Research Paper

Effectiveness of solar disinfection for household water treatment: an experimental and modeling study

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ABSTRACT

Solar disinfection (SODIS) is a simple and low-cost household water treatment (HWT) option used for disinfection of drinking water. In this study, the bacterial inactivation potential of SODIS was evaluated under the solar irradiance observed in different seasons in Bangladesh according to WHO evaluation protocol of HWT, and the SODIS experiments were conducted for both transmissive and reflective reactors using PET bottles and plastic bags. In summer, log reduction value (LRV) more than 5 was observed for the transmissive PET reactors for 6 to 8 hr exposure to sunlight and the treated water complied with the microbial standard of zero colony forming units/100 mL in drinking water. In monsoon and winter, LRV > 4 can be achieved for 16 hr and 8 hr exposure to sunlight, respectively, using reflective reactors. The plastic bag was found to be more effective than PET. A safe exposure time was estimated from the Weibull model to be maintained for SODIS application to achieve 4.0 LRV and also to prevent the re-growth of microorganisms in the treated water. A significant re-growth of microorganisms was observed in the treated water, thus SODIS with other HWT processes can be recommended for use in communities with an unsafe drinking water supply.

Key words | bacterial inactivation, PET bottle, plastic bag, safe exposure time, solar disinfection (SODIS), Weibull model

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HIGHLIGHTS

- Address the effectiveness of SODIS under the local irradiance observed in Bangladesh.
- Used both reflective and transmissive reactors.
- Complete inactivation achieved under strong sunlight condition.
- Reflective reactors are more effective.
- A safe exposure time was estimated.

INTRODUCTION

The Sustainable Development Goal 6.1 of the United Nations aims to achieve universal and equitable access to safe and affordable drinking water for all by 2030. Access to safe and clean water is the keystone of sustainable development. In 2017, about 2.2 billion people globally lack access to safely managed drinking water services, among them, 435 million people taking water from unprotected wells and springs and 144 million people

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collecting untreated surface water from lakes, ponds, rivers, and streams (WHO 2019). Furthermore, a minimum of 2 billion people use a drinking water source contaminated with feces (WHO 2019). Waterborne diseases are still significant factors for overall global mortality and intervention of point-of-use (POU) or household water treatment (HWT) can effectively reduce the health burden of waterborne diseases (Gundry *et al.* 2004). The widely used HWT technologies are chlorination, coagulation and filtration, ceramic and biosand filter, and solar disinfection (SODIS) and are found to be very effective in improving the microbial quality of drinking water (Sobsey *et al.* 2008).

The WHO has recommended SODIS as HWT technology (WHO 2011), a simple and low-cost water disinfection option in which clear water is filled into UV transmitting transparent containers like a glass bottle, plastic bag and PET and put into the sunlight for about 6 hr, including midday hours or 2 consecutive days under cloudy conditions (McGuigan *et al.* 2012) for inactivation of microorganisms. Microbial inactivation occurs through the germicide effect of ultraviolet light and increase of water temperature by solar radiation (Wegelin *et al.* 1994). SODIS is practiced in several Asian, African, and Latin American countries for disinfecting water for drinking (McGuigan *et al.* 2012) and is a cost-effective method widely used in rural areas and rehabilitation camps of disaster-affected regions. The transparent containers required for the SODIS process are locally available in any developing country and the process does not require skilled manpower and supervision, but much effort and training are required to achieve a behavior change and good hygienic practices for its sustainable and consistent application among the users (Islam *et al.* 2015; EAWAG 2016). The SODIS process has proven to be highly effective against a wide range of waterborne species of bacteria, viruses, protozoa, fungi, and others (McGuigan *et al.* 2012).

SODIS has been studied rigorously under both laboratory conditions (controlled solar irradiance, temperature, chemical and biological composition of water) and actual field conditions under variable irradiance and temperature, for a wide range of pathogens and physical and chemical water quality (McGuigan *et al.* 2012). The performance of SODIS has also been evaluated for wastewater, freshwater, seawater, harvested rainwater, public water supply, rain and pond water (Sinton *et al.* 1999; Amin & Han 2009; Mustafa *et al.* 2013; Islam *et al.* 2015). The main parameters affecting microbial inactivation in the SODIS process are solar irradiance and temperature, water turbidity, water composition and nutrient presence, types of microorganisms, reactor types and configurations (Vivar *et al.* 2015). It has been reported that the reflective and adsorptive reactors are more effective in microbial inactivation than transmissive reactor under weak and moderate irradiance conditions (Mani *et al.* 2006; McGuigan *et al.* 2012; Mustafa *et al.* 2013), and polyethylene bags are more effective than PET as the PET bottles cut off a large part of UVB (Gutiérrez-Alfaro *et al.* 2017). The microbial inactivation is typically measured by $\log_{10}$ reduction value (LRV), which compares values of microorganisms before and after the treatment. According to the evaluation protocol of HWT options by WHO (2011), the disinfection process is termed as highly protective if the LRV is ≥ 4 and protective if the LRV is ≥ 2. Currently, there is no standard of LRV for defining safe water; LRV > 3 is usually recommended to determine the effectiveness of the treatment process.

