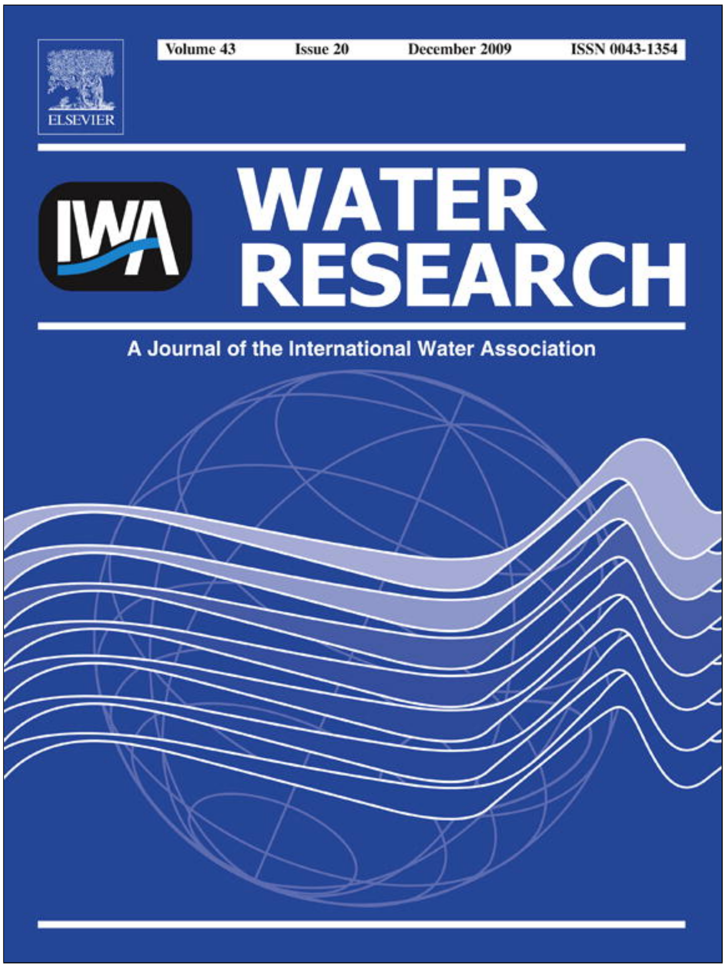
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Roof-harvested rainwater for potable purposes: Application of solar collector disinfection (SOCO-DIS)

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ABSTRACT

The efficiency of solar disinfection (SODIS), recommended by the World Health Organization, has been determined for rainwater disinfection, and potential benefits and limitations discussed. The limitations of SODIS have now been overcome by the use of solar collector disinfection (SOCO-DIS), for potential use of rainwater as a small-scale potable water supply, especially in developing countries. Rainwater samples collected from the underground storage tanks of a rooftop rainwater harvesting (RWH) system were exposed to different conditions of sunlight radiation in 2-L polyethylene terephthalate bottles in a solar collector with rectangular base and reflective open wings. Total and fecal coliforms were used, together with *Escherichia coli* and heterotrophic plate counts, as basic microbial and indicator organisms of water quality for disinfection efficiency evaluation. In the SOCO-DIS system, disinfection improved by 20–30% compared with the SODIS system, and rainwater was fully disinfected even under moderate weather conditions, due to the effects of concentrated sunlight radiation and the synergistic effects of thermal and optical inactivation. The SOCO-DIS system was optimized based on the collector configuration and the reflective base: an inclined position led to an increased disinfection efficiency of 10–15%. Microbial inactivation increased by 10–20% simply by reducing the initial pH value of the rainwater to 5. High turbidities also affected the SOCO-DIS system; the disinfection efficiency decreased by 10–15%, which indicated that rainwater needed to be filtered before treatment. The problem of microbial regrowth was significantly reduced in the SOCO-DIS system compared with the SODIS system because of residual sunlight effects. Only total coliform regrowth was detected at higher turbidities. The SOCO-DIS system was ineffective only under poor weather conditions, when longer exposure times or other practical means of reducing the pH were required for the treatment of stored rainwater for potable purposes.

1. Introduction

At least one-third of the population in developing countries has no access to safe drinking water, which results in major health problems due to waterborne diseases (WHO, 2002). Every day about 6000 children die of dehydration due to diarrhea (Ashbalt, 2004). The two major water problems, namely inadequate supplies and insufficient treatment, particularly in

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developing nations, mean we must search for alternative approaches, including the use of decentralized water supply systems and low-cost, low-energy water treatment technologies, keeping in mind the technical and financial limitations of the poor who live in rural or semi-urban areas.

Rooftop rainwater harvesting (RWH) is seen as an alternative source of drinking water, especially in developing countries (Meera and Ahammed, 2006). A simple rooftop RWH system consists of its catchment area, a treatment facility, a storage tank, a supply facility and piping (Han and Mun, 2008). Potential applications of RWH do exist for roof catchments in areas where a centralized water supply and distribution system are not adequate, and such applications are increasing (Han, 2007). To date, RWH has been used mostly for water for nonpotable purposes, mainly because harvested water is microbiologically contaminated by a variety of indicator and pathogenic organisms, unless special care is taken during collection and storage of the rainwater (Meera and Ahammed, 2006). This requires the minimum treatment of stored rainwater in case it has to be used for potable purposes. There are simple home water purification devices available for the treatment of roof-harvested rainwater, which is generally contaminated by microorganisms and heavy metals (Ahammed and Meera, 2006).

The adaptation of point-of-use drinking water treatment technologies, such as solar disinfection (SODIS), can reduce morbidity and mortality from diarrhea in children living in rural areas and in developing countries (Sobsey, 2002; Hobbins and Mäusezah, 2003). SODIS is very well suited for use in rural and semi-urban communities of developing countries, which do not have access to safe drinking water supplies, in treating the stored rainwater on a small scale and hence for providing daily consumption needs. Solar-based drinking water treatment processes have been investigated using batch reactors with small volumes (Goswami, 1995, 1997; Cooper and Goswami, 1998). Other approaches, including the use of different backing surfaces, have been used to enhance the efficiency of SODIS by increasing the thermal effects of reflective polyethylene terephthalate (PET) bottles (Sommer et al., 1997; Kehoe et al., 2001). In areas with low levels of solar radiation, use has been made of homemade solar collectors, for concentrating the effects of sunlight, to achieve good water disinfection efficiency (Gelover et al., 2006).

