

Roof-harvested rainwater for potable purposes: application of solar disinfection (SODIS) and limitations

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ABSTRACT

Efficiency of solar disinfection (SODIS) was evaluated for the potability of rainwater in view of the increasing water and energy crises especially in developing countries. Rainwater samples were collected from an underground storage tank in 2 L polyethylene terephthalate (PET) bottles and SODIS efficiency was evaluated at different weather conditions. For optimizing SODIS, PET bottles with different backing surfaces to enhance the optical and thermal effects of SODIS were used and different physicochemical parameters were selected and evaluated along with microbial re-growth observations and calculating microbial decay constants. Total and fecal coliforms were used along with *Escherichia Coli* and Heterotrophic Plate Counts (HPC) as basic microbial and indicator organisms of water quality. For irradiance less than 600 W/m², reflective type PET bottles were best types while for radiations greater than 700 W/m², absorptive type PET bottles offered best solution due to the synergistic effects of both thermal and UV radiations. Microbial inactivation did not improve significantly by changing the initial pH and turbidity values but optimum SODIS efficiency is achieved for rainwater with acidic pH and low initial turbidity values by keeping air-spaced PET bottles in undisturbed conditions. Microbial re-growth occurred after one day only at higher turbidity values and with basic pH values. First-order reaction rate constant was in accordance with recent findings for TC but contradicted with previous researches for *E. coli*. No microbial parameter met drinking water guidelines even under strong experimental weather conditions rendering SODIS ineffective for complete disinfection and hence needed more exposure time or stronger sunlight radiations. With maximum possible storage of rainwater, however, and by using some means for accelerating SODIS process, rainwater can be disinfected and used for potable purposes.

Key words | coliform, PET, potability, rainwater, SODIS

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INTRODUCTION

In the face of decreasing water sources and increasing energy crises, Rainwater Harvesting (RWH) may be seen as one of the most appropriate alternatives for supplying freshwater at household level and at community level as well. A rainwater utilization facility to use stored rainwater consists of its catchment area, a treatment facility, a storage tank, a supply facility and pipes (Han & Mun 2008). Despite its long history of application, RWH is rarely used for domestic purposes where abundant water supplies are

available and provided by government and public sectors. However, potential applications of RWH exist for roof catchments in areas where a centralized water supply and distribution system does not exist. Their usage is small but it is growing (Han 2007). RWH has been used at the household level only on a limited scale and mostly for non-potable purposes. The potable use of rainwater, however, is limited and one of the major constraints is the microbial quality of stored rainwater which is not good

mostly due to the possible contamination upon contact with roof catchment. This requires the minimum treatment by simple disinfection methods that are practically suitable according to the resources (cost and energy) available in rural or semi-urban areas of developing countries.

The use of solar energy as an alternative to chlorination is recently developed which is at least economically viable in countries with a high degree of sunlight radiation. SODIS is one of the low cost, low energy disinfection method promoted by World Health Organization (WHO), however, not much scientific and engineering data is available. Although, SODIS efficiency is evaluated by using different sources of contaminated water including wastewater (Sinton *et al.* 2002), freshwater (Dan *et al.* 1997), seawater (Sinton *et al.* 1999) and bathing waters (Mascher *et al.* 2003), however, there have been no detailed studies for evaluation of the SODIS for rainwater disinfection in the context of supplying potable water supplies in rural/semi-urban areas of developing countries.

Solar energy provides two mechanisms of treatment i.e. thermal (pasteurization) and UV-A radiations which can work independently, but studies indicate synergistic effects when they are applied together (McGuigan *et al.* 1998). Disinfection using sunlight was termed as SODIS for the first time almost three decades ago (Acra *et al.* 1984). In these studies, Acra *et al.* used transparent glass and plastic vessel and found solar radiation effective in inactivating a wide range of microorganisms including fecal indicator. The solar-based drinking water treatment processes were further investigated almost a decade later using batch reactors of small volumes for disinfection of drinking water (Goswami 1995, 1997; Cooper & Goswami 1998). Other approaches like different backing surfaces were used to enhance the efficiency of SODIS by increasing the thermal effects of reflective PET bottles (Sommer *et al.* 1997; Kehoe *et al.* 2001).

Disinfection efficiency of SODIS for rainwater treatment is evaluated using general quality indicators and microorganisms. Total and fecal coliform are used to assess bacteriological water quality. These organisms are used to index hygienic quality because total and fecal coliform are usually associated with fecal contamination and thus their numbers reflect the degree of pathogenic risk. Fecal Coliform (FC) is the most widely used indicator to

determine the possible presence of pathogenic organisms and is often used as an indicator to judge water quality. Heterotrophs use organic chemicals as a principal carbon source. HPC can be used to determine the presence of organic matter in water and as an indicator of general water quality.