Although Bangladesh has made considerable progress in water supply coverage, improving health and sanitation over the last decade, there are still about 20 million people who lack access to safe drinking water. The poor segment of the urban people living in the slums is still lacking access to safe and reliable water supply. Moreover, about 28% of the country's total population living in the coastal areas of Bangladesh drink water mainly from rain-fed ponds, pond sand filters (PSF), and rainwater harvesting (RWH). Studies have shown that water from these sources is highly microbiologically contaminated (Karim 2010; Islam *et al.* 2011) and not safe for drinking. As a tropical country, plenty of solar irradiation is available throughout the year and thus SODIS may be used in both urban and rural communities in Bangladesh as a low-cost HWT for the inactivation of microbial pollutants to make drinking water safe, which may have a positive health impact on the vast rural and urban communities.

Islam *et al.* (2015) evaluated the effectiveness of SODIS to treat rain-fed ponds and harvested rainwater under household use conditions in the coastal area of Bangladesh and found a significant reduction of microbial indicators; however, the performance did not meet the WHO protective level (WHO 2011). No study was found to evaluate the effectiveness of SODIS as a HWT option under the local climate conditions prevailing in Bangladesh conferring the WHO evaluation protocol. This study was conducted to evaluate the bacterial inactivation potential of SODIS using *Escherichia coli* as an indicator organism under the solar irradiance observed in different seasons in Bangladesh. The experimental setup and test conditions for the SODIS experiments were followed according to the evaluation protocol of HWT options by the WHO (2011). Using the experimental results, a bacterial inactivation model was developed to estimate the safe exposure time required for achieving 4 LRV by SODIS in different seasons in Bangladesh. Re-growth of microorganisms into the SODIS-treated water has been reported in many studies (Amin & Han 2009; Mustafa *et al.* 2013). The re-growth of the microorganisms into the photo-treated water was also evaluated, which determined the safe storage time before drinking. The study findings may be helpful in advancing SODIS as an HWT option among the coastal and low-income urban communities lacking access to safe drinking water supply, which is necessary to achieve SDG 6.1 in Bangladesh and other south-east Asian countries.

MATERIALS AND METHODS

The performance of SODIS was tested with two types of test water and the evaluation protocol of HWT options by the WHO (2011) was followed in preparing the test waters and spiking with *E. coli*, and conducting the SODIS experiments. The experiments were conducted in three seasons (summer, monsoon, and winter) in the Environmental Engineering Laboratory of Islamic University of Technology (IUT). PET bottles and low density polyethylene (LDPE) plastic bags were used in the SODIS experiments as batch reactors because of their high transparency, availability, and moderate photostability. Commercially available PET bottles of 500 mL capacity (water bottle) were collected locally, and plastic bags (500 mL capacity) were purchased from the local scientific market. All labels from the PET bottle and plastic bag were removed to facilitate enough transmission of UV visible sunlight inside the reactors.

E. coli culture and spiking

The *E. coli* (ATCC 25922) used in the experiment was obtained from the International Centre for Diarrheal Disease Research, Bangladesh (icddr,b), which was cultured on mTEC medium by streak plate procedure. A few loops of *E. coli* were mixed in sterilized 0.85% normal saline (pH: 7.8–8.0) of 500 mL in order to obtain the initial concentration that was spiked into the sample water. *E. coli* concentration was maintained at greater than or equal to 10^5 colony forming units (CFU)/100 mL in the sample water. Spiking was done 1 hr before exposing the containers/bags to the sunlight so that bacteria could adjust with the new environment.

Test waters

Test water 1

Groundwater used in the IUT water supply was collected in a 10 L plastic container. The turbidity of the water was <5 NTU and pH was 7.0–9.0 (WHO 2011). The water was then poured into eight PET bottles and eight plastic bags with an air space of about 15% by volume to allow air circulation for aeration (Reed 1997). Each bottle and plastic bag was then spiked with *E. coli* to ensure an initial count of 5×10^5 CFU/100 mL.

Test water 2

The same groundwater (10 L) was mixed with 1% by volume of autoclaved untreated sewage water collected from IUT sewage line and sterilized in an autoclave at 121 °C for 24 hr. Test water 2 requires turbidity of more than 30 NTU, which was incorporated by adding clay passing through a 200 mm sieve. This clay was taken from an undisturbed soil sample collected at a depth of 30 m below the ground surface. This sample was then sieved with a 200 mm sieve to obtain the clay. The turbidity of the water was >30 NTU and pH was 6.0–10.0. This water was then poured into eight PET bottles and eight plastic bags with a 15% air space. Each bottle and bag was then spiked with *E. coli* to obtain a coliform count of 5×10^5 CFU/100 mL. The average physicochemical and microbial characteristics of both test waters are shown in Table 1.

