56]. A solar disinfection pouch constructed from food-grade, commercially available plastic packaging materials reduced viable plaques of F-specific RNA bacteriophage MS2 by 3.5 log units in comparison to a 5.0 log reduction of enterotoxigenic *E. coli* O18:H11 after 6 h under natural sunlight [9]. However, encephalomyocarditis virus required 12.5 h of simulated sunlight exposure for complete inactivation [22]. Roughly 8–11 h of sunlight exposure only achieved a 1 log reduction of three different classes of coliphage in cistern water under field conditions in Bolivia [52] and viable FRNA coliphages were detected in SODIS reactors fitted with reflectors (increasing the water temperature by an additional 8–10 °C to 64–75 °C) even though *E. coli* was easily disinfected under identical conditions [57]. Safapour and Metcalf were unable to inactivate T2 phage after 8 h exposure to strong sunlight and reflector-boosted water temperatures of 62 °C [58]. Similarly Harding and Schwab were unable to induce any significant reduction in viable murine norovirus populations using UV-A light [59]. The indications are that viral pathogens may prove to be among the most resistant to solar disinfection.

3.3. Protozoa

The ability of endospores of the bacterium *B. subtilis* to withstand solar disinfection was a strong indicator that the infective (oo)cyst stage of protozoan pathogens such as *Giardia lamblia*, *Cryptosporidium spp* and amoebae might prove more resistant to SODIS than bacteria. The primary reason for this is that the infective stage of many waterborne protists is in the form of thick-walled, chitinous cysts or oocysts which contain and protect the feeding or infective stages (trophozoites, sporozoites) of the pathogens. Cysts are known to be resistant to other forms of disinfection such as boiling and chlorination [60–64].

Cysts of *Acanthamoeba polyphaga* have been found to be extremely resistant to SODIS under normal conditions of sunlight and water temperature. It was only when water temperature was

Table 1
Waterborne microbial species that are now known to be inactivated by SODIS.

Microbe	Species	Microbe	Species
Bacteria	*Campylobacter jejuni* [54] *Enterococcus sp.* [22] *Enteropathogenic E. coli* [54] *Mycobacterium avium* [153] *Mycobacterium intracellulare* [153] *P. aeruginosa* [65,154] *Salmonella typhi* [154] *S. typhimurium* [71] *Shigella dysenteriae* Type I [154,155] *Shigella flexneri* [154,155] *Streptococcus faecalis* [22] *Staphylococcus epidermidis* [54] *Vibrio cholerae* [12,122,155] *Yersinia enterocolitica* [54]	Viruses	Bacteriophage f2 [22] Encephalomyocarditis virus [22] Polio virus [56] Rotavirus [22] Norovirus [59]
		Protozoa	*A. polyphaga* (cyst) [56,65] *C. parvum* (oocyst) [69,70,73,74,156] *Entamoeba sp.* (cysts) [104] *Giardia sp* (cysts) [72]
Fungi	*C. albicans* [65] *Fusarium sp.* [65,75]	Helminth	*Ascaris sp (ova)* [104]

raised above 40 °C that any inactivation was observed to occur [56,65]. Such elevated water temperatures are easily achievable in thermally boosted reactors with darkened rear surfaces (See Fig. 4) [10].

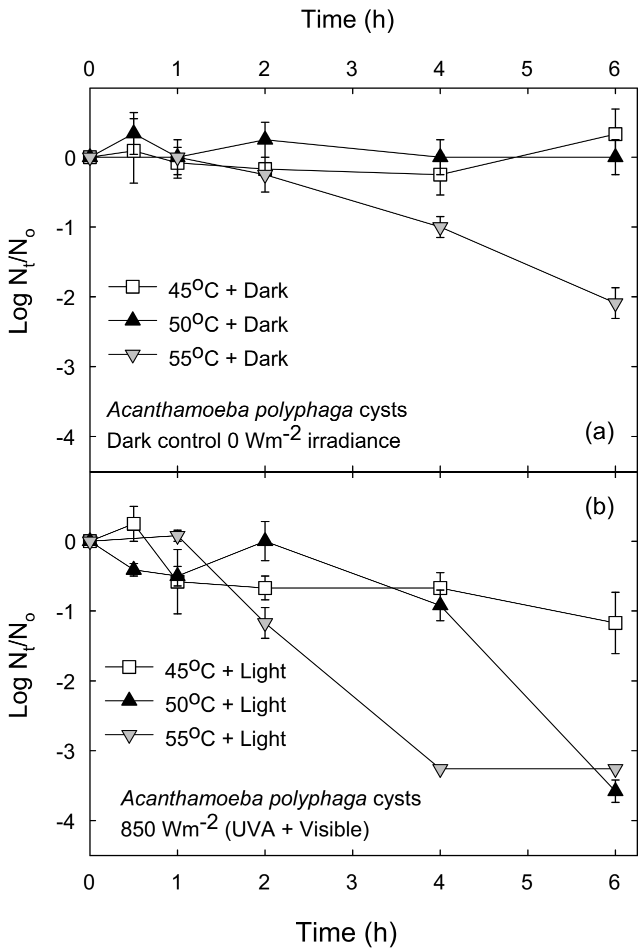

Fig. 4. SODIS inactivation of *A. polyphaga* cysts at a range of temperatures (45–55 °C) exposed to 850 W m^{-2} simulated sunlight [56,65]. Error bars indicate SE of the mean, calculated from triplicate experiments carried out on three separate occasions.

Crytosporidium parvum is responsible for cryptosporidiosis, a particularly debilitating form of diarrhoea. While usually self-limiting in healthy adults, it has been found to cause fatalities in immune-compromised hosts such as those suffering from HIV/AIDS. The *C. parvum* oocyst's capability of surviving in the environment for long periods of time makes waterborne transmission of cryptosporidiosis a serious global issue in drinking water safety [66,67]. Due to the robust oocyst structure, conventional water treatment may not be totally effective, and oocysts may be present and infective in treated water even if no treatment failure has occurred [68]. Viability, excystation assays using DAPI/PI (4′,6′-diamino-2-phenylindole/propidium iodide) vital stains and infectivity tests (Swiss CD-1 suckling mice) showed SODIS exposures at 870 W m^{-2} for 6 and 12 h reduced oocyst infectivity from 100% to 7.5% (standard deviation = 2.3%) and 0% (standard deviation = 0.0%), respectively [69,70] (see Table 2). The dramatic effect of SODIS on *C. parvum* oocysts is demonstrated in Fig. 5. Of the 40% of oocysts that remained viable after 6 h of exposure to simulated sunlight only 27% were capable of excystation. Only 7.5% of these were found to be infective. The phenomenon of infectivity reducing faster than viability under the action of SODIS was also observed for the bacterial species *Salmonella typhimurium* by Smith et al. [71]. In contrast, cysts of *Giardia muris* (acting as surrogate for *G. lamblia*) were rendered completely non-infective (<0.2% infectivity, 95% CI 0.0–7%) after only 4 h exposure when subjected to SODIS conditions of 40 °C water temperature and 870 W m^{-2} irradiance [72]. Ares-Mazas and co-workers have also demonstrated a similarly important effect of temperature on the inactivation of *C. parvum* oocysts during SODIS procedures, independent of UV radiation [73,74].

Table 2
Results of protozoa and helminth inactivation during SODIS tests done in a solar simulator during 6 h exposure [104,125].