SODIS, although recommended by the WHO, has certain limitations, just like any other technology. First, not many scientific and engineering data on the process evaluation are available, especially for rainwater disinfection in the context of supplying potable water in rural/semi-urban areas of developing countries, although SODIS efficiency has been determined using different sources of contaminated water, including wastewater, freshwater, seawater and bathing waters (Dan et al., 1997; Sinton et al., 1999, 2002; Mascher et al., 2003). Furthermore, this technology is limited by the availability and useful life span of plastic bottles—typically only a few months (Wegelin et al., 2001)—and unsuitable weather conditions, e.g., weak or even moderate sunlight radiation, render the process ineffective. Only strong sunlight radiation for about 6–8 h daily is adequate for the complete disinfection of rainwater.

The authors' preliminary works analyzed the efficiency of SODIS for rainwater disinfection under the irradiation conditions in Seoul, South Korea (Amin and Han, 2009). Results showed that the irradiation level was not sufficient to completely disinfect the stored rainwater contained in PET bottles, even under strong weather conditions. To achieve more concentrated effects of sunlight radiation and temperature, modifications were then made to the SODIS system by modifying homemade solar collectors (Gelover et al., 2006), leading to solar collector disinfection (SOCO-DIS).

The objectives of the present study were: (1) to compare the efficiency of SOCO-DIS with that of SODIS under different weather conditions; (2) to optimize the developed SOCO-DIS system by investigating the effects of different base surfaces and base angles of the solar collector; (3) to investigate the effects of varying the initial pH and turbidity values of the rainwater on the efficiency of the SOCO-DIS system and make comparisons with the SODIS system; (4) to compare microbial regrowth in the SOCO-DIS system with that of the SODIS system; and (5) to highlight the limitations of the SOCO-DIS system based on the results of the present investigation, and then make suggestions for further improvement of the method by applying simple techniques.

2. Materials and methods

Rainwater taken from underground storage tanks was placed at rooftop level and exposed to direct sunlight for 9 h, from 9 am to 6 pm, daily during the year 2008. Sunlight radiation was monitored on-site with a SP-110 pyranometer (Apogee Instruments Inc., Logan, USA) connected to a data logger (DT80 Series 2), recording 1-min averages in Watt/m^2 (W/m^2). The spectral range of the Pyranometer used is 0–1750 W/m^2. Environmental and water temperatures were recorded using a thermocouple or thermometer. Nontreated controls were maintained in the same environment under ambient conditions, but they were shielded from sunlight by covering the PET bottles with aluminum foil. Detailed descriptions of the procedures are reported in a previous paper (Amin and Han, 2009).

Basic physicochemical parameters, including pH and turbidity, were analyzed together with bacteriological parameters. However, these values were used only as references because the discussion here is focused mainly on microorganisms during analysis. Most of the inactivation curves in our experiments showed a lag phase, followed by a log-linear phase, and then a tail of final concentration of remaining bacteria (i.e., shoulder + log-linear + tail). This behavior can be modeled with the Geeraerd model, which explains the kinetics during mild-thermal inactivation processes and which has been widely used in many SODIS scientific contributions to fit experimental results (Geeraerd et al., 2000). Finally, microbial regrowth was also investigated by keeping the bottles at room temperature for a few days after exposure to sunlight.

2.1. SODIS and SOCO-DIS systems

In the case of the SODIS system, for the purpose of comparison with the SOCO-DIS system, a 1.7-L rainwater sample in a commercially available 2-L mineral water PET bottle with reflective backing, i.e., with an aluminum foil backing, and

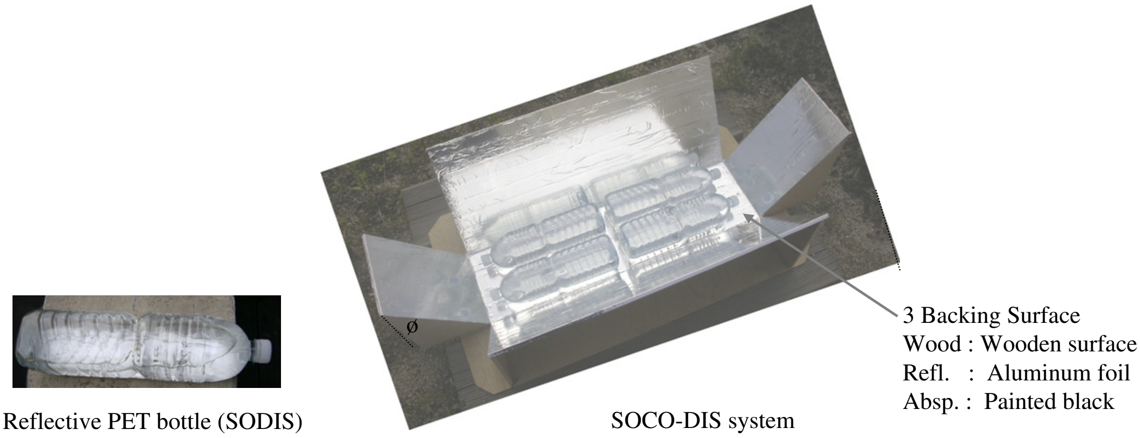

Fig. 1 – Rainwater samples in PET bottles kept directly at rooftop for SODIS and inside collector for SOCO-DIS system.

having a net weight of 62.74 g and a rectangular cross-section (30 cm × 9 cm) to provide the largest surface area for sunlight penetration, was placed on the rooftop of a building where stored rainwater is used (mainly for toilet flushing). In a horizontal position (Fig. 1), this provides a path length of about 9 cm. There are about 15 grooves on each side of the bottle.