Table 1 | Average physicochemical and microbial characteristics of the test waters

Test water	pH	EC (μS/cm)	Temperature (°C)	DO (mg/L)	Turbidity (NTU)	*E. coli* (CFU/100 mL)
Test water 1	7.34–7.50	750–870	37.75–39.6	6.5–6.62	0.85–1.07	5×10^5
Test water 2	7.3–7.41	780–980	37.0–39.2	6.5–6.7	30–33	5×10^5

Batch reactors

Two types of reactors (transmissive and reflective) were used in the SODIS experiments (Figure 1). For transmissive reactors, no backing foil paper was attached and for reflective reactors, reflected food graded foil paper was attached to the back surface of both PET bottles and plastic bags. In summer, only transmissive PET reactors were used in the SODIS experiments. In monsoon, a combination of both reactors (PET and plastic bag) was used and only reflective reactors were used in the SODIS experiments in winter. The experimental conditions and the reactors used in the SODIS experiments are shown in Table 2.

SODIS experiment

The SODIS experiment was conducted by exposing the reactors (PET and plastic) directly into sunlight by placing them on the corrugated tin sheet roof of the parking shed of IUT, which is inclined by a 60° angle to the south. All reactors were shaken before exposure to sunlight and left undisturbed during exposure, typically from 9.00 a.m. (±30 min) to 5.00 p.m. to maintain a total exposure of 8 hr in a day. During the rainy season, the total exposure of 16 hr was done on 2 consecutive days (8 hr in each day). In each hour during the SODIS experiment, one sample (bottle and bag) from each batch was withdrawn from the roof for subsequent physicochemical and microbial analysis. The last water samples of each batch (which were withdrawn after 8 or 16 hr exposure to sunlight) after physicochemical analysis, were kept in the room environment for 24 hr to check the treatment efficacy and monitor the re-growth of microorganisms into the photo-treated water by measuring *E. coli* after 12 and 24 hr of exposure (Giannakis *et al.* 2015). Solar irradiance and air temperature were measured at an interval of 1 min throughout the exposure period using a Solar Survey 200R Pyranometer (Seward Group, UK) with a data logger. A total of 14 sets of experiments (7 sets each with TW1 and TW2) were conducted under three climate conditions (summer, monsoon, and winter) within an annual cycle.

Figure 1 | Reactors used in the SODIS experiments: transmissive (left), PET bottle and reflective (right), plastic bag backing with food graded foil paper.

Evaluation of physicochemical and microbial parameters

Physicochemical and microbial parameters, turbidity, dissolved oxygen (DO), pH, electrical conductivity (EC), and

Table 2 | Experimental condition and reactors for SODIS experiments

Session	Reactors	Exposure time (hr)	Air temp (°C): Min and Max	Ave. solar radiation (W/m^2)	Test water (TW)
Summer (March–May) Strong irradiance	Transmissive (PET)	8	25 and 38	503	Test water 1 and 2
Monsoon (June–October) Moderate irradiance	Transmissive (PET and bag), reflective (PET and bag)	8 and (8 + 8)	27 and 33	491–535	Test water 1 and 2
Winter (November–February) Weak irradiance	Reflective (PET and bag)	8	20 and 30	356	Test water 1 and 2

E. coli of each of the withdrawal samples were measured at an interval of 1 hr. Turbidity was measured using a HACH 2100Q portable turbidity meter and DO, pH, and EC were measured using a calibrated HACH HQ 40D portable digital multi-parameter meter. For enumeration of *E. coli*, 100 mL water samples were filtered through a 0.22 μm pore-size membrane filter paper (Millipore Corp., Bedford, MA, USA), and the filter papers were then placed on mTEC agar in a glass Petri dish following the membrane filtration method (APHA 1998). The *E. coli* counts were expressed as CFU/100 mL samples. All the physicochemical and *E.coli* analyses were done twice and the average of the two values was reported.

Bacterial inactivation and modeling

The inactivation of bacteria (*E. coli*) was measured by log reduction value (LRV), which was calculated by:

$$\mathrm{LRV} = \mathrm{Log}_{10}\mathrm{C1} - \mathrm{Log}_{10}\mathrm{C2} \tag{1}$$

where C1 and C2 are the bacterial counts (*E. coli*) before and after exposure to sunlight. The Weibull frequency distribution model (Stocker *et al.* 2014; Giannakis *et al.* 2015) was used to model the bacterial response to solar radiation, which adapts the cumulative probability density function to bacterial inactivation. The model can be expressed by the classic log-linear model as follows:

$$\frac{N}{N_0} = 10^{\left(-\left(\frac{t}{\delta}\right)^p\right)} \text{ or } \log_{10} N = \log_{10} N_0 - \left(\frac{t}{\delta}\right)^p \tag{2}$$

where N is the (residual) bacterial population at any given time (CFU/mL), N_0 is the initial bacterial population (CFU/mL), t is the investigated time (s), δ and p are the Weibull model-specific constraints (scale and shape parameters). The scale parameter δ marks the time of first decimal reduction. Shape parameter $p < 1$ describes the concave curve, and $p > 1$ describes convex shapes. The model performance was assessed through two parameters: root mean squared errors (RMSE) and R^2-(adj). RMSE value between 0.2 and 0.5 shows that the model can relatively predict the data accurately and R^2-(adj) more than 0.75 indicates good accuracy of the model.