The purpose of this study is to; (1) find the effects of different weather conditions on SODIS efficiency, (2) optimize the already existing simple technology of SODIS by investigating the effects of different backing surfaces of simple PET containers under various climatic conditions, (3) investigate the effects of varying initial pH and turbidity values on the efficiency of SODIS for basic microbial parameters and indicator organisms along with calculating the microbial decay constants and finding the microbial re-growth, and (4) highlight some major constraints or limitations of SODIS based on present investigation and suggestions so as to further improve the method by simple techniques.

MATERIALS AND METHODS

This study is carried out at Seoul National University in Seoul, Korea. The choice of site for sample collection is made mainly with regard to the availability of the rainwater facility installed in couple of buildings at campus. The rough schematic diagram of RWH system in one of these buildings is shown in Figure 1 while detailed description is already published (Han & Mun 2008). Among the components of RWH system are the couple of storage tanks where

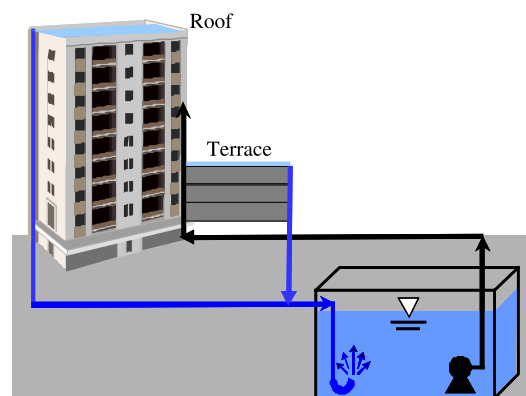


Figure 1 | Rough schematic diagram of RWH system.

rainwater is stored after collecting from roof and terrace catchments with a total surface area of about 4,000 m². The rooftop RWH system mainly provides water for non-potable purposes in these buildings including toilet flushing.

Rainwater, taken from the underground storage tanks, is placed at rooftop by exposing to direct sunlight for 9 h from 9 am to 6 pm every day during the summer and winter seasons of the year 2008. Non-treated controls were maintained in the same environment but shielded from sunlight by covering the PET bottle with that of aluminum foil kept at room conditions. Sunlight radiations were monitored on-site with a SP-110 Pyranometer (Apogee Instruments Inc., Logan, USA) connected to a datalogger (DT80 Series 2) recording 1 minute averages in Watt/m² (W/m²). Environmental and water temperatures were recorded by thermocouple or thermometer.

The sample volume used is about 1.7 L in a 2 L commercially available mineral water PET bottle having a net weight of about 62.74 g with a rectangular cross section (7.5 cm × 23 cm) to provide largest surface area for sunlight penetration. In a horizontal position, as shown in Figure 2, this provides a length path of about 7.5 cm with about 15 grooves on all sides of bottle. PET bottles are used with different backing surface including reflective (Refl.) i.e. with aluminum foil-backing, absorptive (Absp.) i.e. with rear surface painted black, and transmissive (Trans.) i.e. with transparent backing as shown in Figure 2 under all weather conditions.

The water quality analysis was carried out in accordance with the guidelines described in the Standard Methods (APHA 1999). All bacteriological parameters including TC, FC and *E. coli* were measured using the multiple tube fermentation technique (MPN Method) using Difco™

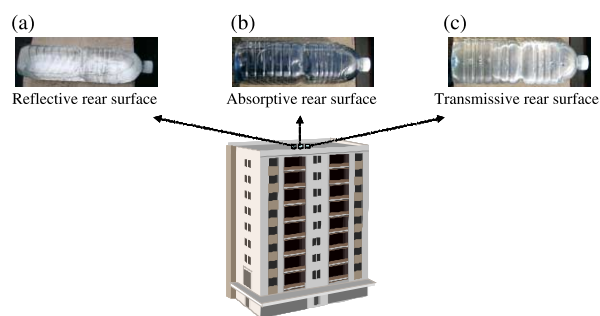


Figure 2 | PET bottles with different backing surfaces kept at rooftop in horizontal positions.

