  Journal of Water and Health | 11.1 | 2013

Application of solar disinfection for treatment of contaminated public water supply in a developing country: field observations

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ABSTRACT

A sustainable and low-cost point-of-use household drinking water solar disinfection (SODIS) technology was successfully applied to treat microbiologically contaminated water. Field experiments were conducted to determine the efficiency of SODIS and evaluate the potential benefits and limitations of SODIS under local climatic conditions in Karachi, Pakistan. In order to enhance the efficiency of SODIS, the application of physical interventions were also investigated. Twenty per cent of the total samples met drinking water guidelines under strong sunlight weather conditions, showing that SODIS is effective for complete disinfection under specific conditions. Physical interventions, including black-backed and reflecting rear surfaces in the batch reactors, enhanced SODIS performance. Microbial regrowth was also investigated and found to be more controlled in reactors with reflective and black-backed surfaces. The transfer of plasticizer di(2-ethylhexyl)phthalate (DEHP) released from the bottle material polyethylene terephthalate (PET) under SODIS conditions was also investigated. The maximum DEHP concentration in SODIS-treated water was 0.38 μg/L less than the value of 0.71 μg/L reported in a previous study and well below the WHO drinking-quality guideline value. Thus SODIS-treated water can successfully be used by the people living in squatter settlements of mega-cities, such as Karachi, with some limitations.

Key words | developing country, efficiency, plasticizer, solar disinfection

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INTRODUCTION

One of the key United Nations Millennium Development Goals is to halve the proportion of people without sustainable access to safe drinking water and basic sanitation by 2015. According to estimates by the World Health Organization (WHO) (WHO 2004), more than one-third of the population in developing countries do not have access to safe drinking water. Statistics show that each year 1.8 million people die of diarrhea; 90% of them are children under the age of five, primarily in developing countries. Currently, practitioners and researchers are searching for ways to develop sustainable solutions to reduce the mortality due to water-related diseases.

The United Nations Statistics Division reports that approximately 16 million people in Pakistan lack access to improved water. Annual mortality among children below five years of age is 9%. Most of the people in Karachi consume microbiologically contaminated water, and this situation leads to high risk for waterborne diseases. The present scenario demands development of point-of-use (POU) water treatment alternatives that are low-cost, sustainable, low-maintenance and green. There are a number of POU water treatment technologies which encompass heat and UV-based systems, chemical treatment methods and physical removal processes (Peter-Varbanets *et al.* 2009). Most people in Karachi and other cities of Pakistan either boil water or use commercially available water purification units.

SODIS or solar disinfection is an effective water treatment process mostly used to remove pathogens from the

doi: 10.2166/wh.2012.119

water which can be used for drinking and other purposes. In this method, microbiologically contaminated water is filled in polyethylene terephthalate (PET) transparent plastic bottles and exposed to sunlight for a specific period of time. This uncomplicated method disinfects the water by inactivating the waterborne pathogens (Berney *et al.* 2006a). SODIS has a high potential for application as a POU water treatment technology. This method is now used by more than 2 million people in 31 countries for the treatment of their drinking water (Schmid *et al.* 2008).

More than 40% of Karachi's population live in squatter settlements. These areas have limited and contaminated water supplies. Luby *et al.* (2000) conducted a study in a squatter settlement of Karachi and found that 85% of the drinking water samples were contaminated with coliform bacteria. Therefore, these people need application of POU technology to obtain safe drinking water and SODIS has the potential to be used by residents of squatter settlements. Most previous studies on SODIS were conducted in various parts of the developed world. Among the developing countries, field trials have been carried out in Haiti, India and Nepal, but there is no reported detailed research conducted in Pakistan.

There are also concerns about health risks associated with the use of PET bottles, because of the possibility of migration of toxic chemicals from them into the drinking water. During the SODIS process, water in PET bottles is exposed to heat and light. This exposure may result in the formation of photoproducts and also migration of PET compounds from bottles into the water. Schmid *et al.* (2008) conducted a study to quantify migration of plasticizers and to identify and characterize additional organic compounds released from PET during the SODIS process. They studied the migration of organic components from PET bottles used for SODIS in Honduras, Nepal and Switzerland. However, no such studies have been carried out for bottles manufactured in Pakistan. Hence, it is important to check the leaching of plasticizers in SODIS-treated water under local conditions.

In the present study, the authors discuss the performance and effectiveness of SODIS under local climatic conditions of a mega-city located in the developing world. In the setting of a developing country, contaminated public water supply samples containing naturally occurring organisms have been used instead of laboratory grown microorganisms. Moreover, the impact of physical interventions on the efficiency of SODIS along with microbial regrowth and concentration of plasticizer in SODIS-treated water has been assessed.