RESULTS AND DISCUSSION

Physicochemical characteristics

The change in physicochemical parameters of the test waters during the SODIS experiments was found to be insignificant except for water temperature. All water samples (both TW1 and TW2) had pH within the neutral range; a slight increase in DO level was observed in both test waters. The turbidity of TW1 did not change, but a decrease in turbidity of TW2 was observed, possibly due to settling of particles during the experimental period. Water temperature was found to increase during the SODIS experiments. No significant difference between the physicochemical parameters of water in transmissive and reflective reactors during the experiment was observed. All monitored physicochemical parameters of the water were within the guideline values of drinking water, according to ECR (1997) and WHO (2004), except turbidity of TW2.

Solar radiation and temperature

The variation of solar radiation and water temperature during the SODIS experiments under the three climatic conditions is shown in Figure 2. During summer, higher solar radiation under the strong sunlight condition was observed, reaching a maximum within 3 hr of exposure (strong sunlight). In monsoon, a scatter pattern of solar irradiance was observed as the sky remains cloudy for most of the time (moderate sunlight). In winter, relatively lower but almost continuous solar irradiance was observed with a maximum peak after 3 hrs of exposure (weak sunlight). The inactivation of bacteria in the bottles and plastic bags occurred by the combined effect of the upcoming UV radiation and the heat energy provided by the heated corrugated tin roof, and the temperature was also found to reach the maximum level at midday after 3 to 4 hr of exposure.

Bacteriological inactivation

The bacterial inactivation of test waters in the two types of reactors under the three climatic conditions is shown in

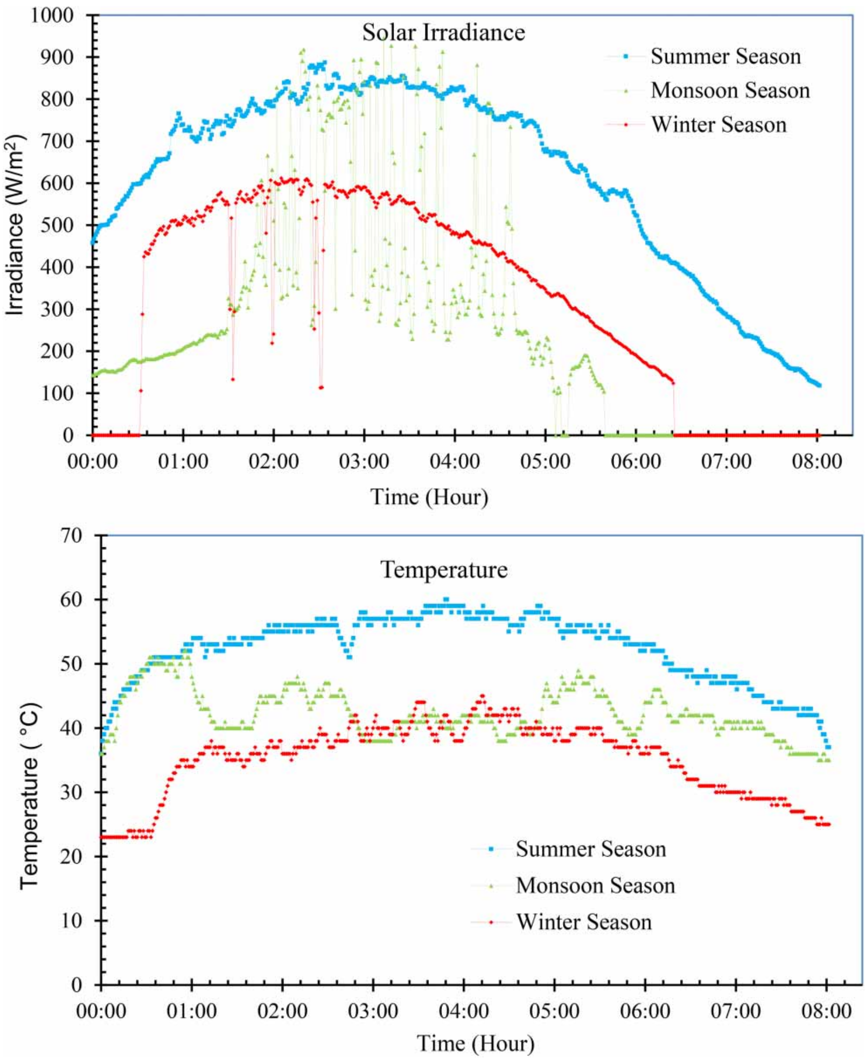

Figure 2 | Variation of solar irradiance and water temperature during SODIS experiments during summer, monsoon, and winter.