Protozoa	Illness	SODIS (6 h @ 550 W m^{-2})
Entamoeba invadens cysts	Amoebic dysentery (reptile model)	1.92 log kill
Naegleria gruberi cysts	Non-pathogenic *Naegleria* model	3.59 log kill
A. castellanii cysts	Encephalitis	2.16 log kill
G. lamblia cysts	Giardiasis	1.96 log kill
Ascaris suum ova	Ascariasis	1.42 log kill

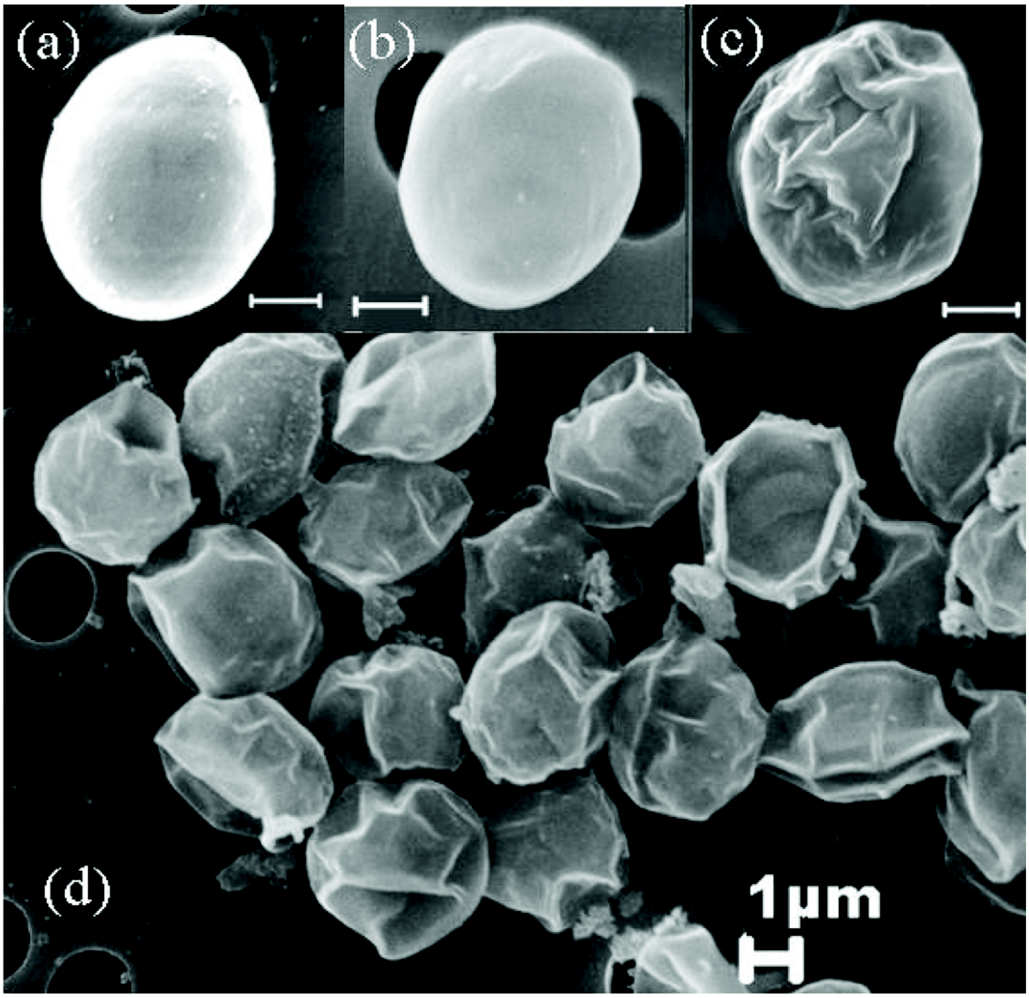

Fig. 5. Scanning electron micrograph of oocysts of *C. parvum*. (a) *C. parvum* at 40 °C at time = 0 h. (b) *C. parvum* at 40 °C at time = 10 h. (c) *C. parvum* at 40 °C + 870 W m^{-2} at time = 10 h. (d) Wide field view of *C. parvum* at 40 °C + 870 W m^{-2} at time = 10 h. Magnification is ×30,000. In each case the scale bar represents 1 μm [72].

3.4. Fungi

For healthy adults, few fungi can be realistically classed as waterborne human pathogens. However, immune-compromised individuals are at risk from a variety of fungal commensal species such as *Candida albicans* and *Aspergillus fumigatus*. Lonnen and co-workers demonstrated that *C. albicans* is readily inactivated within 6 h [65,75]. However, the majority of fungal solar disinfection studies have concentrated on plant pathogens of relevance to intensively cultivated horticultural and aquaponic crops. Sichel et al. [75,76] have reported that the order of sensitivity to solar disinfection for five wild species within the genus *Fusarium* is as follows, when exposed to strong natural sunlight; *Fusarium oxysporum* > *Fusarium solani* > *Fusarium verticillioides* > *Fusarium anthophilum* > *Fusarium equiseti*. A comparison of inactivation kinetics for a variety of microbial species is illustrated in Fig. 6.

4. Solar reactors for water disinfection

While plastic bottles are cost-effective SODIS reactors, one of the main drawbacks is the limit they place on the unit volume treated – usually less than 2 L per batch. If larger batch reactors are required then the ability of the reactor wall to transmit sunlight is one of the most important criteria. In this regard, non-coloured glass is preferred. Extensive work by Acra et al. showed that ordinary glass bottles and glass jars could transmit up to 90% of solar radiation particularly in wavelengths in the UV-A region [18]. Borosilicate glass tubes could be a good solution for flow solar reactors since they transmit up to 90% of the available UV-A as well as 45% in the more germicidal UV-B range [77]. Although glass is a suitable

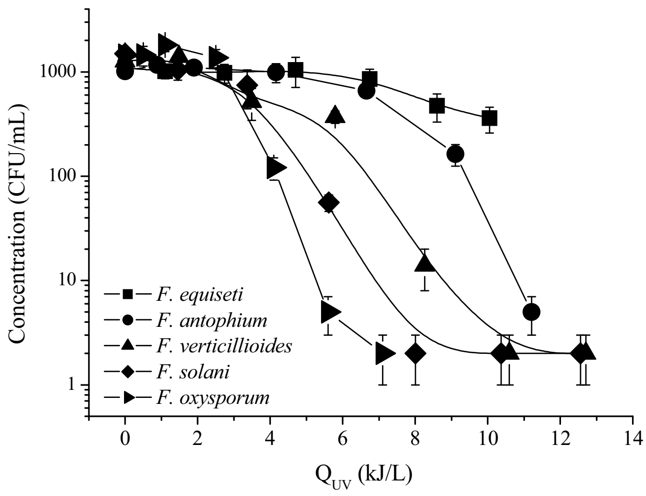

Fig. 6. Solar disinfection of the *Fusarium* under natural solar light as a function of accumulated solar UV-A energy per unit of volume (Q_{UV}) [107].

material in the use of flow solar reactors, for everyday batch disinfection of contaminated water, SODIS users will be required to fill water in containers everyday and this could be heavy due to the use of glass and could also be a potential source of injury if glass breaks. Use of glass bottles can also place a financial burden on low income users since there is often a deposit paid on return of the bottle to the point of purchase. Glass SODIS reactor bottles are therefore often stolen for this deposit if the user is unable to expose the bottles in a secure location.