MATERIALS AND METHODS

Experimental setup

The experiments were carried out at the NED University of Engineering and Technology between October 2010 and September 2011. Water supplied by the local water agency, Karachi Water and Sewerage Board, to different localities of the city was collected in PET bottles. Previous studies (Meera & Ahammed 2008) indicate that laboratory grown organisms, when compared with naturally occurring organisms, inactivate at faster rates. Therefore, for this study, water already contaminated (naturally) with microorganisms was used. Water samples were taken using sterile 1.5-L PET bottles and transported in darkness to the NED University for solar experimentation and microbiological analysis of samples. Water collected in PET bottles was exposed to direct sunlight on the rooftop of the departmental building. Time of exposure was 8 h from 09:00 to 17:00 h. A set of 24 experiments was performed to evaluate the effect of sunlight on the microbial inactivation with different weather conditions throughout the annual cycle.

Batch reactors

Commercially available PET containers were used as batch reactors for all experiments. They were selected with the following factors in mind:

1. Size: 1.5 L was selected as appropriate for family as well as individual use. Two bottles (12 glasses) for each family member can supply the daily drinking water and other supplementary needs.
2. Availability: Easily and abundantly available in all parts of the country.
3. Backing surfaces: In order to evaluate the impact of physical interventions on the efficiency of microbial inactivation under local weather conditions (strong,

moderate and weak sunlight with or without clouds), two types of backing surfaces were designed for the reactors: absorptive and reflective (Figure 1). For absorptive surfaces, the back of the reactor was painted black while for reflective back surface provision a double layer of food-grade aluminum foil was attached to the back surface. PET bottles with no backing surface (without paint or aluminum foil) acted as transmissive reactors (Figure 1).

Sample analysis

Microbiological examination

Microbiological examination (total coliforms (TC) and fecal coliforms (FC)) of water samples in duplicate collected from different sources was performed according to the guidelines published in the *Standard Methods for the Examination of Water and Wastewater* (APHA 1995). Control bottles were stored in the dark. Aliquots were removed at regular intervals for bacterial analysis by the multiple tube fermentation technique (MPN method). Lactose broth (Merck) was the medium of choice for the presumptive phase for the determination of total coliforms for 15 tubes at different dilutions (10, 1.0 and 0.1 mL). Tubes were incubated at 35 ± 0.2 °C for 24 ± 2 h. Tubes were examined after 24 h and re-incubated for maximum 48 ± 2 h when no gas had formed in 24 h. Tubes showing turbidity and production of gas were considered positive for total coliforms and transferred into brilliant green lactose bile (BGLB) broth for the confirmation phase. These tubes were incubated at 35 ± 0.5 °C for 48 ± 2 h to allow the organisms maximum time for growth. Gas production in BGLB broth indicated a positive confirmed phase.

Figure 1 | Polyethylene terephthalate (PET) bottles with (1) reflective, (2) transmissive and (3) absorptive backing surfaces.

Positives tubes with growth and gas bubbles (lactose broth) were transferred to EC broth (Merck) for a fecal coliforms test using the same MPN method. The growth from each positive lactose broth tube (presumptive phase) was transferred to the EC broth tube (completed test) using a sterile metal loop of 3 mm diameter. These tubes were incubated at 44.5 ± 0.2 °C for 24 h. Fecal coliforms have the ability to grow at the elevated temperature, i.e. 44.5 °C. This temperature is used for the completed phase which allows growth of fecal coliforms only. Gas production within 24 h was considered as a positive reaction for fecal coliforms.

Heterotrophic and total plate count was determined by the streak plate method using nutrient agar (Merck) as a selective medium. A water sample of 1 mL from each batch reactor (absorptive, reflective and transmissive surface) was serially diluted and then samples from appropriate dilutions were streaked on nutrient agar plates. The plates were incubated at 37 ± 0.5 °C for 48 h. After the incubation period, growth was recorded and colony forming units (CFU)/mL were calculated for each sample.

For water that had been treated (exposure to sunlight for 8 h), microbial regrowth was determined to check the efficacy of the treatment and to test how long the microbes in water remain inactivated. Sample bottles were kept at room temperature for 1 week and then regrowth was checked.