A solar collector consisting of five wooden pieces, four covered with aluminum foil as side wings and one a base (Fig. 2), represents the SOCO-DIS system. This offered a fixed 0.75 m × 0.25 m rectangular base area, which could hold four 2-L PET bottles. Two wings were built with 0.35 m × 0.25 m rectangles and others with 0.75 m × 0.35 m rectangles, with the same vertical angle (ø) of 30° with respect to the horizontal position of the box.

2.2. *Microbial analysis*

All bacteriological parameters including total coliform (TC), fecal coliform (FC) and *E. coli* were measured using the multiple-tube fermentation technique (MPN method). The water quality analysis was carried out in accordance with the guidelines described in the Standard Methods for the Examination of Water and Wastewater (APHA, 1999). DifcoTM Lauryl Tryptose Broth (Becton, Dickinson and Company) was used for the presumptive phase of all three parameters, and DifcoTM Brilliant Green Bile Broth (Becton, Dickinson and Company), DifcoTM EC Medium (Becton, Dickinson and Company) and BactoTM EC Medium with Mug (Becton Dickinson France S.A.) were used for the confirmation phase of TC, FC and *E. coli*, respectively. Heterotrophic plate count (HPC) was determined by the pour plate method using DifcoTM Plate Count Agar (Becton, Dickinson and Company). The final concentrations are expressed as the number of colony-forming units (CFU) per milliliter of the original sample. We have reported a detailed description of these methods previously (Amin and Han, 2009).

The detection limit of the MPN method is 0 CFU/100 ml for TC, FC and *E. coli*, and 10 CFU/ml for HPC. All experiments were performed at least three times, and in many cases up to seven times, to avoid any experimental errors. The error bars are shown in almost all the time graphs. The *R*-squared values presented for validating the results are based on statistical criteria.

3. Results and discussions

3.1. *Sampling site and characteristics*

The choice of site for sample collection was made mainly with regard to the availability of the rainwater-collection facilities installed at Seoul National University, Seoul, South Korea. A rough schematic diagram of the RWH

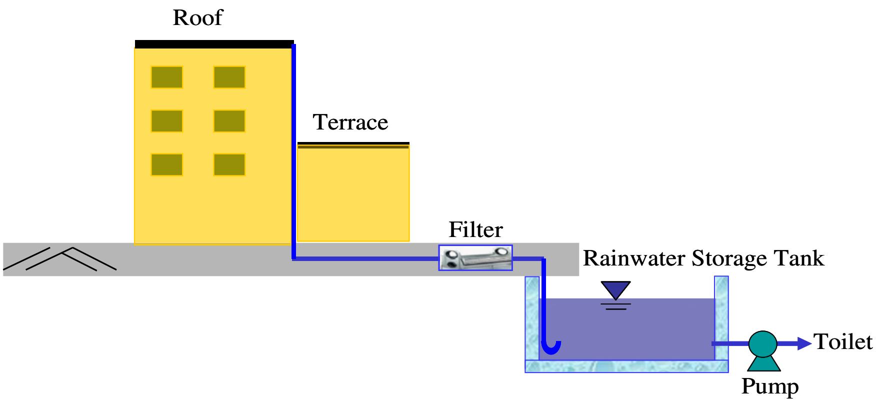

Fig. 2 – Schematic diagram of Rooftop RWH system.

Table 1 – Reference values of parent rainwater samples.

Physiochemical parameters					Microbial parameters			
Initial Temp. °C	pH	EC μS/cm	DO mg/l	Turbidity NTU	TC CFU/ 100 ml	FC CFU/ 100 ml	*E. coli* CFU/ 100 ml	HPC CFU/ml
23–25	7–9	150–500	5–9	1–5	880–1100	400–450	200–250	1500–2000

system in one of the facilities is shown in Fig. 2. The rooftop RWH system here mainly provides water for non-potable purposes in these buildings, including for toilet flushing. A detailed description of the different components of this system, and others, has been reported previously (Han and Mun, 2008).

Rainwater samples that were exposed to direct sunlight for about a whole day were moved and kept at room conditions for further 1–7 days to check any microbial regrowth. Table 1 shows the reference values of the parent rainwater samples taken from the rainwater storage tank in the RWH system from time to time. The parent rainwater samples had a neutral pH value of 7, a low initial turbidity of <5 NTU, and an initial temperature of about 23–25 °C. These are the standard initial values of rainwater samples throughout in this study, unless mentioned otherwise. The amount of bacteria in all these samples occurred naturally in stored rainwater, mainly because of the catchment surface (without inoculating or spiking any bacteria into the underground rainwater tank).

One of the reasons for the different initial values of all parameters is the time period of about one year during which the samples were collected from the underground concrete rainwater tank. Another reason is the different sample collection times, with some samples taken directly after a rainfall event, when the water level in the tank is high, and others up to two weeks after rainfall, when the water level is low. Samples were always collected from the outlet point in the underground rainwater tank, which is at a height of about 1.35 m from the base of the tank. All rainwater samples had very low turbidity values and a pH usually in the neutral range. Any difference between the initial values was not very significant for the purposes of these experiments, however, because the disinfection efficiency is compared in terms of microbial percentage removal.

3.2. *Characteristics of different weather conditions*

Bacteriological parameters were measured at appropriate time intervals, usually every 2 h during the 9 h exposure time. The PET bottles were kept undisturbed during all experiments. They had an air space of about 15% of the bottle volume for air circulation, to achieve aeration (Reed, 1997). The solar collector, which had a rectangular base covered with aluminum foil, except where mentioned, was kept horizontal. Irradiance and temperature values corresponding to different weather conditions, which are specific to the weather conditions of Seoul, Korea (Latitude: 37°35′ North, Longitude: 127° 03′ East), are shown in Figs. 3 and 4.