Plastic bottles have proved to be suitable SODIS reactors, specifically PET bottles. Though PET bottles do not transmit UV-B, their thin wall thickness allows them to efficiently transmit 85–90% in the UV-A region if the bottles are not old or scratched [21]. Unlike glass which is inert and does not release photoproducts, plastic bottles have the potential to leach compounds into water after exposure to strong sunlight conditions. Research involving chemical analysis has been conducted concerning the potential leaching of photoproducts into water. So far, results show that in some cases photoproducts such as terephthalate compounds remain on the surface of the container but do not migrate into the water [78]. Other compounds such as the carbonyls and plasticisers are found in the water but are well below the limits set for drinking water quality [14,79]. However, doubts continue to linger about the safety of water disinfected in plastic bottles in light of the disclaimers made by manufacturers in the bottling industry who instruct users not to reuse plastic bottles. PET bags [80] have also been used as SODIS reactors by placing the bags on a black surface to enhance solar disinfection. SODIS bags maximise the area for photon collection and minimise the path length for light penetration through the water to be treated. These SODIS bags could be deployed in emergency situations where access to drinking water is an immediate issue. The latter application can be limited due to the lack of PET bottles in disaster areas whereas bags have the advantage that they can easily be transported and stored in large quantities. A SODIS pouch which consisted of two materials – a metallized plastic to reflect light and a black plastic to absorb solar radiation was also found effective in inactivating *E. coli*, *S. typhimurium*, *Shigella sonnei* and *Staphylococcus aureus* [9]. SODIS bags can be fabricated from materials like low-density polyethylene, which was investigated by Dunlop et al. [8]. They examined the efficiency of a range of SODIS bags configurations using *E. coli* in model and real surface water [8]. The release of potentially dangerous compounds from PET bottles into water under both solar disinfection and long-term exposure conditions has been studied by Ubomba-Jaswa et al. For this purpose a biological approach was used in the form of the *Salmonella* Ames-Fluctuation assay to detect genotoxins in water samples stored in PET bottles exposed to SODIS conditions [81]. Under SODIS conditions, bottles were exposed to 6 h of sunlight, followed by overnight room temperature storage. They were then emptied and refilled the following day and exposed to sunlight again. Negative genotoxicity results were obtained for water samples that had been in PET bottles and exposed to normal SODIS conditions (strong natural sunlight) over 6 months. Genotoxicity was detected, however, after 2 months in water stored in PET bottles and exposed continuously (without refilling) to sunlight for a period ranging from 1 to 6 months. Interestingly, similar genotoxicity results were also observed for the dark control (without refill) samples at the same time-point and in no other samples after that time; therefore, it is unlikely that this genotoxicity event was related to solar exposure.

Even though researchers have, so far, failed to detect PET plastic photodegradation products or any other harmful or genotoxic substances at concentrations likely to be harmful in solar disinfected water [78,81], concerns about such contaminants remain a significant barrier to increased uptake of SODIS. This psychological barrier must be addressed if SODIS usage is to be increased. Consequently, SODIS dissemination and adoption programmes may have to consider the possibility of promoting the use of glass rather than plastic bottles since glass is so much more optically stable.

5. Enhancement technologies for solar disinfection

5.1. Thermal enhancement

Since strong synergy between optical and thermal inactivation has been observed at temperatures >45 °C [21], a number of enhancement methods have been attempted by accelerating the rate of thermal inactivation of organisms through the use of absorptive materials and painting PET bottles black [12] in order to aid in the absorption of solar radiation. In most cases the water temperatures necessary to reach a synergistic effect between sunlight and temperature are not reached during exposure in bottles in practice. Induced water temperatures remain for long periods of time within the “preferred” growth temperatures for enteric bacteria (25–40 °C). Thermal enhancement has been achieved by: (i) painting sections of the bottles with black paint [82]; (ii) circulating water over a black surface in an enclosed casing which was transparent to UV-A light [57]; (iii) using a solar collector attached to a double glass envelope container [83]. Solar reflectors [10,11,78] can also increase the temperature of water but not to the same extent as the use of absorptive materials or blackening of bottles. All of these studies have achieved different degrees of success with respect to enhancing the heat transfer to the contaminated water. However, depending on the reflector, UV-A will still be available on cloudy days for reflectors to enhance the optical inactivation of solar disinfection unlike blackened surfaces which are unable to raise the temperature of water sufficiently on cloudy days.

From the thermal point of view, bottles or tubes painted with conventional black paint are among the least efficient systems for converting sunlight into heat [84]. The most economic solar collectors have an average conversion efficiency of around 30%. Painted bottles or tubes have a lower efficiency than these. According to the principles of heat transfer, it takes approximately 2 h to heat 1 L of water inside a painted bottle from 20 to 45 °C, assuming summer weather conditions, global irradiances of around 800 W m^{-2} and a 30% conversion efficiency. In winter, depending on ambient temperature, the system would not reach the desired temperature mainly due to heat losses to the environment. Previous works have tried to couple a solar thermal collector to a radiation collector device to address this problem [24]. More efficient solar thermal collectors are available but their cost is prohibitively high to be considered as a part of a SODIS system for use in the developing world.

5.2. Heterogeneous photocatalysis

Photocatalysis is the acceleration of a photoreaction by the presence of a catalyst. When a semiconductor is irradiated with above band-gap illumination, the radiation energy is absorbed and electrons are promoted from the valence band to the conduction band giving rise to the formation of electron–hole pairs. If the charge carriers reach the semiconductor/water interface they may participate in redox reactions. When an electron acceptor (normally dissolved oxygen) and electron donor are adsorbed close to the surface of the semiconductor particle, a series of electron transfer reactions may occur so that different reactive oxygen species (ROS) are produced. The ROS are very active, indiscriminate oxidants, especially the hydroxyl radical [85]. The ROS can not only destroy a large variety of chemical contaminants in water but also cause fatal damage to microorganisms [86].

The photocatalytic properties of several semiconductors have been investigated (TiO_2, ZnO, Fe_2O_3, etc.). Amongst these, the most widely used for water treatment applications is titanium dioxide (TiO_2), also called titania. TiO_2 is a wide band semiconductor whose band-gap energy of 3.2 eV, corresponds to photons of wavelength shorter than 390 nm (UV-A). If the interest is solar application, materials active in the visible range are desirable.

TiO_2 may be utilised in aqueous suspension or may be immobilized on a supporting solid substrate. Most studies have reported that suspension reactors are more efficient due to large surface area available for the reaction. The main drawback of using nano- or micro-particles in suspension is the requirement for post-treatment retrieval or recycling of the catalyst, potentially making the treatment more complex and expensive. Therefore, treatment reactors utilising immobilized TiO_2 have gained more attention. Unfortunately, immobilising TiO_2 on a solid substrate reduces the surface area available for reaction and limits the mass transfer of reactants to the photocatalyst surface in addition to making it more expensive [87]. Most studies on photocatalytic disinfection suggest the hydroxyl radicals as the primary species responsible for microorganism inactivation. The oxidative effect of TiO_2 photocatalysis occurs by direct contact of the catalyst particle with the bacteria, so the first damage should occur at the outer membrane [88]. Other contributions reported other ROS like H_2O_2, $O_2^{\bullet-}$ to be responsible for inactivation. These ROS may cause fatal damage to microorganisms by disruption of the cell membrane or by attacking DNA and RNA. Other modes of TiO_2 action have been proposed including damage to the oxygen transport system within the cells or increased ion permeability in the cell membrane.

The capability of TiO_2 to inactivate a wide range of pathogens has been a fruitful field of research since 1985 [89]. *E. coli* was the most frequently studied microorganism for water disinfection studies [87], as it is an indicator of faecal contamination and reference for water quality. Other bacteria (including spore-forming species) and fungi such as *Bacilus pumilus* [90], *Serratia marcescens*, *S. aureus* [91,92], total coliforms [93], *Pseudomonas aeruginosa*, *S. typhimurium*, *Enterobacter cloacae*, *Saccharomyces cerevisiae*, *C. albicans*, *F. solani* were also inactivated using TiO_2 photocatalysis [94,95]. In addition plant pathogens were found to be inactivated in water using TiO_2 catalyst like spores of *F. solani*, *F. oxysporum*, *F. verticillioides*, *F. equiseti* and *F. anthophilum* [65,75]. Other infectious agents such as viruses and prion proteins were also investigated, and some authors demonstrated the inactivation capacity of illuminated TiO_2 to degrade and inactivate them in water [86,96]. Moreover, the capability of immobilized TiO_2 to inactivate oocysts of *C. parvum* was demonstrated under natural sunlight [69].