Physicochemical examination

Physical and chemical parameters, such as temperature, electrical conductivity (EC), dissolved oxygen (DO), turbidity and pH, were analyzed by *Standard Methods* (APHA 1995). Water temperatures and weather conditions were recorded hourly, and pH and temperature were measured periodically using a pH meter (Mi151, Martini) and a digital thermometer with type K thermocouple (DT012, Summit), respectively. DO was measured using a DO meter

(DO1175 P/N: 50175-00, HACH) with a DO probe (50180, UK) while EC was measured using a conductivity meter (HACH 51800-10 with electrode P/N 51975-00). Turbidity of water samples was measured by a turbidity meter (HACH 16800).

Solar radiation

Sunlight radiation was monitored on-site at regular intervals of 60 min with a SP-110 Pyranometer (Apogee Instruments Inc., Logan, USA). The initial water temperature was $28.07 \pm 1.0\,^{\circ}C$ across all experiments. The solar radiation data and maximum water temperatures provided relative data for diverse weather situations.

Plasticizer analysis

In the first step, pure (distilled) water was used to fill four PET bottles, and the bottles were stored under two different conditions: (a) usual SODIS conditions; and (b) SODIS conditions with additional heating.

Colorless PET beverage bottles appropriate for SODIS of raw water were pre-rinsed and filled with pure water (water for chromatography, Merck, Germany). Exposure to sunlight was conducted on 2 consecutive sunny, cloudless days (12 and 13 October 2011) at the NED campus, Karachi, Pakistan (lat. 24°56′03″N). Two bottles (used + reused, where used indicates a bottle that was used a second time and reused indicates a bottle that has been used more than twice) for SODIS treatment were exposed in horizontal position at a maximum ambient temperature of 34 °C while two bottles (used + reused) were put half-way in a water bath kept at 60 °C.

The samples were analyzed by gas chromatography (Perkin Elmer Clarus 500 GC Autosystem, Norwalk, USA). Samples were prepared and analyzed following the procedure discussed by Bosnir *et al.* (2007).

RESULTS AND DISCUSSION

Sample characteristics

Table 1 shows typical data for the physicochemical and microbial characteristics of water samples used during various experiments. All water samples had pH values close to the neutral range and low turbidity values (<3.5 NTU). All monitored physicochemical parameters were within the prescribed WHO guideline values for drinking water. However, the microbiological parameters did not meet the WHO drinking water guideline values. The difference between the initial values of physicochemical parameters was not very significant for the purpose of the current study as experiments are conducted for determining the efficiency of disinfection in terms of microbial percentage removal and not of other physical and chemical parameters.

Diverse weather conditions

Table 2 shows the temperature and solar radiation values corresponding to diverse weather conditions. To compare the effectiveness of SODIS under different weather conditions (weak, moderate and strong), experiments performed between October 2010 and November 2011 were grouped into three categories. Experiments in which solar radiation values were in the range 200–480 W/m^2

Table 1 | Average physicochemical and microbial properties of untreated water

Physicochemical parameters				
Temperature (°C)	**pH**	**Turbidity (NTU)**	**DO (mg/L)**	**EC (µS/cm)**
23.7	7.8	2.9	3.9	876.2
Microbial parameters				
Total coliforms (CFU/100 mL)	**Fecal coliforms (CFU/100 mL)**	**Heterotrophic plate counts (CFU/100 mL)**		
827	82.3	250		

DO, dissolved oxygen; EC, electrical conductivity.

Table 2 | Diverse weather conditions and number of experiments performed

Weather condition	Weak sunlight	Moderate sunlight	Strong sunlight
Months	Jun, Jul, Aug	Jan, Feb, Sep, Nov, Dec	Mar, Apr, May, Oct
Number of experiments	6	10	8

were categorized as weak weather experimental conditions while those in which solar radiation values were in the range 480–700 and 700–1,000 W/m^2 were categorized as moderate and strong weather experimental conditions, respectively. Sunlight intensity in strong weather conditions is almost 2.4 times the intensity of weak weather conditions, while the intensity during moderate weather is 1.8 times the intensity in weak weather conditions. The patterns of sunlight intensity variation for the entire experimental period are represented in Figure 2, which shows the average values of irradiance for different weather conditions. The figure clearly depicts three distinctive phases of solar radiation: increasing, constant and decreasing phases. Sunlight intensity in strong weather conditions is almost 1.3 times the intensity of moderate weather conditions. The first 2–4 h are critical for the SODIS process, because microbial contaminants are deactivated by the synergistic effect of both temperature and heat, which in turn is linked to sunlight intensity.