Weather is categorized into three types, depending on low, medium and high sunlight radiations. Weak weather represents sunlight radiation of 200–450 W/m^2, with an average value of about 300 W/m^2, for about four months of the year (from November to February); moderate weather represents sunlight radiation of 450–700 W/m^2, with an average value of about 580 W/m^2 during September, October, March and April; strong weather is represented by sunlight radiation of 650–1000 W/m^2, with an average value of about 880 W/m^2 for about four months from May to August. These months of the year correspond to different weather conditions according to the weather pattern at experimental sites. Fig. 3 represents the patterns of sunlight intensity variations, using the hourly average values of irradiance for different weather conditions. This is a quite common radiation pattern that can be generalized for one whole day's

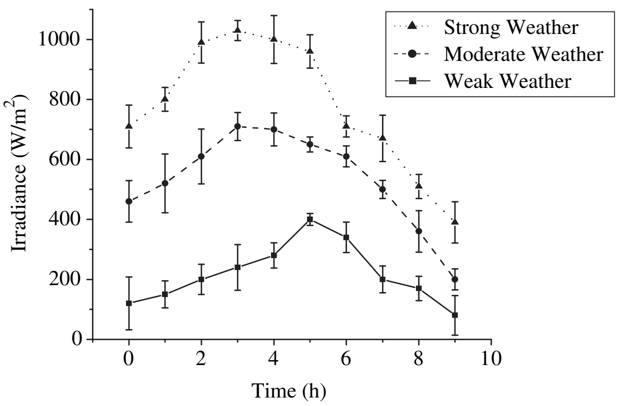

Fig. 3 – Irradiance changes with exposure time under different weather conditions.

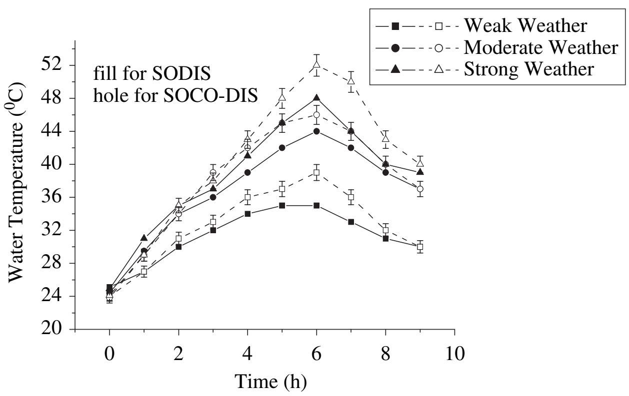

Fig. 4 – Water temperature comparison between SODIS and SOCO-DIS system under different weather conditions.

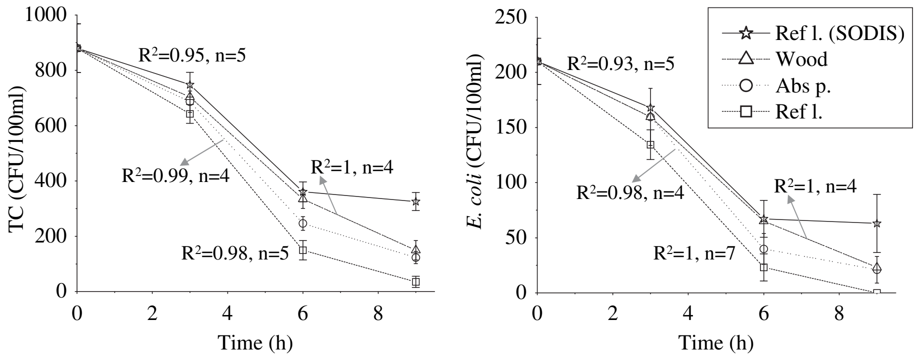

Fig. 5 – Microbial inactivation with different base surfaces of solar collector with low turbidity (5NTU) and neutral pH values under moderate weather conditions.

exposure time for respective weather conditions in many locations around the globe. This is a three-phase radiation pattern of increasing, constant and decreasing phases, respectively, with equal time intervals of about 3 h, with the middle phase being critical for disinfection. The difference between the sunlight intensity of weak and moderate weather conditions is about twofold, and it is threefold between weak and strong weather conditions.

The temperature changes under each of the weather conditions were measured at regular intervals of 1 h, to compare the SODIS and SOCO-DIS systems for all three weather conditions. The results are shown in Fig. 4. These are the representative results of about 8–10 repetitions for different experimental analyses under the same conditions. Time 0 h corresponds to 9 am, when the irradiation of rainwater samples began; irradiation ended at 6 pm, corresponding to 9 h. These are the average temperature values of all four bottles that were kept inside the solar collector. In the case of the SOCO-DIS system, usually a difference of 5 °C is observed between the weak and moderate or the moderate and strong weather conditions. Water temperature is almost dependent on weather conditions: the stronger the sunlight radiation, the higher the water temperature, with a maximum value usually in the afternoon, after which it drops with decreasing radiation. Thus, weak or even moderate weather conditions may not be suitable for the synergistic effect of radiation and temperature, because the water temperature is below 50 °C (Simon et al., 2007). Temperature changes in a SOCO-DIS system were compared with those in a SODIS system. Fig. 4 shows that the temperature difference is about 2–4 °C, with a greater increase in temperature in the SOCO-DIS system due to the concentrated effect of sunlight radiation as the radiation is reflected back onto the PET bottles because of the open wings on the side.

The higher temperatures may not cause any health risks and traces of the plasticizers di(2-ethylhexyl) adipate and di(2-ethylhexyl) phthalate, which leach from PET bottles, are well below the respective limits for drinking water fixed by the WHO. Furthermore, photochemical aging of PET bottles does not change the quality of water stored in PET bottles with regard to the aldehyde, organic photoproducts, and additive or phthalate concentrations, even for water stored for up to 3–4 months (Wegelin et al., 2001).