TiO_2 suspensions for water disinfection for human consumption requires post-treatment recovery, since TiO_2 powder cannot be left in drinking water due to insufficiently assessed health risks and unacceptable taste. Moreover, the suspended TiO_2 forms a milky suspension which prevents light penetration into the inner regions of the bottle or photo-reactor [87]. Photocatalytic disinfection using immobilized catalyst usually had limited yields or involved technical effort leading to high cost [97]. The microbicidal activity of irradiated TiO_2 immobilized against different pathogens in water using either UV-A lamps or sunlight has also been considered and has been found to be effective against *Clostridium perfringens* spores, *E. coli* [98] and *C. parvum* [69,99].

Attempts to increase TiO_2 efficiency by doping it with metal elements, such as iron, silver, copper or with non metals like sulphur, are on-going [100,101]. Different types of titania catalysts have been also evaluated for disinfection, using either suspensions or immobilized systems. Suspensions presented better disinfection capacities compared with immobilized titania [97]. Research into using tubes coated with TiO_2 in order to treat large volumes of water in continuous flow reactors seems promising [83].

5.3. Chemical additives

In addition to the photocatalyst TiO_2 several other chemical additives have been investigated as possible enhancements for SODIS inactivation. Citrus based additives have attracted much attention. Fisher et al. [102] reported that the addition of 125 mg/L sodium percarbonate in combination with either citric acid or copper plus ascorbate accelerated inactivation of MS2 coliphage, *E. coli* and *Enterococcus* spp by factors of 1.4–19. Harding and Schwab [59] show SODIS combined with lime juice/pulp to be effective at greatly reducing *E. coli* levels in just 30 min. They report *E. coli* reductions of ∼6 log units for enhanced bottles compared to 1.5 log units for standard SODIS in the same time (30 min) – a treatment time on a par with boiling and other HWT methods. Heaselgrave and Kilvington have examined riboflavin as a SODIS additive and report riboflavin significantly enhanced the efficacy of simulated solar disinfection (SODIS) at 150 W m^{-2} against a variety of microorganisms, including *E. coli*, *F. solani*, *C. albicans*, and *A. polyphaga* trophozoites (>3–4 $\log_{10}$ after 2–6 h; $P < 0.001$). With *A. polyphaga* cysts, the kill (3.5 $\log_{10}$ after 6 h) was obtained only in the presence of riboflavin and 250 W m^{-2} irradiance [103]. Enhanced inactivation with riboflavin (SODIS-R) was also observed for cysts of *Acanthamoeba castellanii* where a 2.16 $\log_{10}$ inactivation was observed with SODIS alone at 6 h compared to a 3.84 $\log_{10}$ inactivation with SODIS-R [104].

5.4. Flow reactors

Several reactor designs have been considered to enhance solar disinfection. Some flow reactors have focused on increasing the optical inactivation component of sunlight inactivation using solar collectors and reflectors [83,105]. Attempts have been made to increase thermal inactivation using flat plates painted black to absorb solar radiation solar heating support [106], while others have centred their attention on incorporating TiO_2 photocatalyst [107–109]. Caslake et al. [110] developed a solar disinfection system based on a PVC circuit covered by an acrylic layer transparent to the UV range for drinking water disinfection in remote locations of developing countries. The system worked without catalyst and was used for disinfection of contaminated river water in Peru. In spite of high turbidity, they obtained 4 log reduction for total coliforms. These contributions increased the output of treated water in given solar exposure time.

Ubomba-Jaswa et al. [37] studied the limitations of large volume SODIS treatment when scaled-up through the use of larger batch volumes or continuous flow recirculation reactors. They used two types of solar reactors for disinfection tests, a borosilicate glass tube used as batch system (0 L min^{-1} flow rate, 2.5 L total volume), and two higher volume (14 and 70 L) solar photo-reactors fitted with compound parabolic collectors (CPCs) and recirculation systems at two flow rates (2 and 10 L min^{-1}). Among others, the authors studied the effect of the total volume of treated water and the flow rate on inactivation. They observed that increasing flow rate has a negative effect on inactivation of bacteria, irrespective of the exposure duration (Fig. 7). It seems that at a given time-point there needs to be maximum exposure of bacteria to UV to ensure complete inactivation rather than having bacteria repeatedly exposed to sub-lethal doses over a long period of time. The authors determined the inactivation patterns of *E. coli* during solar exposure under varied UV irradiances and accumulated doses and found that complete inactivation of *E. coli* occurred at all studied solar irradiances (from 14 to 45 W m^{-2}) as long as an uninterrupted solar UV dose >108 kJ m^{-2} was reached. This indicates that inactivation of bacteria is

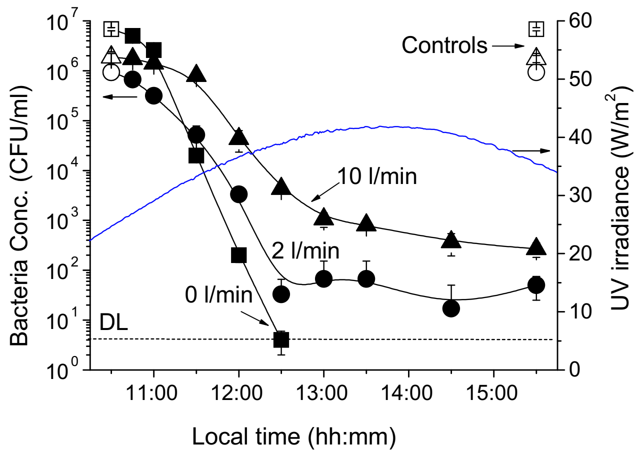

Fig. 7. Inactivation curve of *E. coli* in reactors (i), (ii) and (iii) during natural sunlight exposure. Open symbols represent control samples. Flow rate: 0 L min^{-1} (■), 2 L min^{-1} (●), 10 L min^{-1} (▲). Dashed line (—) shows the detection limit (DL). Each point represents the average of triplicate measurements of duplicate experiments and error bars show standard deviation. UV irradiance (0.295–0.385 mm) data representative of one of the days is displayed on the right *y*-axis [37].

Fig. 8. Solar CPC reflector of anodised aluminium installed in a photo-reactor prototype made with glass tubes of 5 cm external diameter (picture taken at Plataforma Solar de Almería, Spain).

dependent on the UV dose rather than the UV irradiance. They used this result to explain why complete inactivation of bacteria is more frequently observed for static batch systems rather than continuous flow or recirculating reactors. When the water with bacteria remains static under solar light it was constantly illuminated and hence the required uninterrupted UV dose was achieved and complete inactivation to below the detection level took place. With continuous flow systems, the lethal dose was also delivered to the bacteria but in an intermittent manner, resulting in a ~2 log CFU/mL concentration of residual viable bacteria remaining after the 5 h period [37]. Other contributions on the reciprocity law at low and high fluence rates has been carried out in laboratory conditions [111,112]; but extrapolation of results from the laboratory to the field is not easy and experimental validation remain to be confirmed under real sunlight conditions with volumes of water of at least 2 L.

This study has important implications for those attempting to scale-up SODIS through the use of pumped, re-circulatory, continuous flow reactors. If the operational parameters are set such that the microbial pathogens are repeatedly exposed to sub-lethal doses of solar radiation followed by a period within which the cells have an opportunity to recover or repair, complete inactivation may not be achieved.

A single pass, continuous flow SODIS reactor capable of delivering 10 L min^{-1} of treated water has been piloted by Gill and Price [45] in a Kenyan rural village to treat surface waters from a small collection dam. The reactor used ~120 m of 47 mm diameter Pyrex tubing at the focus of a CPC reflector (concentration factor = 1.0), assembled in eight panels. While only preliminary measurements were made soon after the reactor was completed, these indicated that coliform populations were being reduced from 10^2 to 0 CFU/mL after a 20 min single pass residence time. No details of the cost of manufacture or construction were available so it is not apparent how affordable such a reactor might be for other situations. Despite the concerns raised about the effective inactivation achievable in recirculation and high flow rate SODIS reactors an application may still be possible in the (pre-) treatment of grey water. Pansonato et al. have reported 2 log reductions in *E. coli* levels using a 51 L continuous pilot-scale reactor prototype using grey water [113].