Lauryl Tryptose Broth (Becton, Dickinson and Company) for the presumptive phase of all these parameters in a series of fifteen test tubes for all three dilutions of 10, 1 and 0.1 ml and thus 5 tubes per each dilution. Positive tubes with growth (gas bubble or effervescence) were subjected to confirmation phase after 24 ± 2 h or 48 ± 4 h of incubation at 35°C in presumptive phase. Difco™ Brilliant Green Bile Broth (Becton, Dickinson and Company) and Difco™ EC Medium (Becton, Dickinson and Company) were used for the confirmation phases of TC and FC respectively and Bacto™ EC Medium with Mug (Becton Dickinson France S.A.) for *E. coli* confirmation. All positive tubes in the presumptive phase were further incubated for additional 24 ± 2 h or 48 ± 4 h at 35°C for TC, 24 ± 2 h (additional 24 ± 2) at 44.5 ± 0.2°C in water bath incubator for FC and 24 ± 2 h at 44.5 ± 0.2°C in water bath incubator for *E. coli*. Most probable numbers (MPN) were recorded against the combinations of all positive tubes (gas production with growth, effervescence or yellow color, in case of TC and FC and bright blue fluorescence using a long-wavelength UV lamp in case of *E. coli*).

HPC was determined by the Pour Plate Method using Difco™ Plate Count Agar (Becton, Dickinson and Company). One milliliter of each water sample was serially diluted in a set of test tubes each containing 9 ml of sterile distilled water. Then, 1 ml of each dilution was plated out respectively in duplicates employing the use of nutrients agar medium kept in molten form at 45°C. Having allowed the agar medium to set, the culture plates were incubated aerobically at 35°C for 48 h. The plates were observed for growth and selected for counts. The culture plates in which the number of colonies was in the range of 30–300 and their respective duplicates were selected. The average count was multiplied by the reciprocal of the dilution and expressed as the number of colony-forming units (CFU) per milliliter of original sample.

Basic physicochemical parameters including pH, turbidity, and DO are analyzed along with bacteriological parameters but these values are used only as references while the discussion is focused mainly on microorganisms during analysis. Inactivation rate constants (k , h⁻¹) for the observed decrease in microorganisms were calculated by linear regression analysis for quick comparison by assuming the first-order reaction kinetics ($R^2 > 0.9$ except where

Table 1 | Reference values of parent rainwater samples

Physiochemical parameters					Microbial parameters			
Initial temperature, °C	pH	EC, $\mu\text{S}/\text{cm}$	DO, mg/l	Turbidity, NTU	TC, CFU/100 ml	FC, CFU/100 ml	<i>E. coli</i> , CFU/100 ml	HPC, CFU/ml
23–25	7–9	150–500	5–9	1–5	880–1,100	400–450	200–250	1,500–2,000

mentioned). k value was evaluated for entire exposure time except for clear initial lag period; where the evaluation is performed only for middle stage and especially when calculating ' k ' value for HPC. Microbial re-growth is also investigated by keeping the bottles at room temperature for few days after exposed to sunlight.

RESULTS AND DISCUSSIONS

The efficiency of SODIS is investigated under different weather conditions depending on the irradiance range by using different types of container's rear surface and by changing the initial parameters like sample's pH and turbidity values. Bacteriological parameters were measured at appropriate time intervals usually after every 2 h during 9 h's exposure. The sample was removed and then kept at room condition for further one day to one week for observing the microbial re-growth, if any. Table 1 shows the reference values of parent rainwater samples taken from the main storage tank in RWH system from time to time during the whole experimental analysis in the year 2008.

Since in this study, samples are taken over a period of about six months, so this is one of the reasons for different initial values of all parameters. Every time, the sample is collected from the outlet point in underground rainwater tank which is situated at a height of about 1.35 m from the base of the tank. The samples are collected right after

rainfall when the water level in tank is full and also, sometime, until two weeks after rainfall when the water level is low. The difference between initial values is insignificant and the efficiency of SODIS is compared in terms of microbial percentage remained over time.

EFFECTS OF WEATHER CONDITIONS (RADIATION AND TEMPERATURE EFFECTS)

Table 2 shows the irradiance and temperature values corresponding to different weather conditions. The months of the year corresponding to different weather conditions are also mentioned according to the weather pattern at experimental sites. The water temperature is measured at regular intervals of 1 h by keeping the device inside of bottles while the air temperatures are not recorded. The maximum temperature values corresponding to different container types under different weather conditions are also shown in Table 2. These are the representative results of about 8–10 repetitions for different experimental analysis under same conditions.