Table 2 shows the months of year and their classification with respect to diverse weather conditions along with number of experiments performed. The months of June, July and August had low sunlight intensity, as these months remain cloudy for most of the time during the monsoon season. It also shows that moderate weather conditions having solar radiation in the range 480–700 W/m^2 exist for nearly half the year.

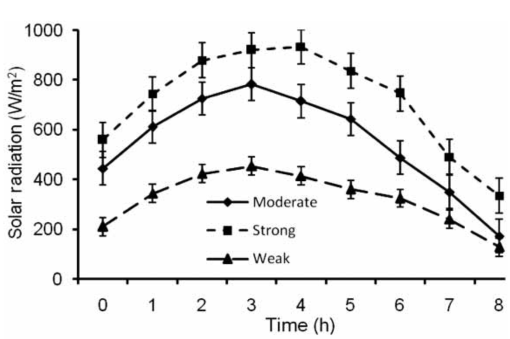

Figure 2 | Solar radiation variation under different weather conditions during the experimental period. Error bars show standard error of the mean.

SODIS efficiency during diverse weather conditions

The variation in temperature of water in the three types of reactors (absorptive, transmissive and reflective) and solar radiation under strong sunlight conditions is shown in Figure 3(a). The solar radiation at the start of the experiment was 650 W/m^2 while after the first hour had elapsed, it increased to 890 W/m^2, and reached its maximum during the second hour (995 W/m^2). Temperature in the batch reactors also increased concurrently. The initial water temperature in the batch reactors was 28.5 °C. The temperature in the absorptive reactor reached its maximum

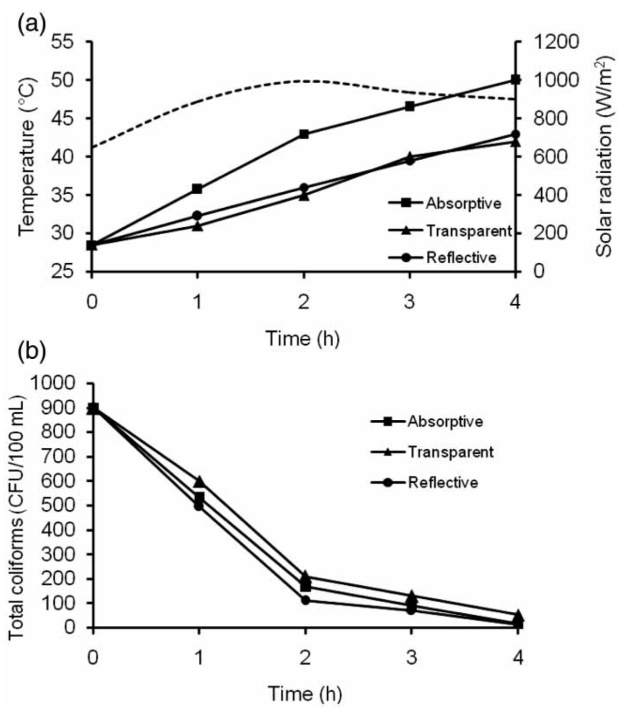

Figure 3 | (a) Changes in temperature and solar radiation for reactors under strong sunlight condition, and (b) microbial inactivation in reactors under strong sunlight condition.

at 4 h. During the exposure period, the highest water temperature of >50 °C was attained in the absorptive reactor followed by 43 and 41 °C in the reflective and transparent reactors, respectively. Figure 3(b) shows microbial inactivation in the three types of reactors. More than 90% of the total coliforms were inactivated during the first 4 h of exposure. The reactor with reflective backing had lower numbers of total coliforms and was marginally more effective than the transmissive reactor. The absorptive reactor also displayed a similar pattern, but microbial inactivation was more rapid in the fourth hour and complete inactivation was observed in the fifth hour, which was accompanied by a sharp rise in the temperature of treated water, which reached 50 °C. It is observed that the absorptive reactor provides the most effective surface for SODIS treatment under strong sunlight conditions. This is in accordance with results by Mani et al. (2006). The improved performance of the absorptive reactor is probably because of the absorption of solar radiation by the black-painted surface of the reactor, which in turn increased the temperature to its maximum resulting in early and complete inactivation of total coliforms by the synergistic effects of heat and light.