Regarding the up-scaling issues of SODIS, the recent contribution of Polo-López et al. [114] proposes a continuous single pass flow reactor, which would deliver solar disinfected water in the outlet of the reactor. This is a sequential batch photo-reactor which decreased the treatment time required for complete bacterial (*E. coli*) inactivation and increased the total output of water treated per day, reducing user-dependency. For this, the authors incorporated a CPC reflector of concentration factor 1.89 which reduced the residence time needed for disinfection and therefore, treated a higher volume of polluted water in the same time. The system also incorporated an electronic UV-A sensor which controlled the discharge of the treated water into a clean reservoir tank following receipt of the pre-defined UV-A dose. If this reactor could be constructed with six modules, it would produce at least 90 L of potable water per day, and approximately 31,500 L during a typical year.

5.5. Solar mirrors

The SODIS bottles are usually only illuminated on the upper side of the reactor that faces the sun. There have been several attempts to concentrate solar radiation using solar mirrors with the aim of increasing the radiation inside the bottles. Aluminium foil attached to the back of the bottles increased disinfection rate constants by a factor of 2 [10]. Rijal and Fujioka [115] used also solar reflectors and observed improved efficiencies which they attributed solely to the increase in water temperature of the system. Reflective solar boxes can reduce disinfection time to 3–4 h [82].

Navntoft et al. [77] have examined the optimum concentrating optics to enhance the radiation reaching the bottles in SODIS. They reported improved solar disinfection results for suspensions of *E. coli* in well-water using compound parabolic collectors (CPC) (Fig. 8). They showed an enhanced efficiency of solar disinfection for batch reactors under sunlight in cloudy and clear sky conditions. They demonstrated that the CPC mirror enhances the SODIS efficacy and in all cases reduced the total treatment time to disinfect the water.

McLoughlin et al. [48] studied the use of three types of static solar collector profiles for the disinfection of water containing *E. coli*. They demonstrated that three lab-scale solar photo-reactors with aluminium reflectors consisting of compound parabolic, parabolic and V-groove profiles all enhance the effect of the natural solar radiation, although the CPC is more efficient than the parabolic or V-groove profiles. They also proved that low concentrations of titanium dioxide on a rod inserted in the reactors moderately enhance the overall disinfection performance in the compound parabolic reactor. In a subsequent study [47] this group examined low cost compound parabolic collectors using solar radiation and *E. coli* as the target microorganism. The results proved that bacterial deactivation rates using sunlight alone can be enhanced by low concentrations of titanium dioxide suspended in the water. Their results were unclear, however, when they used a standardised UV-dose threshold. As a result, they suggest another disinfection mechanism in the reactor configuration, both a synergistic effect between UV light and the mechanical stress of recirculation, or, a stroboscopic shock effect in which bacteria are intermittently exposed to light and dark in the reactor.

A recent contribution by Ubomba-Jaswa et al. proposed the use of a new SODIS enhanced batch reactor (EBR) design fitted with a compound parabolic collector (CPC) for the disinfection of 25 L of water in ≥6 h of strong sunlight [49]. This prototype thereby avoids the need for a constant supply of PET bottles. The authors suggested that the EBR needed to: (i) be constructed from materials of minimum cost; (ii) be robust in nature so that it can withstand adverse environmental conditions and (iii) require very little maintenance. The reactor consisted of a cylindrical container placed along the linear focus of the CPC (Fig. 9). The use of flow was avoided in the reactor, as previous experiments had shown increasing flow rate had a negative effect on bacterial inactivation. This was due to the fact that inactivation of bacteria was more effective when bacteria were exposed to minimum lethal UV-A doses over a short period of time, rather than receive repeated sub-lethal doses over a longer period of time, which is likely to occur using re-circulated flow [37]. Furthermore, flow-through systems might require higher maintenance and operational costs. The use of the CPC provides an enhancement to the disinfection process by concentrating available solar radiation and therefore, reducing the amount of exposure time required for bacterial inactivation under cloudy conditions. In previous studies a 3-year-old CPC with reflectivity reduced from its original homogeneous 82% value along the concentrator to a non-homogeneous value between 27% and 72%, still ensured that complete bacterial inactivation was achieved even on cloudy days [77]. The authors studied the microbial inactivation efficacy of the reactor by a 7-month study of *E. coli* K-12 inactivation in 25 L volumes of natural well-water and turbid water. They demonstrated that the CPC enhancement delivers good disinfection results [49].

5.6. Cost-benefit of enhancement technologies

No discussion of SODIS enhancement technologies would be complete without some consideration being given to cost. Households relying on SODIS tend to be at the lower end of the socio-economic spectrum. Consequently, SODIS is usually selected when sufficient resources are not available to afford more expensive (but not necessarily more effective) treatments such as chlorination, filtration or some other HWTS technology further up the "water-ladder". SODIS is sometimes selected because no other operational costs are incurred once the bottle has been procured. Given that cost and sustainability are so intrinsically linked to SODIS use, the benefit of associated enhancement technologies must be evaluated not only in terms of efficacy but also with regard to affordability. If a household is reliant upon SODIS and cannot afford any other HWTS technology it is extremely unlikely that they can afford chemical additives such as titanium dioxide, riboflavin, psoralens or citric acid [59]. Realistically speaking, the only situation where SODIS enhancements might be viable is where the benefit in quality, speed and/or treated volume provided by the enhancement can offset the additional cost and provides "added value". Such a situation was observed by one of the authors (KMcG) in rural Uganda in 2011 where a local school teacher combined harvested rainwater and solar disinfection. Since harvested rainwater tends to be lower in turbidity, she sold the treated, clearer water at a small profit to neighbours who otherwise relied on highly turbid water from unprotected water sources. Larger scale SODIS reactors may be economically viable when used in a community setting where they provide treated water for several households or for a small clinic or school. However, apart from the preliminary and inconclusive study reported by Gill and Price [45] of a continuous flow SODIS reactor installed in a Kenyan rural village to treat surface waters from a small collection dam at this time, no comprehensive study examining the utility of SODIS in such a setting has been reported.

6. Water quality used in disinfection studies

The presence of organic and inorganic matter present in the water during disinfection has an important effect on both the kinetics and the final disinfection result, similar to the decontamination of organics in water using photocatalysis. The inhibiting effect of different electrolytes is well known in photocatalysis, with phosphates being the species with the highest detrimental effect on the efficiency of the process. For SODIS, the presence of inorganic and organic matter has been shown to slow the disinfection process also [116,117].

Microbial inactivation studies in flow reactors have used different types of water, e.g. sewage water, well-water, distilled water and de-ionised water. Using a natural source of water such as well-water, sewage water and river water gives a better prediction of microbial inactivation under real conditions. Using natural water avoids weakening of bacterial cells due to an unfavourable osmotic environment (lack of ions). Bacteria showed better survival rates in flow reactors under dark conditions when suspended in well-water as opposed to distilled water [116]. By using water containing ions, bacterial cells are subjected to less osmotic pressure as the solute ion concentration in the well-water is similar to that within the cell. While cell death due to osmotically driven cellular lysis is unlikey when using distilled or de-ionised water, it does mechanically weaken the cell membrane by causing the phospholipid bi-layer to flatten, which results in conformational changes in integral membrane proteins [118].