For comparison purposes of water temperatures, the parent rainwater samples had a neutral pH value of 7 with initial turbidity in the range of 2–5 NTU and initial temperatures of about 23–25°C. These are the standard initial values in this study unless mentioned otherwise. Figure 3 represents the pattern of sunlight intensity by using

Table 2 | Irradiance and temperature values corresponding to different weather conditions

Weather conditions (Months of the year)	Weak sunlight (November to February)			Moderate sunlight (September to October & March to April)			Strong sunlight (May to August)		
	Refl.	Absp.	Trans.	Refl.	Absp.	Trans.	Refl.	Absp.	Trans.
Irradiance range (average), W/m^2	200–450 (300)			450–700 (580)			650–1,000 (880)		
Container type	Refl.	Absp.	Trans.	Refl.	Absp.	Trans.	Refl.	Absp.	Trans.
Maximum water temperature, °C, Mean (S.D.)	35 (0.82)	37 (0.94)	34.6 (0.61)	44 (1.02)	48 (1.3)	43 (0.98)	48 (1.24)	53 (1.18)	48 (1.42)

Note: S.D. Standard Deviation for $n = 8-10$.

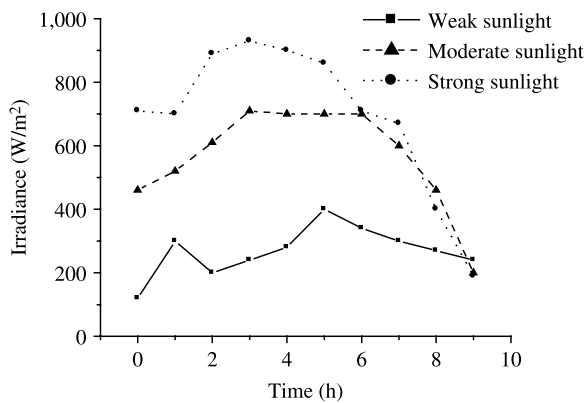


Figure 3 | Irradiance changes with exposure time under different weather conditions.

the hourly average values of irradiance for categorizing the weather condition. These are the mean values of about 15–20 repetitions performed during all the experiments. Similar pattern of sunlight irradiance can be observed for exposure time at different weather conditions and can be generalized for any location in the world. This is a 3-phase radiation pattern of increasing, constant and decreasing phases, respectively, with equal time intervals of about 3 h with middle phase being critical for SODIS. The difference between the sunlight intensity of weak and moderate weathers is about twice and it is three fold between weak and strong weather conditions.

Temperature comparison is made among three types of containers (different backing surfaces) as shown in Figure 4. Although these are the average values of about 8–10 samples taken from time to time but the confidence intervals are not shown mainly because of very small difference between different types at each point. Standard

deviations and mean values of maximum temperature are, however, mentioned in Table 2. The values shown in each case are the mean values of about five repetitions performed during different experiments. Absorptive container can increase the water temperature by absorbing radiation while reflective container enhances the radiation effects by reflecting and returning radiation into water sample.

There is almost exponential rise in water temperature with a maximum value in the afternoon after which it drops with decreasing radiation. Temperature is affected by weather conditions and is directly proportional to sunlight intensity. Thus, moderate weather conditions are not fit for SODIS as far as the thermal effects of sunlight are considered alone since the maximum temperature attained is less than 50°C which is considered as the effective temperature for microbial removal. Relatively low temperature under weak sunlight conditions may have negative effects on SODIS by activating or helping microorganism's growth, if the synergistic effects of thermal and UV-radiations are ignored. As shown in Figure 4c, during strong weather conditions, the maximum temperature is above 50°C only in absorptive containers and hence the thermal effects can be thought to contribute for microbial inactivation.

THE EFFECTS OF DIFFERENT BACKING SURFACES UNDER DIFFERENT WEATHER CONDITIONS

Selection of best type of container suited under different weather conditions is one of the main objectives of this

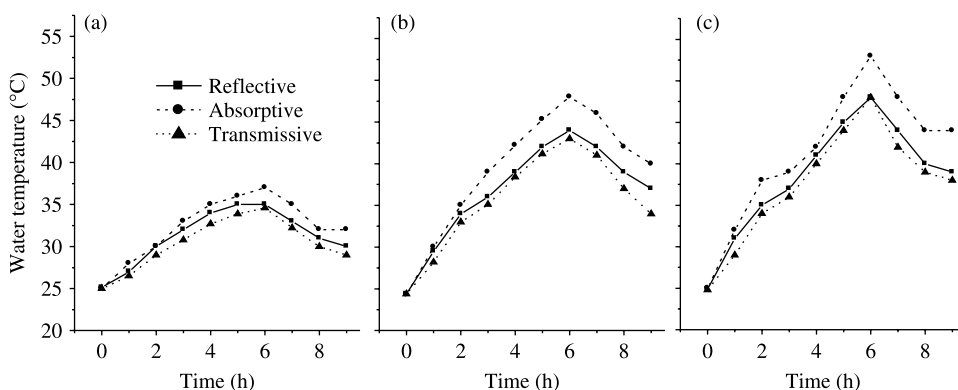


Figure 4 | Temperature changes with exposure time under; (a) Weak, (b) Moderate, and (c) Strong sunlight conditions.