3.3. *The effects of the collector's base angle and different backing surfaces in the SOCO-DIS system*

To improve the amount of radiation reaching the water, the solar collector was kept at an angle of 37° (latitude of the location), facing the midday position of sun. The disinfection efficiency resulting from the inclined settings compared with a simple case, namely the horizontal position of the collector, and with that of a collector direction changed continuously according to the sun's position, was determined at regular intervals throughout the day under weak sunlight conditions. A solar collector in which the direction can be changed continuously according to the sun's position is considered the best choice (for experimental purposes), but it would require much more labor.

The better disinfection efficiency in inclined and changed settings of solar collector might be due to the exposure of the collector, and hence rainwater samples, to direct sunlight by minimizing the possible shading effect of the wings at different time intervals during a whole day of exposure. Microbial inactivation in the SOCO-DIS system was increased by 10% by simply changing the collector's position from horizontal to inclined. The best selection for optimum disinfection efficiency would therefore be the inclined position of the collector; this was the final choice made, and applicable to the following experimental results and discussion.

The disinfection efficiency of a SOCO-DIS system with a solar collector having different base surfaces, including reflective (Refl.), i.e., a base covered with aluminum foil,

Table 2 – Comparison of kmax (1/min) with different base surfaces of collector with low turbidity (5NTU) and neutral pH values under moderate weather conditions.

Microbial parameters	SODIS (Refl. PET bottle)	SOCO-DIS with different backing surfaces		
		Wood	Absp	Refl.
TC	0.10	0.37	0.34	0.58
FC	0.11	0.45	0.45	1.39
E. coli	0.09	0.44	0.35	1.06
HPC	0.10	0.27	0.34	0.32

Table 3 – Experimental conditions for parameter's selection of SOCO-DIS system and for comparison with SODIS.

Parameter	Weather condition	Initial Temperature, °C	SOCO-DIS (Refl. & Inclined Collector)		SODIS (Refl. PET)
			pH	Turbidity	Turbidity/pH
Standard Conditions	–	23–25	7	<5	<5/7
Effect of Sunlight	Weak, Moderate & Strong	//	7	<5	<5/7
Effect of pH	Moderate	//	5,7,10	<5	<5/5
Effect of Turbidity	Weak	//	7	<5, 20, 100	<5/7
Microbial Re-growth	Weak	//	5,7,10	<5	<5/10
	Moderate	//	7	<5, 20, 100	100/7

absorptive (Absp.), i.e., with a base surface painted black, and a simple wooden surface (Wood), was evaluated under moderate sunlight conditions and the results compared, as shown in Fig. 5. Results are shown for TC and *E. coli*; the other two parameters, FC and HPC, are discussed only in terms of the decay constant (see Table 2). All these experiments were repeated 3–5 times and the results presented are the mean average values of each point.

The absorptive base surface increased the water temperature by absorbing radiation up to 48 °C (results not shown), compared with 46 °C in a standard reflective base, as shown in Fig. 4. The thermal effects, however, did not significantly contribute to the microbial inactivation, as shown when comparing the results of the absorptive base surface with those of the reflective base surface, where disinfection efficiency is higher and rainwater is almost completely disinfected. This may be because the reflective base of the solar collector enhances radiation effects by reflecting and returning the radiation to the water samples. With insignificant thermal or synergistic effects because of lower temperatures, it can be concluded that UV radiation effects are prominent under moderate sunlight conditions. Both absorptive- and transmissive-type surfaces have almost similar disinfection efficiency; the absorptive base yielded about 10% better results because of the synergistic effects of temperature, which are absent in the case of the transparent base surface. Under strong weather conditions, however, the absorptive base surface may become more effective because of the thermal effects from the increased temperatures.

Table 2 presents a brief comparison of all four microbial parameters based on the inactivation rate constants calculated, based on the Geeraerd model. The comparison was performed among three different types of base surfaces. The efficiency of the SOCO-DIS system was also compared with that of SODIS system with the best rear surface under these weather conditions, which is a reflective backing. The comparison was performed under moderate weather conditions, with rainwater having a neutral pH and low initial turbidity values.

The microbial inactivation under weak (results not shown) and moderate sunlight conditions clearly demonstrates that a reflective backing can enhance the microbial inactivation, irrespective of the intensity of sunlight. This is most probably due to the return of UV-A and short-wavelength visible

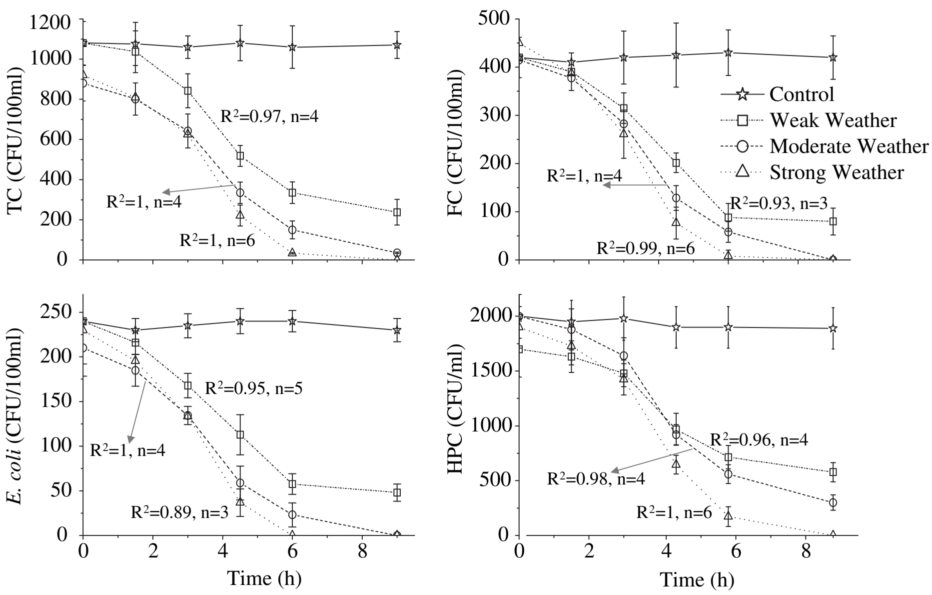

Fig. 6 – Microbial inactivation in SOCO-DIS system under different weather conditions with low turbidity (5NTU) and neutral pH values.