Though the presence of ions may help to retain bacterial integrity, if ions are present in high concentrations they could have a limiting effect on the SODIS process. UV-A mediates its biological effects on bacteria by reactive oxygen species (ROS) such as hydrogen peroxide and hydroxyl radicals [119]. If bicarbonates (HCO_3^-) are present in water they react with hydroxyl radicals producing $CO_3^{\bullet -}$ which has a slower reaction with organic molecules when compared to $^{\bullet}O$ [120]. Furthermore, HCO_3^- induces photo-absorption which limits the amount of light reaching bacteria in water. Other anions such as phosphates, chloride and sulphates are shown to be absorbed by bacteria but do not illicit a direct effect on solar inactivation unless in the presence of a photocatalyst such as titanium dioxide.

7. Clinical field trials

Successfully completing clinical trials or health impact assessment studies of point-of-use household water treatment among communities in developing countries is an extremely difficult task. Conroy et al. conducted the first clinical trial of solar disinfection which was carried out among the Maasai community along the Kenya–Tanzania border in 1996 [19,121]. They found a reduction in incidence of diarrhoea in children under the age of 5 years (odds ratio = 0.66, 95% CI 0.55–0.87). Odds ratio is a relative measure of risk, telling us the ratio of the odds of an event occurring in one (test) group relative to the odds of it occurring in another (control) group.

Fig. 9. SODIS enhanced batch reactor of 25 L containing water of 0 and 100 NTU (picture taken at Plataforma Solar de Almería, Spain) [49].

The protective effect of SODIS against cholera was dramatically demonstrated by Conroy et al. [122] during an epidemic in an area of Kenya in which a controlled trial of solar disinfection and diarrhoeal disease in children aged under 6 had just finished. In their retrospective study they reported three cases of cholera in 155 children aged under 6 years in the households using solar disinfection compared to 20 cases in 144 children of that age in the control households giving an odds ratio of 0.12 (95% CI 0.02–0.65, $P = 0.014$).

A SODIS study in the Tamil Nadu region of South East India, Rose et al. [123] demonstrated a significant reduction in the incidence, duration, and severity of diarrhoea in children receiving solar disinfected water. The incidence of diarrhoea in the intervention group was 1.7 per child-year, and among controls 2.7 per child-year, with an incidence rate ratio of 0.64 (95% CI 20.48–0.86). The risk of diarrhoea was reduced by 40% by using solar disinfection. However, the study did not distinguish between dysentery and other types of diarrhoea. The fact that Rose et al. [123] reported this significant reduction in diarrhoeal disease in children receiving solar disinfected water, despite 86% of the children in the intervention group supplementing their drinking water from sources other than that treated by the SODIS, raises the intriguing possibility that part of the observed reduction in waterborne disease may arise from a protective immunological response resulting from a daily challenge of ingested, inactivated pathogens. Until this can be confirmed or disproved through sensitive immunological analysis of antibody responses from long-term SODIS users this must remain a thought-provoking hypothesis.

A small scale SODIS implementation study was completed by Mani [124] across three different climactic regions within India: Gorakhpur (Indo-Gangetic plain), Jodhpur (arid) and Alappuzha (Keralan coastal region). This study was particularly interesting since they used a 1 L PET bottle that had been specifically designed for SODIS [11] and all household members within the test group used SODIS water. These researchers reported a significant reduction in the numbers of cases of diarrhoea/gastro-enteritis in all field locations.

A large multi-country study of the health impact of SODIS on childhood diarrhoea was completed by McGuigan between 2006 and 2010 as part of the SODISWATER Project [125]. This European Union funded project conducted 12-month duration health impact assessments (HIAs) among peri-urban and rural communities in Kenya [126], Zimbabwe and S. Africa [127]. A fourth HIA separately funded by the Irish government was subsequently run among rural communities in Cambodia in parallel with the EU SODISWATER HIAs using the same protocols and methodologies [125,128]. For children under age 5 years, proper use of SODIS (compliance > 75%) resulted in significant reductions in dysentery incident rate ratios (*incident rate in SODIS group divided by incident rate in control group*) ranging between 30% and 55% in Kenya, S. Africa and Cambodia (see Table 3). The Zimbabwe study was ultimately unsuccessful owing to: (i) a 3 months government enforced suspension of all foreign funded projects prior to national elections and (ii) a nationwide cholera epidemic during which chlorine disinfection tablets were distributed freely to the entire population. While the distribution in Zimbabwe of freely available chlorine tablets by the major aid agencies for those at risk was the correct course of action, it nevertheless produced drastic reductions in SODIS compliance within the study test group who no longer saw a need to practice the technique. By the time that the cholera epidemic had passed and chlorine tablets were no longer freely available, most of the SODIS bottles that had been distributed to the test groups were lost, discarded or used for other purposes (storing fuel, cooking oil, beer, milk etc.).

The Kenyan arm of the SODISWATER programme produced additional results that suggest that the health benefits conferred by SODIS may extend beyond a reduction of waterborne disease. Anthropometry measurements of weight and height for children under age 5 years participating in the Kenyan phase of the SODISWATER health impact assessment showed median height-for-age

Table 3
Preliminary dysentery days incident rate ratios (=incident rate in SODIS group divided by incident rate in control group) observed for the SODISWATER health impact assessments of SODIS [125].

Country	Dysentery days incidence rate ratio	95% confidence interval	*P*-value
Kenya [126]	0.56*	0.40–0.79	<0.001
Cambodia [128]	0.43*	0.20–0.95	0.036
S. Africa [127]§	0.35*	0.17–0.76	0.011

* Statistically significant.
§ For participants with >75% compliance/motivation.

was significantly increased in those on SODIS (0.8 cm 95% CI 0.7–1.6 cm, $P = 0.031$), over a 1-year period. Median weight-for-age was higher in those on SODIS, corresponding to a 0.23 kg difference in weight over the same period, however, the confidence interval spanned zero and the effect fell short of statistical significance (95% CI −0.02 to 0.47 kg, $P = 0.068$) [126]. The significance of this anthropometric benefit has been questioned by Hunter et al. who have pointed out that the technical error in un-standardised height measurement for children under the age of 2 years can be as high as 1.4 cm [129]. However, this uncertainty is only relevant for less than 20% of the height measurements reported by du Preez et al. [130].

Against the successes reported for SODIS in the field, significant concerns were raised by Mäusezahl et al. about the value of solar disinfection following the publication in 2009 of the results of a large SODIS trial in Bolivia [131]. Despite extensive health promotion intervention, compliance with SODIS was very low (32%), and the SODIS group did not show a statistically significant reduction in incidence of diarrhoea (relative risk 0.81, 95% CI 0.59–1.12). The trial result is difficult to interpret, as pointed by Bhutta [132] and McGuigan et al. [128]. The lack of an observed significant reduction in disease could have been a failure of SODIS to reduce risk, or a failure of the intervention to produce sufficient compliance with SODIS to achieve a reduction in risk. Unfortunately, the measure of compliance used by Mäusezahl and his colleagues is difficult to interpret. It was measured using "four different subjective and objective indicators". It is, therefore, unclear as to what their stated compliance rate of 32% reflects.

Both Hunter [133] and Schmidt and Cairncross [134] suggest that a large fraction of any observed reduction in disease rates in un-blinded household water treatment studies may be attributed to bias (reporter, observer, recall or publication) associated with subjective outcome measures such as self reporting which has been used in almost all of the SODIS studies [129]. Conducting a randomized, controlled and blinded study of SODIS in developing countries would present significant challenges in any developing world setting with regard to the feasibility of treatment, randomization and distribution of SODIS treated water by third parties independent of the study households. If the care-giver is to be truly unaware of whether the water they are consuming in their household is in the intervention or control groups then a third party is required to administrate the treatment elsewhere and distribute the water to the participating households. Access to a space sufficiently large to expose several hundred 2-L bottles without fear of interference within an urban setting, would be problematic. Since the recommendation is that SODIS water is consumed within 48 h of treatment, this distribution would have to be carried out in such a way that sufficient water was provided to each of the rural or peri-urban households every 2 days – amounting to the treatment and transport of more than 2000 L (2 metric tonnes – assuming 750 participants) on each occasion. The intervention thus trialled would bear so little relationship to real-life point-of-use water treatment that the external validity of the trial would be questionable. Studies demonstrating post-collection contamination of water reinforce the necessity for household water treatment to occur *at the point of use*. Anyone who has been involved with field research in the area of household water treatment and storage technologies in the developing world will know that likelihood of successful project completion is extremely sensitive to the simplicity of the trial methodology. The gain in internal validity will necessarily be at the cost of a significant loss of external validity.