Figure 3. The initial *E. coli* count was 5×10^6 CFU/100 mL in both test waters and a sharp decline in microbial level during the first 2 hr of the experiment was observed and more than 99% of *E. coli* was found to be inactive during the first 4 hr of exposure. In summer (strong sunlight condition), complete inactivation of *E. coli* was observed after 6 and 8 hr of exposure for TW1 and TW2, respectively, complying with the drinking water standard of zero *E. coli*/100 mL according to both the WHO guidelines (2004) and ECR (1997). In the other two seasons under weak and moderate sunlight conditions, significant amounts of *E. coli* were found to be present in the treated water and the water did not satisfy the microbial standard of 0 CFU/100 mL, but inactivation of more than 99.5% was observed. A higher bacterial inactivation of TW1 in both reactors was observed, as the water was more transparent, with low turbidity, which allowed complete penetration of sunlight into the water. The turbidity of TW2 was about 30 NTU; this higher turbidity might hinder light penetration into the water, causing less inactivation of *E. coli*. Turbidity less than 30 NTU is recommended for effective solar disinfection using SODIS (Sommer *et al.* 1997). The experimental results indicated that SODIS can be used for complete disinfection of drinking water during the summer period in Bangladesh; however, in other seasons, the process could not provide complete inactivation of

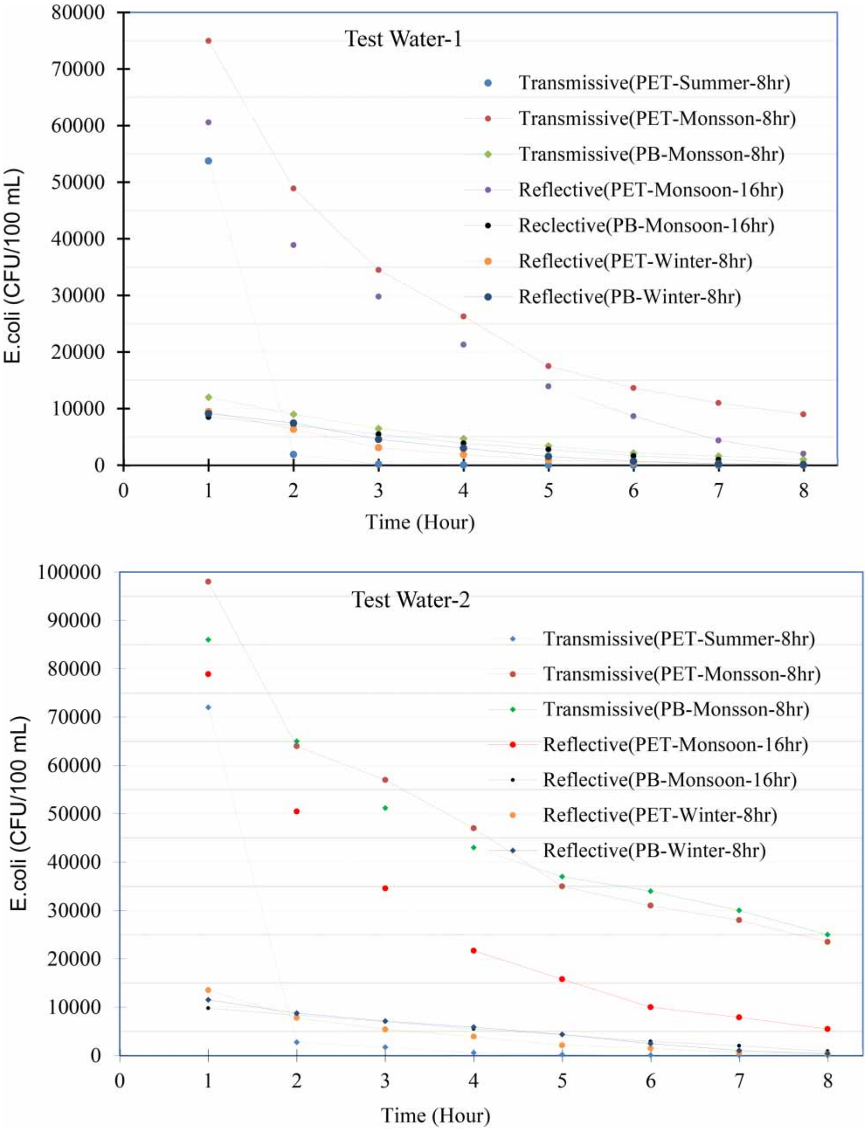

Figure 3 | Inactivation curves of *E. coli* of TW1 and TW2 in transmissive and reflective reactors exposed in summer, monsoon, and winter climate conditions.

microorganisms in water. Islam *et al.* (2015) reported incomplete disinfection of *E. coli* and fecal coliform in the SODIS-treated pond and harvested rainwater by exposing the PET bottles to sunlight outside of the house for 6 hr during the summer in the coastal areas of Bangladesh. The experimental conditions of SODIS conducted by Islam *et al.* (2015) were different from this study, as the SODIS bottles were not placed on the tin roofs, and also due to poor handling of the SODIS bottles during the experiment.