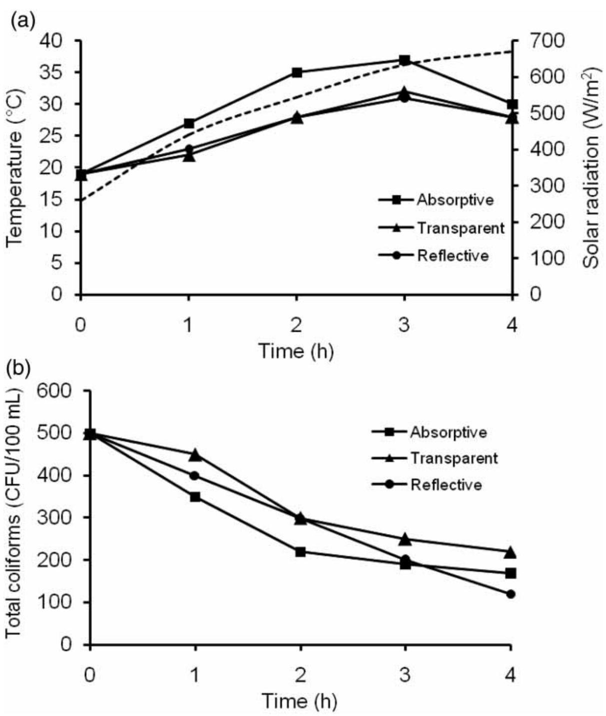

Figure 4 | (a) Changes in temperature and solar radiation for reactors under moderate sunlight condition, and (b) microbial inactivation in reactors under moderate sunlight condition.

Figure 4(a) shows variation in temperature of water in the three types of reactors and solar radiation under moderate sunlight conditions. The solar radiation at the start of the experiment was 260 W/m^2, while after the first hour had elapsed it increased to 440 W/m^2 and reached its maximum during the fourth hour (670 W/m^2). Temperature in the batch reactors also increased concurrently. The initial water temperature in the batch reactors was 19 °C, while the maximum water temperature attained was 32 °C in the reflective and transmissive reactors, and 37 °C in the absorptive reactor. During the first 4 h of exposure, more than 70, 60 and 50% of the total coliforms were inactivated in the reflective, absorptive and transmissive reactors, respectively. Under moderate sunlight conditions, microbial inactivation was enhanced by the reflective backing. It follows that the reflective reactor showed maximum removal (Figure 4(b)). This is likely due to the return of UVA and short wavelength visible radiations into the reactor after reflecting from the aluminum foil. This mechanism results in increased destruction of cellular constituents and, hence, increased microbial inactivation in the reflective reactor as compared to absorptive and transmissive reactors. This finding is in agreement with the work of Mani et al. (2006) and Amin & Han (2009), who carried out experiments in Kerala, India and in Seoul, South Korea, respectively. None of the reactors showed complete inactivation of microbial contamination under moderate sunlight conditions.

Figure 5(a) shows variation in temperature of water in the three types of reactor and solar radiation under weak sunlight conditions. The solar radiation at the start of the experiment was 70 W/m^2, while after the first hour had elapsed, it increased to 110 W/m^2 and reached its maximum during the third hour (220 W/m^2). The temperature in the batch reactors also increased concurrently. The initial water temperature in the batch reactors was 23 °C, while the maximum water temperature attained was 28 °C in absorptive, 27 °C in reflective and 26 °C in the transmissive reactor. It is clear from Figure 5(b) that under weak sunlight conditions microbial inactivation is almost negligible during the initial exposure time. However, microbial inactivation increased during the third and fourth hours, which are peak hours of solar radiation in all types of weather conditions.

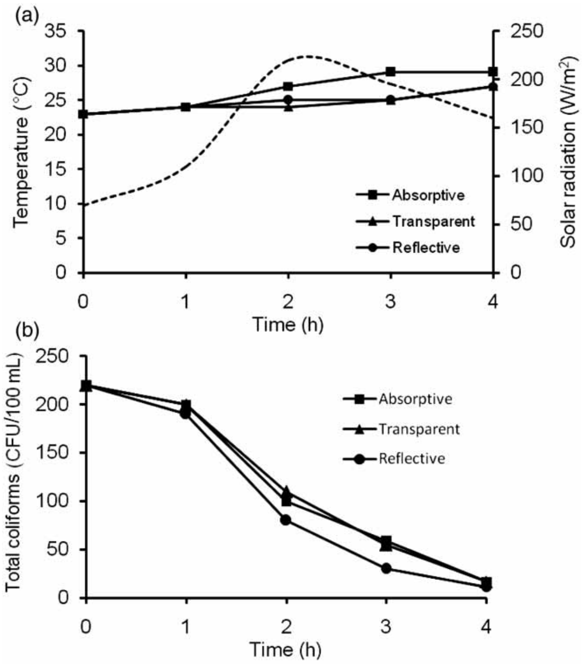

Figure 5 | (a) Changes in temperature and solar radiation for reactors under weak sunlight condition, and (b) microbial inactivation in reactors under weak sunlight condition.