In his meta-analysis of household water treatment studies Hunter [133] further suggests that the long-term benefits of disinfection-only interventions such as chlorination and SODIS reduce over time with duration of use. Consequently SODIS may be most effective as an intervention against waterborne disease for short periods of time such as in the immediate aftermath of natural or humanitarian disasters.

8. Behavioural factors determining the adoption and sustained use of SODIS

For SODIS to effectively reduce diarrhoea, compliance must be high. This means that SODIS treated water must form a significantly large percentage of drinking water consumed. They have to drink SODIS water constantly, habitually and without interruption to supply. SODIS compliance implies behaviour change, since users must organize bottles, wash and fill them with water, put them in the sun and collect them afterwards. Additionally the cup or glass used for drinking has to be cleaned before consumption because otherwise there is a high risk of recontamination [135]. All of these steps require changes in both the behaviour of the SODIS user and in their daily routine. Such changes call for changes in behavioural determinants. The task of applied behavioural science is to determine which factors contribute to and which behavioural factors hinder sustained use of SODIS. Behavioural factors include personal, socio-cultural, and environmental conditions perceived and processed by the individual when forming the intention to actually use SODIS.

Several scientific articles have investigated behavioural factors when explaining SODIS use. Rainey and Harding [136,151] used the Health Belief Model as a framework to explain acceptability of solar water disinfection in Nepal. In their qualitative approach they found evidence that factors such as perceived risk, perceived barriers, perceived benefits, self-efficacy, and cues to action are connected with SODIS use [136]. Rose et al. [123] determined the acceptability of solar water disinfection with focus group discussions and in-depth interviews finding that topics such as ease of use, financial implications, mechanisms of action, and limitations of solar disinfection (e.g. missing bottles) were factors mentioned by the interviewees.

The intention to use and consume solar disinfected drinking water by households in Nicaragua was successfully explained by Altherr et al. [137a] measuring and analysing attitude, subjective norms (what the person thinks that he or she should do), and self-efficacy. Heri and Mosler (2008) [137b] assessed the attributes of SODIS innovation in 536 Bolivian households on the basis of descriptive norms (how many others are using SODIS), injunctive norms (how do others approve or disapprove the use of SODIS), number of promotional strategies, and alternative treatments (boiling). They were able to explain with these factors the intention to use and consume SODIS water that they had observed.

A survey on the use of SODIS with 878 households in slums of Harare in Zimbabwe conducted by Kraemer and Mosler [138] showed that the uptake of SODIS could be determined very well in terms of persuasion research factors such as knowledge, affect, attitude, involvement, convictions (time, money, health), self-efficacy, social influence, and self-persuasion (talking about an innovation self-convinces the person). Finally, Graf et al. [139] analysed hygiene behaviour and SODIS uptake in 500 households in the Kibera slum in Nairobi (Kenya). Using factors such as perceived risk, severity, causes of diarrhoea, biomedical knowledge, action knowledge, belief in importance of clean water, and social norms, they could accurately explain both SODIS uptake and hygiene behaviour.

The different types of SODIS users have been identified and differentiated by Kraemer and Mosler [140]. They defined SODIS user types, as: (i) non-user; (ii) fluctuater (using SODIS and then not); (iii) late beginner; (iv) irregular user; (v) regular user and (vi) relapser. They showed that regular users perceive a higher need to use SODIS and have a higher use-habit than irregular users. Irregular users are higher in the factors of need, attitude, intention and habit than fluctuaters. The main difference between fluctuaters and late beginners is intention, which has to be higher in order for fluctuaters to move into the stage of the late beginners. The non-users exhibit the lowest values of all the groups in all the factors. Relapsers have similar or even higher values in need, intention and attitude as fluctuaters and late beginners, but exhibit the lowest habit of all the groups. Tamas and Mosler have also analysed differences between relapsers and continuers of SODIS [141]. They revealed that relapsers have lower values for all psychological variables compared to overall continuers. Low-value relapsers differ from high-value relapsers in that they rate the taste of SODIS water as better, prefer to use SODIS, and think others approve when they use SODIS. Interestingly, high-value relapsers have values almost as high as low-value continuers, differing only in their degree of habit. It can be reasoned that the cause of people becoming relapsers lies mainly in the lack of habit, which they obviously did not manage to maintain, unlike those who remained as continuers. Using a comprehensive behaviour change model Mosler [142] analysed in a long-term study which factors change when long-term users of SODIS, non-users, or 'tryers' (using SODIS occasionally), transform their behaviour type or stay in their current behaviour type [143]. Data were obtained by conducting six panel interviews about the use of solar water disinfection (SODIS) over a period of 14 months, with 694 households, in the slum areas of Harare, Zimbabwe. They demonstrated that progressing to a higher level of user type (increasing use of SODIS), or staying at a high level of use is related with the user's ability to avoid being hindered by other habits, remembering the behaviour in respective situations, and noticing that other people are also using SODIS.

Tamas and Mosler investigated the effects of two different behavioural interventions. First they used health volunteers as promoters who were given a set of persuasive messages (SODIS makes you healthier, is easy to do, is cheap etc.) that they were told to use during household visits to inform and persuade members of the household. Additionally they used prompts in the form of cardboard cuboids displaying the reminder sentence "put the water bottles out into the sun" and an A4 sized poster with the sentence "we commit ourselves to drink water disinfected by SODIS". These prompts were distributed with instructions to hang them visibly inside or outside the house (see Fig. 10). As can be seen from panel 4 in Fig. 11 the persuasion intervention alone increases the percentage of consumed SODIS water significantly compared to the control condition (45% compared to 32%) but persuasion in combination with the prompt intervention is the most effective intervention strategy (59% of SODIS water). This research shows that behavioural

Fig. 10. Prompts used in the Bolivian behavioural intervention study. Left hand the poster with the sentence "We are committing ourselves to drink water disinfected with SODIS"; right hand the cuboid with the main message "One has to put the bottles with water out into the sun".

factors derived from psychological theories can explain both intention to use and actual use of SODIS. The behaviour change process is not influenced by solely one factor but by a multitude of factors which have to be taken into account when planning behaviour change interventions for SODIS use. With these findings behaviour change strategies which target specific factors can be developed and implemented.

A quite different question is how to disseminate SODIS among populations in need of safe drinking water. Meierhofer and Landolt [144] conclude from their global dissemination programme that a widespread dissemination of SODIS can be achieved if promoters are convincing, committed, and respected within the community; if enough bottles are available; several training events are arranged; and if people see many others performing SODIS (Fig. 12). The findings of Moser and Mosler [145] point out that early adoption of SODIS was predicted by increased involvement in the topic of drinking water and that adoption in the middle of the diffusion process was predicted by increased involvement, by opinion leaders, and by recognition of a majority who supported the technology. Finally, late adoption was caused by perceiving that a majority had already adopted SODIS. Tamas et al. [146] investigated several dissemination strategies and found that interpersonal strategies were more effective than centralized strategies. Centralized strategies such as health fairs did not reach as many people and did not greatly change behaviour, while interpersonal strategies (promoters, opinion leaders) were successful in both of these respects. Furthermore, the applied centralized strategy was the most expensive promotional