The performance of SODIS for bacterial inactivation in terms of LRV is shown in Table 3. In summer, bacterial inactivation of more than 5 LRV was observed for both test waters using transmissive reactors (PET and plastic bag), indicating a highly protective level performance of SODIS. However, in monsoon, protective performance level with an exposure of 8 hr was observed for both test waters using both transmissive and reflective reactors, and highly protective level performance for TW1 was achieved using reflective reactors (PET and plastic bag) for 16 hr exposure to sunlight on 2 consecutive days. In winter, a highly protective level performance can be obtained using reflective reactors for both test waters. As mentioned by

Table 3 | Performance of SODIS in microbial inactivation in LRV according to WHO guidelines (WHO 2011)

Session	Reactor	Exposure time (hr)	Test water (TW)	Log reduction value (LRV)	Performance level
Summer (March–June)	Transmissive (PET)	8	TW 1	5.40	Highly protective
		8	TW 2	5.14	Highly protective
Monsoon (July–October)	Transmissive (PET)	8	TW 1	2.62	Protective
		8	TW 2	2.32	Protective
	Transmissive (plastic bag)	8	TW 1	3.70	Protective
		8	TW 2	2.30	Protective
	Reflective (PET)	16	TW 1	3.38	Protective
		16	TW 2	2.96	Protective
	Reflective (plastic bag)	16	TW 1	4.22	Highly protective
		16	TW 2	3.75	Protective
Winter (November–February)	Reflective (PET)	8	TW 1	4.62	Highly protective
		8	TW 2	4.20	Highly protective
	Reflective (plastic bag)	8	TW 1	4.72	Highly protective
		8	TW 2	4.10	Highly protective

Test water 1 (LRV) = n:8; mean: 4.0942; standard deviation: 0.9335.
Test water 2 (LRV) = n:8; mean: 3.538; standard deviation: 1.0579.

Amin & Han (2009), the reflective reactor with aluminum foil is more appropriate for SODIS treatment during weak and moderate sunlight conditions due to the fact that short-wavelength visible radiations and UVA rays are reflected back by the aluminum foil, thus amplifying the irradiation. This process causes an increase in the damage of cellular components and consequently enhances the process of bacterial inactivation. During the monsoon and winter in Bangladesh, moderate to weak sunlight prevails and reflective reactors are more effective to achieve a higher protective level performance of SODIS. The overall bacterial inactivation of SODIS in TW1 was found to be higher than TW2 (Table 3) because of lower turbidity, which allows more transmissibility of UV irradiation into the water. Moreover, the bacterial inactivation efficiency of plastic bags was found to be higher than PET bottles in monsoon and winter (Table 3), which supports the earlier findings of Gutiérrez-Alfaro *et al.* (2017).

E. coli was considered as a test organism to conduct the SODIS experiment because *E. coli* is globally considered as an acceptance indicator of fecal pollution of drinking water and it is more resistant to SODIS than other bacteria and microorganisms found in water such as *Enterococcus faecalis, Campylobacter jejuni, Staphylococcus epidermidis, Shigella flexneri, Salmonella typhimurium*, and *Salmonella enteritidis* (Boyle *et al.* 2008). Since a complete inactivation of *E. coli* in the photo-treated water in the summer period was observed, this also ensures the inactivation of these microorganisms and the treated water complies with the microbial standard of 0 CFU/100 mL in drinking water. Complete inactivation of *E. coli* under strong sunlight conditions was also reported in the literature (Boyle *et al.* 2008) and exposure for 2 consecutive days under cloudy conditions was recommended (EAWAG 2016), which agreed with the findings of this study.