The heterotrophic plate count (HPC) test was performed for all water samples by using nutrient agar as a growth medium. The CFU/mL were calculated for these samples taken at different time interval during the SODIS treatment. Bactericidal effects of solar radiation were determined for three different surfaces (reflective, absorptive and transmissive) (Figures 6–8).

Under moderate and strong sunlight conditions, microbial inactivation was significant within the first 1.5 h (Figure 7 and 8). An exponential decrease in HPC was noted during later hours. This decrease in microbial count

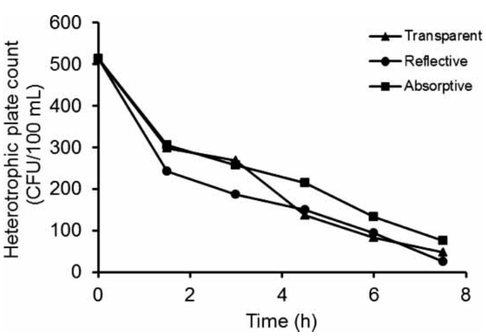

Figure 6 | Microbial inactivation (heterotrophic plate count) under weak sunlight condition.

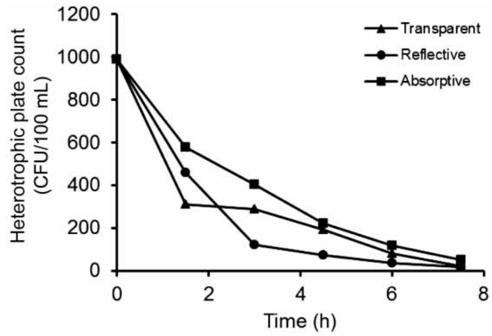

Figure 7 | Microbial inactivation (heterotrophic plate count) under moderate sunlight condition.

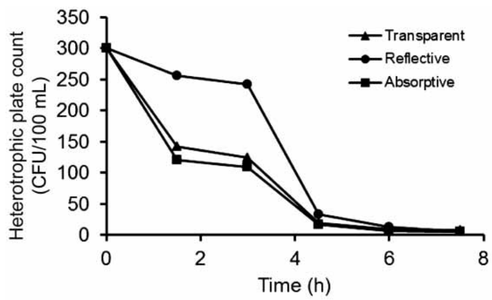

Figure 8 | Microbial inactivation (heterotrophic plate count) under strong sunlight condition.

occurred during the hours when the sunlight was highest on that day. In both conditions, inactivation starts after the treatment and there was no lag period of microbial growth. Moreover, the reflective surface was found to be most appropriate for SODIS treatment during weak and moderate sunlight conditions. This may be due to the fact that short wavelength visible radiations and UVA rays are reflected back due to the aluminum foil. This process causes an increase in the damage of cellular components and consequently enhances the process of microbial inactivation. These results are in accordance with findings by Amin & Han (2009).

Figure 8 indicates the inactivation of bacteria during strong sunlight conditions. There is no pronounced change in bacterial count during the first 3 h in case of the reflective surface, while the absorptive and transparent back surfaces showed the results similar to weak and moderate sunlight conditions in which there was a sharp decrease in bacterial growth during early hours of treatment. There was no lag period of growth and the best results were achieved with absorptive surfaces. Strong sunlight conditions cause temperature enhancement in the black back absorptive type PET bottles. Thus, the inactivation of microorganisms is due to synergistic interactions of thermal and optical effects. This finding is in agreement with Amin & Han (2009) and Mani *et al.* (2006).

Results of experiments conducted throughout the annual cycle indicate that SODIS is effective in achieving complete disinfection only under strong sunlight conditions. However, substantial improvement in water quality was achieved during moderate conditions. Thus, SODIS can be used by residents of squatter settlements of Karachi as a POU technology effectively for complete disinfection of contaminated water only under strong sunlight conditions. In the case of strong sunlight conditions for both TC and FC parameters, SODIS led to the achievement of potable water guideline values, i.e. 0 CFU/100 mL for both TC and FC.

Microbial inactivation kinetics

Microbial population inactivation kinetics was determined using the following mathematical equation (Jacobs 1960):

$$\frac{dN_t}{dt} = -kN_t \tag{1}$$

where $dN_t/dt =$ rate of change in concentration of organisms with time, $k =$ inactivation rate constant, T^{-1}; $N_t =$ number of organisms at time t; $t =$ time.