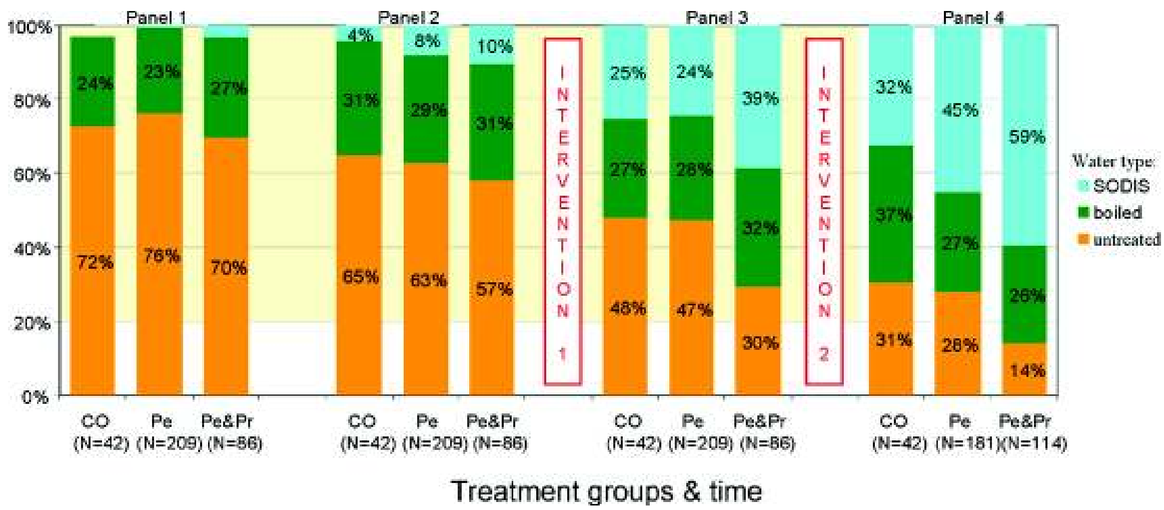

Fig. 11. Consumed percentages of the total water consumption of untreated, boiled and SODIS water of the control, persuasion and prompt intervention groups over time. Co = control, Pe = persuasion intervention, PF&SF = persuasion and prompt intervention [146,152].

Fig. 12. Solar disinfection in use in (a) Harare, Zimbabwe and (b) the Svey Rieng area of Cambodia by a family who were not part of any SODIS study but have "self-adopted" the technique after seeing neighbours within the same village using the technique.

strategy (music, animator, food for staff, advertising, prizes for competitions) while the opinion leaders proved very inexpensive and the 2 weeks of employment of the promoters cost about half that of the health fair. For the interpersonal strategies, promoters were found to be more effective than opinion leaders in the short-term, but there was no difference between these two interpersonal communication strategies in the long run.

In summary, to bring SODIS from the bench-top to the roof-top it is vital to know which behavioural factors persuade people to put SODIS bottles on their roofs. Additionally, the type of dissemination strategy to be applied under which conditions has to be investigated. A sophisticated application of behaviour change strategies will produce high adoption rates of SODIS.

9. Discussion and concluding remarks

Solar disinfection is at a great disadvantage compared to other household water treatment and storage (HWTS) techniques such as chlorination or filtration [147]. Since SODIS does not rely on a product that has been commercially manufactured for the specific purpose of water disinfection there is usually no large manufacturing corporation funding advertising campaigns to promote either the product or technique. The standard bottles which are typically used for SODIS are used for a fundamentally different purpose than that originally intended and for this reason bottle manufacturers are often reluctant to support promotion of the technique.

The introduction of SODIS to stakeholders in a developing world region is usually greeted with considerable initial scepticism from people who may have hoped for a more technological solution to their water contamination problem such as a ceramic [148] or biosand [149] filter. Instead they are presented with plastic bottles that in other circumstances might have been discarded as waste and consigned to the rubbish tip. It can be difficult to convince someone who has had a lifetime of acclimatisation to strong sunlight and has never considered the possibility that sunshine could have a disinfecting effect. The task of promoting SODIS is further hampered by concerns centring on the possibility that harmful chemicals leach from the plastic after prolonged use. For these, and other, reasons it is not surprising that in 2011 the WHO/UNICEF Joint Monitoring Programme found that SODIS is used by less than 1% of the households using HWTS throughout the developing world [150].

SODIS is not a universal solution to the problem of access to safe drinking water. Other HWTS interventions are available and are as effective, if not more so. However, these come at an increased cost. The people who rely upon SODIS tend to be at the bottom of the economic ladder with the least financial resources. In 2007 Clasen et al. [7] estimated that at $0.63 per person per year, solar disinfection is the lowest cost household based intervention against waterborne disease when compared with chlorination ($0.66), filtration ($3.03), flocculation/disinfection ($4.95) or source-based

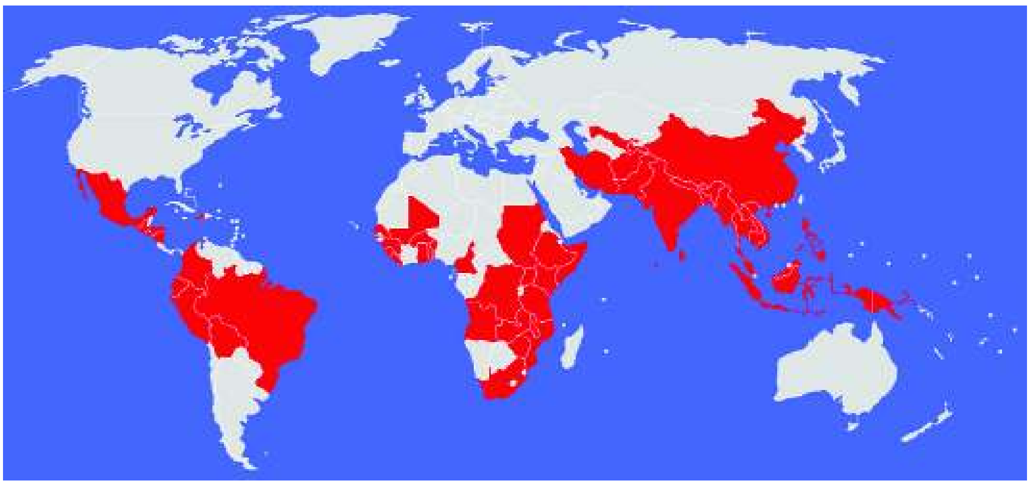

Fig. 13. A map of the World indicating the 55 countries where, in 2009 [144], SODIS was in daily use by more than 4.5 million people.

interventions ($1.88 in Africa or $2.61 in Asia). In fact, over the past 10 years the authors have found that a frequent reason for a household continuing to use SODIS has been on the basis of economic benefit first rather than improvement of health. SODIS can improve household finances in several ways such as:

(i) reduced costs for fuel used to boil water.
(ii) reduced morbidity increases availability for income generating activities by the caregiver.
(iii) reduced illness-associated costs (oral rehydration solution, medicine, transport to local medical facilities, etc.).

SODIS could therefore, be viewed as a "gateway" HWTS intervention facilitating households to access more reliable, but more expensive, point-of-use household water treatments higher up the water-ladder. The advantage of SODIS as a short-term, emergency water treatment in post-natural disaster and humanitarian crisis situations has been recognised by the WHO and UNICEF since 2005.

After more than 30 years of intensive research, the efficacy of SODIS cannot be argued. Laboratory studies have shown that it is effective against almost all waterborne microbial species of pathogenic interest [54,148,149]. Clinical trials of the technique in the developing world clearly indicate that when implemented correctly and used regularly, SODIS can significantly reduce rates of childhood dysentery and infantile diarrhoea by as much as 45% [19,121,122,124,126–128,144,151]. In our opinion the SODIS hypothesis has been proven. Solar disinfection is currently in daily use by more than 4.5 million people in more than 50 countries across the developing world (Fig. 13). The future challenges now lie in enhancing the microbicidal process and developing effective strategies to assist in HWTS scale-up.

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