Table 4 – Comparison of kmax (1/min) between SODIS and SOCO-DIS system at different weather conditions with low turbidity (5NTU) and neutral pH values.

Microbial parameters	Weak weather		Moderate weather		Strong weather	
	SODIS	SOCO-DIS	SODIS	SOCO-DIS	SODIS	SOCO-DIS
TC	0.02	0.20	0.10	0.58	0.18	1.24
FC	0.08	0.20	0.12	1.29	0.21	0.96
E. coli	0.05	0.18	0.09	1.02	0.14	0.77
HPC	0.03	0.14	0.10	0.32	0.15	1.66

radiation after being reflected by the aluminum foil, leading to the increased damage of cellular components and consequently increased inactivation of microorganisms. This finding is in agreement with previously reported results (Kehoe et al., 2001), but in contrast with the earlier results recorded under strong weather conditions. The best selection for optimum disinfection efficiency, therefore, would be use of the reflective backing on the collector's base; this was the final choice made and is applicable to the following experimental results and discussion.

3.4. *Comparison of the SODIS and SOCO-DIS systems*

After the best angle and base surface of the collector were selected, the disinfection efficiency of the SOCO-DIS system was compared with that the SODIS system. In the case of SODIS, PET bottles with reflective backing were used, and disinfection efficiency was compared with that of the SODIS system when using the best characteristics of the SOCO-DIS system, i.e., reflective base surface set at an inclination to the midday position of the sun, as determined earlier. Table 3 summarizes the experimental conditions used when selecting the various key parameters in the SOCO-DIS system and for comparison purposes with the SODIS system.

3.4.1. *The effects of radiation and temperature effects on microbial inactivation*

The disinfection efficiency of the SOCO-DIS system was determined under different weather conditions, depending on the irradiance range of natural sunlight available on different days during the experiments. Fig. 6 shows a comparison of the disinfection based on the sunlight intensity, with the reflective backing of the collector's base adjusted at an inclined angle to the midday position of the sun. The pH of the rainwater samples was neutral and initial turbidities were low (<5 NTU). Almost all experiments were repeated about five times. Results are presented based on the mean average values of each point and corresponding standard deviations for each case are tabulated in Table 4. Time 0 h corresponds to 9 am, when the irradiation of rainwater samples commenced; irradiation ended at 6 pm, corresponding to 9 h.

Disinfection exhibited three stages of treatment depending upon the sunlight intensity; the middle stage was critical. During the initial lag period, in the case of TC under weak weather conditions, a persistent nature of nonfecal organisms against sunlight effects was evident for a few hours. This was most probably resistant to UV attack at low wavelengths. HPC, however, showed prolonged resistance, even under strong sunlight or against a full UV range, compared with other parameters. Microbial inactivation was due to two mechanisms of treatment—thermal or pasteurization—and UV-A radiation; although these can work independently, earlier studies indicate synergistic effects when they are applied together (McGuigan et al., 1998). These synergistic effects are evident under strong weather conditions, during which rainwater is disinfected completely, as shown in Fig. 6. The relative removal of indicator microorganisms was HPC < TC < FC/*E. coli*. Only HPC and, to some extent, TC showed resistance to disinfection under moderate weather conditions, while the SOCO-DIS system proved ineffective under weak weather conditions, mostly because the synergistic effects of radiation and temperature are absent.

Microbial inactivation is directly related to sunlight intensity. This is very obvious, because of the strong optical effects of short wavelength components of sunlight in solar UV (300–400 nm), especially in the UV-B range (300–320 nm). UV-B is highest (as a proportion of solar irradiance) when the sun is at its highest altitude near solar noon, as is clear from an increase in the inactivation rate at this time, from 11 am to 3 pm, in the conducted experiments. All the results showed a similar

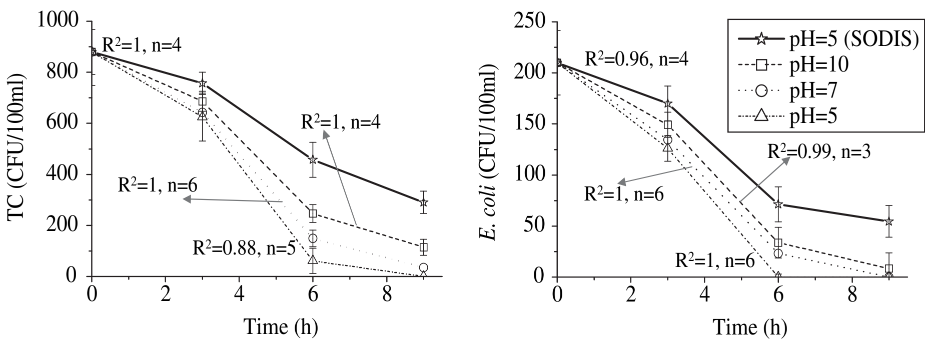

Fig. 7 – Effects of different initial pH values on microbial inactivation with time for low turbidity (5NTU) rainwater under moderate weather conditions.

Table 5 – Comparison of kmax (1/min) for different initial pH values with low turbidity (5NTU) under moderate weather conditions.

Microbial parameters	SODIS (pH = 5)	SOCO-DIS at different pH values		
		10	7	5
TC	0.25	0.36	0.58	1.39
FC	0.36	0.58	1.40	0.86
E. coli	0.17	0.56	1.06	0.66
HPC	0.14	0.30	0.32	2.10

tendency, signifying a close relationship between sunlight intensity and the time required to inactivate microorganisms. The temperature measured inside the bottles indicated that it is not a predominant factor in the elimination of microorganisms—it is mainly the radiation that determines the efficiency of SODIS. Another important factor is the presence of natural organic matter (HPC concentrations), which may also act as a photosensitizer and hence improve the disinfection efficiency (Curtis et al., 1992). Table 4 compares the microbial inactivation of the SOCO-DIS system with the SODIS system for all four microbial parameters based on microbial decay rate constants at neutral pH and low turbidity values (<5 NTU) under all weather conditions.