Modeling bacterial inactivation

Figure 4 shows the Weibull model fits the SODIS experimental results for both types of reactors under different climatic conditions for TW1. Table 4 presents the data concerning the parameters of the Weibull inactivation model derived from the test data and also provides information for the estimated time required for 4-log reduction (highly protective level performance) for TW1 under different solar radiation prevailing during the experiments. The value of $p < 1$ was found, indicating the concave downward nature of the bacterial inactivation curve. The value of R^2-(adj) varies from 91% to 99%, and RMSE is also low (0.128–0.343); thus, the model fits the SODIS experimental data quite well. The exposure time required for 4-log reduction as calculated by the model was about 3 hr during the summer under strong sunlight conditions, but for other seasons more prolonged exposure to sunlight is

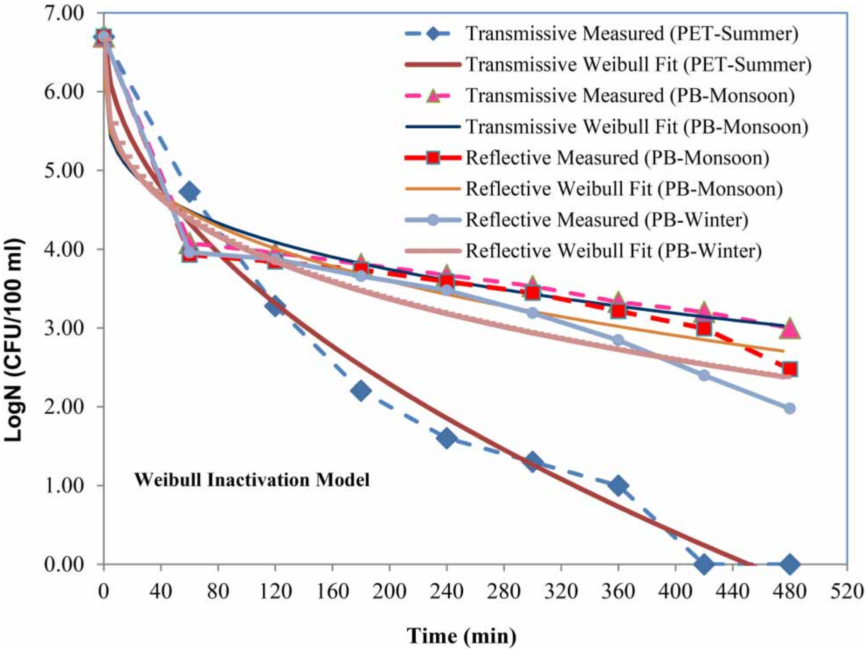

Figure 4 | Weibull inactivation model: model fit of the experimental data.

Table 4 | Weibull model parameters, required exposure time and UV dosage and safe time

							Exposure time and dose for 4-log removal			
Season	**Reactor**	**δ (min)**	**p**	**Log N_0 (CFU/ 100 mL)**	**Root MSE**	**R^2-(adj)**	**Average solar intensity (W/m^2)**	**Exposure time required (hr)**	**Exposure dose (W-hr/m^2)**	**Safe exposure time for 4 LRV (hr)**
Summer (March–June)	Transmissive (PET)	10.41	0.51	6.77	0.29	0.98	503	3	1,509	4.1
Monsoon (June–October)	Transmissive (PET)	17.83	0.28	6.44	0.128	0.98	491	42	20,622	50.9
	Transmissive (PB)	7.09	0.28	6.32	0.242	0.96	491	17	8,347	20.9
	Reflective (PET)	10.24	0.29	6.68	0.185	0.96	535	20	10,700	24.5
	Reflective (PB)	10.47	0.33	6.26	0.343	0.94	535	12	6,420	14.9
Winter (October–March)	Reflective (PET)	17.37	0.41	6.13	0.319	0.96	356	8.5	3,026	10.7
	Reflective (PB)	3.89	0.3	6.66	0.302	0.95	356	7	2,492	8.9

required. In monsoon (moderate irradiance), exposure in sunlight for 2 or 3 successive days would require a 4-log reduction. In summer, for transmissive PET bottles, an average dose of around 1,509 W-hr/m^2 results in 4-log reduction, but in winter, an average dose of approximately 3,026 and 2,492 W-hr/m^2 is required to achieve a 4-log reduction of the microbial population using reflective PET and plastic bag reactors, respectively (Table 4). Although the average solar irradiation during the monsoon is much closer to summer, uneven distribution of sunlight due to a frequent cloudy sky was observed, which results in a much higher solar dose required for the 4-log removal as compared to other seasons (Table 4). The exposure dose or time for 4 LRV as obtained from this study is much higher that other reported studies (Giannakis *et al.* 2015; Castro-Alférez *et al.* 2018), as the solar irradiance observed during the experiments was different from other reported studies.

One of the objectives of this study was to estimate the exposure time required for attaining a highly protective level performance ($\geq$4-log removal) of SODIS under different climatic conditions, and Table 4 shows the calculated exposure time needed for attaining 4 LRV. However, to satisfy the microbial quality of drinking water, sufficient exposure time must be maintained to ensure complete disinfection of microorganisms without re-growth in a subsequent dark incubation for about 48 hr; thus, extra time for the predicted inactivation time by the model is necessary. Castro-Alférez *et al.* (2018) introduced the 'safe exposure time' which defines the exposure time required for achieving the desired level of bacterial inactivation to be maintained during SODIS application for preventing the re-growth of microorganisms in the photo-treated water and this is given by Equation (3). The safe exposure time for 4 LRV for each SODIS experiment is also shown in Table 4.