By integrating Equation (1),

$$\ln \frac{N_t}{N_0} = -kt \tag{2}$$

where N_0 and N_t represent the numbers of cells (CFU/mL) at zero time and at time t, respectively.

$$k = \frac{1}{t} \ln \frac{N_t}{N_0} \tag{3}$$

Table 3 represents the k values for microbial parameters including TC, FC and HPC for all three weather conditions and for the three types of surface. Values of k were calculated using Equation (3). The microbial inactivation was in accordance with the first order kinetics. Best results were achieved with reflective PET bottles at weak and moderate

Table 3 | Microbial decay rate constants (h^{-1}) for various reactors under diverse weather conditions

	Weak sunlight			Moderate sunlight			Strong sunlight		
Parameters	**Ref**	**Abs**	**Tra**	**Ref**	**Abs**	**Tra**	**Ref**	**Abs**	**Tra**
Total coliforms	1.2 ± 0.22	0.78 ± 0.04	0.63 ± 0.03	0.81 ± 0.14	0.68 ± 0.03	0.62 ± 0.07	0.73 ± 0.17	0.92 ± 0.20	0.70 ± 0.07
Fecal coliforms	0.70 ± 0.1	0.61 ± 0.02	0.57 ± 0.09	0.50 ± 0.03	0.46 ± 0.03	0.43 ± 0.06	0.29 ± 0.05	0.45 ± 0.02	0.23 ± 0.14
Heterotrophic plate count	1.07 ± 0.3	0.95 ± 0.21	0.72 ± 0.07	0.48 ± 0.01	0.40 ± 0.02	0.33 ± 0.06	0.51 ± 0.05	0.55 ± 0.12	0.53 ± 0.03

Ref, reflective; Abs, absorptive; Tra, transmissive, $n = 3$–4.

sunlight conditions, while for strong sunlight conditions, the absorptive reactors were found to be the best for SODIS treatment (Table 1). These results were in agreement with findings by Amin & Han (2009), while the results of strong sunlight are in accordance with the findings by Sommer et al. (1997). Strong sunlight causes an increase in the temperature due to the absorbance by the black surface and this indicates that at high temperature, thermal and optical effects of sunlight showed synergistic interactions.

In this study, the k value or decay constant was higher than those reported previously (Wegelin et al. 1994; Amin & Han 2009). Inactivation rate constants were in the range of 0.2–1.2 h^{-1} for different backing surfaces of PET bottles. This may be due to different experimental conditions such as turbidity, salinity, water temperature, pH and solar radiation during different weather conditions and sources of water sample (pond or river water, rain water, raw water and wastewater), as all these factors have an effect on the k value. Growth conditions and the physiological state of bacteria also have an impact on growth rate and inactivation rate due to the use of any disinfectant. For the current study, the higher k values may be due to this fact, which results in the quick inactivation of bacteria as fast-growing bacteria are more sensitive to stresses than slow-growing bacteria. Bacteria in the exponential phase of their growth show high sensitivity to mild heat and sunlight as compared to stationary or lag phase cultures (Berney et al. 2006b).

Microbial regrowth

During this study, microbial regrowth or reactivation of microorganisms was also monitored. SODIS-treated water samples in batch reactors were stored for 1 week at room temperature under dark conditions. Regrowth of microorganisms was found to occur in 51% of samples. Some bacteria revived after many hours of storage and showed a reversal of the effects of SODIS. These bacteria have self-defense mechanisms or some resistance to the stresses, which are usually produced by UV attack, such as oxidative stress. Damage-tolerance mechanisms (Kim & Sundin 2001) and cellular repair mechanisms of bacteria, such as photo-reactivation (Rincon & Pulgarin 2003) also help them to recover and grow again. This mechanism is capable of repairing partially damaged cells and thus helps in the recovery of these organisms; it results in the reactivation of sub-lethally injured bacteria following illumination and allows them to regrow (Kim & Sundin 2001; Amin & Han 2009).

Absorptive reactors had long-lasting inhibitory effects on bacteria as regrowth occurred in only 42% of the samples, while the transparent surface was found to be least inhibitory as regrowth was found to occur in 58% of the samples. Reflective reactors showed moderate results as growth appeared in 53% of the samples after several hours of SODIS-treatment. Enhanced suppression of regrowth in absorptive reactors is likely to be due to the synergistic effects of temperature and UV rays, which permanently kills bacteria and prevents repair mechanisms from working. Returns of UV rays through the reflective reactors increase the damage of cellular components and permit few bacteria to regrow. Transmissive reactors showed a reduced rate of complete inactivation, because of the repair mechanisms of bacterial cells, which operates fully during the treatment as most of the UV rays are transmitted through the water and thus unable to kill the bacteria. Overall regrowth patterns were as follows: transmissive reactors > reflective reactors > absorptive reactors.