SODIS proved to be ineffective for achieving complete disinfection even under strong sunlight radiation; however, a direct correlation between radiation and inactivation was observed, as for the SOCO-DIS system. In the case of SODIS, no parameter, under any weather conditions, led to the achievement of potable water guideline values, namely 0 CFU/100 ml for TC, FC and *E. coli* and 10 CFU/ml for HPC. The difference in disinfection efficiency between the two systems can be summarized as follows: the SOCO-DIS system is about 20–30% more efficient than the SODIS system. The main reason for this is the enhanced effects of concentrated radiation and the synergistic effects of temperature, mainly under strong and moderate weather conditions.

3.4.2. *The effects of initial pH values on disinfection efficiency*

Among the numerous operating parameters affecting disinfection, the effects of only two basic physicochemical parameters, i.e., pH and turbidity, were evaluated. Fig. 7 shows the microbial changes in rainwater samples in the SOCO-DIS system with different initial pH values and in the SODIS system with the lowest pH. Three pH values were chosen for the SOCO-DIS system, representing acidic, neutral and basic conditions. Dilute HCl and NaOH were used for pH adjustment. Comparisons were performed under moderate weather conditions with rainwater with a low initial turbidity value (<5 NTU). In the SOCO-DIS system, rainwater with acidic pH offered the best disinfection efficiency for all the microbial parameters, without exception. TC and HPC, which were not removed under standard sampling conditions of neutral pH, were also completely inactivated at low pH values. The overall disinfection efficiency increased by 10% by decreasing the pH values from basic to neutral condition, and by 20% by reducing the pH levels to acidic conditions.

Low pH may increase the inactivation rate by presenting significant additional stress to the cells, for example by requiring the cells to expend energy in maintaining pH homeostasis, thus accelerating the depletion of adenosine triphosphate (ATP), the main energy storage and transfer molecule in the cell, and/or the reducing equivalents. Biosynthetic reaction comes to a halt as a consequence of ATP depletion and there is a loss of the cells' ability to maintain integrity, especially with respect to membrane systems (Foegeding et al., 1996). The resulting metabolic stress due to low pH may also reduce the rate at which energy-consuming proteins in the cell can scavenge reactive oxygen species (ROS), such as hydroxyl radicals, superoxide radical anions, hydrogen peroxide, and singlet oxygen, and/or repair damaged DNA, facilitating a more rapid photoinactivation. ROS damage external structures of microorganisms, such as cell membranes.

Table 5 shows a comparison of the microbial inactivation achieved with the SOCO-DIS system at different initial pH values for all four microbial parameters, based on the microbial decay rate constant, with that of the SODIS system (best case of low pH) under moderate weather conditions, with low initial turbidity values (<5 NTU). These findings differed from those of previous studies: no effects of initial pH values on *E. coli* inactivation rates were evident (Rincon and Pulgarin, 2004). This difference might be due to the different source waters and sunlight conditions used. The acidification to pH 5 or below has a significant effect on disinfection rates, as was reported previously (Fisher et al., 2008). There are no health-based guidelines for pH; the 1996 Annual Report of the National Health and Medical Research

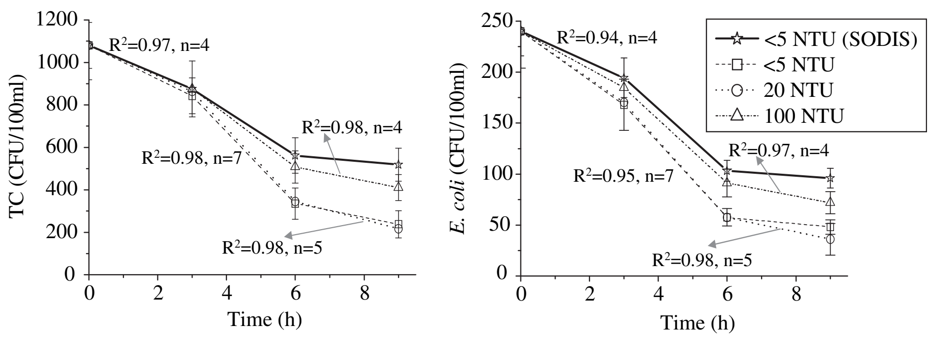

Fig. 8 – Effects of different initial turbidity values on microbial inactivation with time for neutral pH rainwater under weak weather conditions.

Council (NHMRC, 1996) indicates that the consumption of food or beverages with low (2.5) or high (11) pH does not result in adverse health effects.

3.4.3. *The effects of initial turbidity values on disinfection efficiency*

The disinfection efficiency of the SOCO-DIS system was compared by changing different initial turbidity values under weak weather conditions, as shown in Fig. 8. Rainwater collected from an underground storage tank had a turbidity of less than 5 NTU. For comparison purposes, higher values were achieved by adding kaolin.

Samples with low turbidity showed better results, although this difference is insignificant up to about 20 NTU. However, the SOCO-DIS system showed poor performance in terms of all microbial parameters at higher turbidity, and disinfection efficiency decreased by almost 10–15%. This could be because of a loss of UV due to scattering and absorption by suspended particles in rainwater samples. Overall, the disinfection efficiency of the SOCO-DIS system was about 20–30% better than that of the SODIS system at all respective turbidity values. Highly turbid water may undergo a substantial temperature increase because of the absorption of solar radiation by suspended particles, which may contribute to higher disinfection efficiencies (Joyce et al., 1996). However, results showed that rainwater failed to reach temperatures high enough for better disinfection efficiency under weak weather conditions. Higher turbidity may also result in microbial regrowth if appropriate sunlight irradiance, and hence moderate temperatures, are not reached.