$$t_{\text{safe exposure}} = t_{\text{model}} + 0.2\, t_{\text{model}} + 30 \quad (3)$$

Re-growth of microorganisms

The re-growth of the microorganisms in the treated water was examined by placing the photo-treated water in a dark room for a subsequent period of 24 hr. Re-growth of microorganisms was found to occur in both test waters, and Table 5 shows the *E. coli* count in the treated water during the post-irradiation period. Although complete disinfection was observed in both test waters after 8 hr of exposure during summer, a significant microbial count was detected after 12 and 24 hr of post-irradiation periods, possibly due to repair of partially damaged cells. Re-growth potential of microorganisms in TW2 was found to be higher since this water comprised untreated sewage water with nutrients required for microbial growth, and the inactivated microorganisms undergo repair and reproduce quickly utilizing the nutrients and ions available in TW2 (Giannakis *et al.* 2015). It is thus essential to maintain sufficient exposure time to control the microbial re-growth in the photo-treated water while storing the water in-house before drinking. More experiments will be necessary to explore the safe storage time of water treated by SODIS before microbial re-growth.

CONCLUSIONS AND RECOMMENDATION

The bacterial inactivation of SODIS was assessed using reflective and transmissive reactors (PET and plastic bag) under the solar irradiance observed in different seasons in Bangladesh. A complete bacterial inactivation (*E .coli*) can be achieved for an exposure of 8 hr during the summer using UV-transmissive PET reactors; however, incomplete inactivation was observed under the moderate to weak solar irradiance in monsoon and winter seasons. The reflective plastic bags were found to be more effective under the moderate and weak sunlight conditions. A safe exposure

Table 5 | Re-growth of microorganisms in the photo-treated water after 12 and 24 hr post-irradiation

			Re-growth of microorganisms (CFU/100 mL)					
			TW 1			**TW 2**		
Season	**Reactors**	**Exposure time (hr)**	**After 12 hr**	**After 24 hr**	**Delta (LRV)[a]**	**After 12 hr**	**After 24 hr**	**Delta (LRV)[a]**
Summer (March–June)	Transmissive PET	8	170	1,200	2.3208	260	1700	1.9095
Monsoon (June–October)	Transmissive PET	8	62,300	91,500	−2.3414	70,200	98,500	−2.6734
	Transmissive PB	8	26,200	53,400	−1.0275	75,000	96,000	−2.6822
	Reflective PET	16	30,000	72,000	−1.4773	48,200	81,000	−1.9484
	Reflective PB	16	6,890	18,539	−0.0480	8,950	25,440	−0.6555
Winter (October–March)	Reflective PET	8	2,000	16,500	0.4025	9,000	21,500	−0.1324
	Reflective PB	8	700	10,650	0.6926	2,500	19,860	−0.1979

[a] Delta (LRV) = LRV (after disinfection) − LRV (after 24 hr of storage).

time was estimated (Table 4) that needs to be maintained during SODIS application in field application to ensure 4 LRV and also to prevent the re-growth of microorganisms during the post-irradiation period. No significant change in physicochemical water quality of the test waters during SODIS experiments was observed and a higher level of turbidity in water was found to decrease the SODIS performance.

The study results showed that the microbial standard of zero *E. coli* in the treated water can only be achieved during the summer under strong sunlight condition. However, a significant re-growth of microorganisms was found in the photo-treated water despite complete inactivation of *E. coli* being observed during the summer. Thus, SODIS can only be used as an HWT option during the summer period by exposing the water in sunlight on a tin roof for about 8 hr using a PET bottle; however, the safe storage time needs to be evaluated which requires more research on microbial re-growth and control to determine the safe storage time before drinking. In other seasons, long exposure for about 16 to 20 hr on 2 consecutive days is required for 4 log10 removal, the application of which may be difficult to maintain in the field. More research and experiments are needed to accelerate the SODIS process in order to reduce the exposure time required for effective disinfection of water during the monsoon and winter seasons.

The turbidity of the urban supply water, PSF water, and harvested rainwater was found to be less than 5 NTU (Karim 2010); thus, the water is very transparent and mostly suitable for SODIS. However, the turbidity of rain-fed pond water used for drinking water in the coastal area in Bangladesh was found to be very high (>30 NTU); this water needs pretreatment like filtration and sedimentation to reduce turbidity before disinfection by SODIS. For rural application, PET bottles are the most suitable reactor for SODIS because they are widely available, low-cost and are considered safe as the leaching of plasticizers, di(2-ethylhexyl) adipate, di(2-ethylhexyl) phthalate and other photochemical elements from PET have been reported well below the limiting value for drinking (Schmid *et al.* 2008; Amin & Han 2009). SODIS application in the urban and rural context in Bangladesh needs more study into its potential for producing safe water from the available unsafe water supply sources currently being used for drinking water.

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DATA AVAILABILITY STATEMENT

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

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