Plasticizer concentration

Table 4 shows concentrations of di(2-ethylhexyl)phthalate (DEHP) in SODIS-treated water under different exposure conditions. Concentrations of DEHP in water from bottles (used and reused) exposed to sunlight and heated to 60 °C are higher than the level in the sample from reused bottles exposed to sunlight at ambient temperature. Table 4 compares the results of the present study with the study of Schmid et al. (2008). Under usual SODIS experimental conditions, DEHP was not detected in the samples from used bottles exposed to sunlight at ambient temperature. However, DEHP concentration in the water of reused bottles manufactured locally was 0.10 μg/L, which is lower than the concentration in water samples of bottles from Nepal (0.18 μg/L) and Switzerland (0.30 μg/L). Under special SODIS experimental conditions (sun + 60 °C), the plasticizer concentration in water obtained from the used bottles was 0.16 μg/L, equal to the concentration

Table 4 | Concentration of di(2-ethylhexyl)phthalate in PET bottles used in the exposure experiment and comparison with previous study (Schmid *et al.* 2008)

				DEHP (μg/L)		
Bottle No.	**Size (L)**	**Status**	**Exposure**	**Pakistan (this study)**	**Nepal**	**Switzerland**
1	1.5	Used	Sun + 60 °C	0.16	0.71	0.16
2	1.5	Reused	Sun + 60 °C	0.38	0.44	0.15
3	1.5	Used	Sun	ND	0.38	0.10
4	1.5	Reused	Sun	0.10	0.18	0.30

ND, not detected.

found in bottles from Switzerland and lower than that in bottles from Nepal. However, DEHP concentration in the water of reused bottles manufactured locally was 0.38 μg/L higher than the concentration in water samples of bottles from Switzerland, which was 0.15 μg/L and lower than samples associated with bottles from Nepal (0.44 μg/L). Bosnir *et al.* (2007) studied migration of phthalates from plastic containers into soft drinks and mineral water and found higher DEHP concentrations of up to 50 μg/L in the mineral water. The WHO guideline value for DEHP in drinking water is 8 μg/L. The levels of DEHP detected in water samples of this and other previous studies are below the WHO guideline value for drinking water.

A toxicological risk assessment carried out for maximum DEHP concentrations by Schmid *et al.* (2008) revealed a minimum safety factor of 8.5 and a negligible carcinogenic risk of 2.8×10^{-7} demonstrating that the SODIS procedure is safe with respect to human exposure to DEHP. The maximum value for which the risk assessment was carried out was 0.71 μg/L and the maximum value revealed in this study is 0.38 μg/L indicating a further reduced risk when compared with the previous study.

CONCLUSIONS

The inactivation of pathogens in contaminated public water supply by application of SODIS was investigated. Physical intervention improved the SODIS performance and 100% pathogen removal was achieved in batch reactors. Absorptive reactors showed the best performance under strong sunlight conditions while reflective reactors showed the best performance under moderate sunlight conditions. The results of SODIS experiments conducted under local conditions are very encouraging. This simple, green and low-cost technology can be adopted by residents of squatter settlements to obtain safe drinking water. Thus, SODIS can be confidently applied to obtain drinking water which meets WHO drinking water guideline values under specific conditions. However, during weak and moderate sunlight conditions, there are some limitations. Microbial regrowth was found to occur not in all but a few samples. Absorptive reactors were most effective in inhibiting regrowth of microorganisms as compared to reflective and transmissive reactors. It can also be concluded that the SODIS procedure under local conditions is safe with respect to human exposure to DEHP.

Future research should focus on investigation of the impacts of physical and chemical interventions on enhancing the SODIS performance and also on the use of increased batch reactor volumes. Moreover, new avenues for accelerating the inactivation of not only bacteria but also viruses by SODIS need to be investigated. To acquaint the local people with this technology, a brochure in the native language illustrating SODIS is under preparation.

ACKNOWLEDGEMENTS

The authors are grateful to NED University of Engineering and Technology for funding the project 'Application of Solar Disinfection for Treatment of Contaminated Water'.

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First received 18 July 2012; accepted in revised form 24 October 2012. Available online 27 December 2012