3.4.4. *Microbial regrowth in SOCO-DIS system and comparison with SODIS*

Yet another factor that had to be considered was microbial regrowth or reactivation of microorganisms if the water is to be stored for several hours after exposure. For this purpose, rainwater samples were stored under dark conditions and at room temperature by covering the irradiated PET bottles with aluminum foil, in the same way as the control samples, for one week after exposure to sunlight. The microbial changes observed for TC and *E. coli* are shown in Fig. 9. These samples, with different initial turbidity values at neutral pH and with different initial pH values at low turbidity, respectively, were initially exposed to sunlight under weak and moderate weather conditions. Microbial regrowth in the SOCO-DIS system was compared with that in the SODIS system only at basic pH and high turbidity values.

In the case of SODIS, *E. coli* regrowth was observed for samples with basic pH and high turbidity values, while TC regrowth was observed only in samples with high turbidities, and mostly because of weak sunlight conditions. Regrowth was not observed in the case of the SOCO-DIS system for TC, even at high turbidities, possibly because of residual sunlight effects. *E. coli* regrowth, however, was observed mainly under weak weather conditions and higher turbidities, but not at basic pH, at least after one day of exposure. Once again this is possibly because of residual sunlight effects under moderate weather conditions. This regrowth might be due to the repair of partially damaged microorganisms, indicating negative/reversal effects of SODIS, and hence requiring additional measures to control microbial regrowth. Rainwater with acidic or neutral pH and low turbidity up to 20 NTU did not pose any problem of microbial regrowth.

The presence of TC or *E. coli* in stored samples indicates the resistance of these groups to stressful conditions, caused by UV attack at higher turbidities. These organisms recover by means of some documented cellular repair mechanisms, such as photoreactivation (Kim and Sundin, 2001).

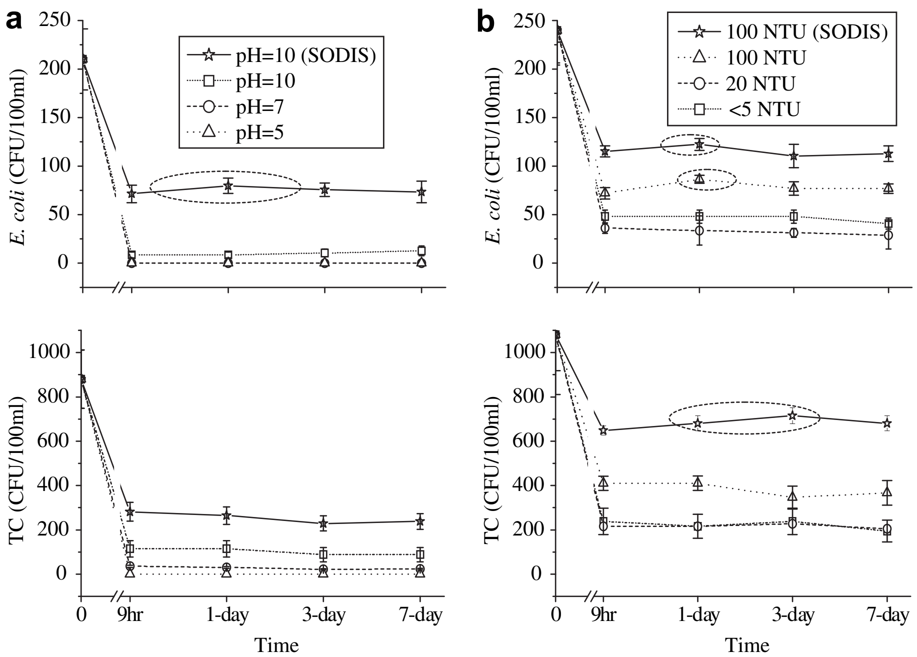

Fig. 9 – Microbial re-growths for different initial; (a) pH values under moderate sunlight with low turbidity (5NTU), and (b) turbidity values under weak sunlight with neutral pH.

4. Conclusions

The disinfection efficiency of a solar-based SOCO-DIS system was determined for the treatment of stored rainwater, for small-scale potable water supply, as is particularly required in rural or semi-urban areas in developing countries. The process efficiency of the SOCO-DIS system was compared with that of a SODIS system under different weather conditions. Overall, a 20–30% increase in the disinfection efficiency of the SOCO-DIS system was achieved, mainly due to the concentrated effects of sunlight radiation and the synergistic effects of thermal and optical inactivation. The inefficiency of SODIS has thus been significantly improved upon by the SOCO-DIS system, and rainwater can now be completely disinfected under strong and even moderate weather conditions.

The SOCO-DIS system was further optimized by using different base surfaces and angles of the solar collector. Changing the collector's angle during the day did not lead to a significant difference in the disinfection efficiency of the SOCO-DIS system; the collector's position with respect to the midday position of the sun offered the optimum disinfection of exposed rainwater. Among the three different base surfaces used, the reflective surface showed a 10–15% better disinfection efficiency than the absorptive and simple surfaces, possibly due to the reflection of radiation by the side wings and the base of the collector, and the return thereof to the water samples.

The disinfection efficiency of the SOCO-DIS system was also significantly improved by changing the initial pH and turbidity values of the water. Rainwater was completely disinfected only at low pH values under moderate weather conditions, thus improving the process efficiency by 10–20% as the initial pH values changed from basic to acidic values. Higher turbidities than 30NTU also decreased the process efficiency of the SOCO-DIS system, by 10–15%, as in the case of the SODIS system, hence requiring the rainwater to be filtered.

The problem of microbial regrowth that was observed for SODIS at higher pH and turbidities was also reduced, most probably due to the residual effects of sunlight radiation; only TC regrowth at higher turbidities was observed. The SOCO-DIS system seems to be ineffective for complete disinfection only under the investigated weak weather conditions and, therefore, a longer exposure time (longer than the usual one day) is required. Alternatively, some other means of modifying and improving the SOCO-DIS system are required for complete disinfection of rainwater.

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