study. For this, transmissive, absorptive and reflective containers are used to compare the efficiency of SODIS at weak, moderate and strong sunlight conditions as shown in Figure 5. Results are shown for TC and *E. coli* and remaining two parameters of FC and HPC are discussed only. In all these experiments, repetitions were realized for about 3–5 times and the results are presented based on the mean average values of each point. Confidence intervals are not presented on these graphs because of small difference between three types at each point; however, corresponding standard deviations for each case are mentioned in Table 3.

Figure 5a shows microbial inactivation for such comparison under weak sunlight conditions. Microbial inactivation is almost negligible for first one and half an hour which represents the lag period where the bacteria showed some resistance to solar inactivation after which exponential inactivation of all microbial parameters is observed for further 3–4 h which are peak hours of sunlight irradiation on any day and under every weather conditions. This initial lag period was double for HPC meaning about 3h. For last 2–3 h of exposure, there is not much reduction at least under weak sunlight intensity where synergistic effects are negligible because of decreasing temperature and radiation at this stage.

Reflective container showed maximum removal which is about 50 and 60% for TC and FC/*E. coli* respectively, representing FC/*E. coli* more sensitive to optical inactivation than TC. The difference with other types of backing surfaces is about 5–10% for all three parameters signifying the effects of radiation which are returned into the water solution because of the reflective backing. With insignificant thermal or synergistic effects because of low temperature, it can be concluded that UV radiation effects are prominent under weak sunlight conditions.

The microbial inactivation under weak and moderate sunlight conditions clearly demonstrate that a reflective backing can enhance the microbial inactivation, irrespective of the intensity of sunlight, most probably due to the return of UVA and short-wavelength visible radiations after reflecting from the aluminum foil, leading to the increased damage of cellular components and consequent increased inactivation of microorganisms. This finding is in agreement with earlier results (Kehoe *et al.* 2001), however in contrast with the earlier results under strong weather conditions.

Figure 5c represents the case of strong weather for similar effects of different backing surfaces. Comparing results with that of weak and moderate sunlight intensity, two significant findings are observed. First of all, initial lag stage is not observed and inactivation continued for last

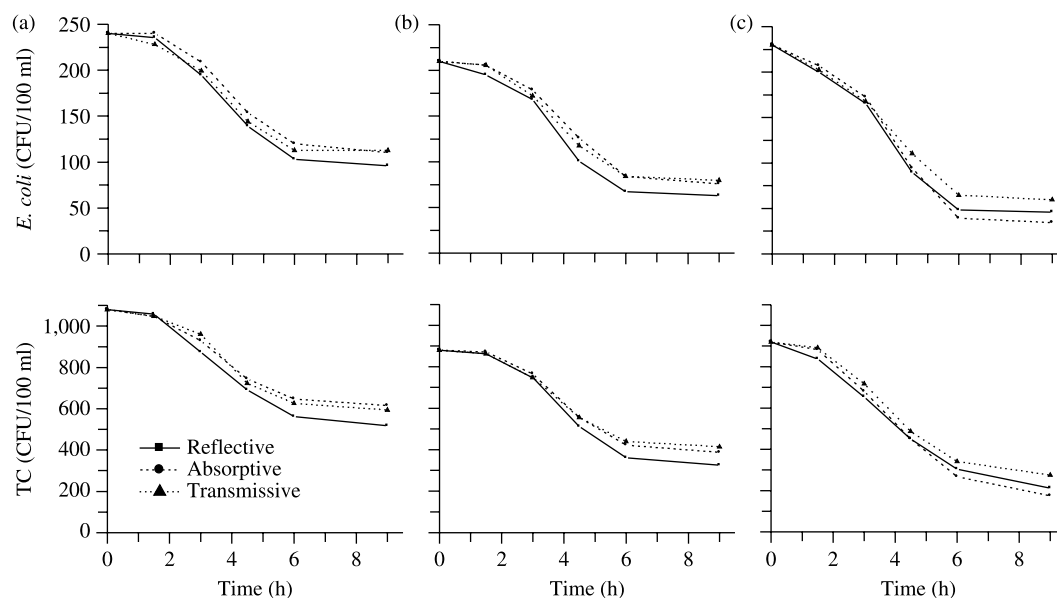


Figure 5 | Microbial inactivation with different backing surfaces of PET bottles under; (a) Weak, (b) Moderate, and (c) Strong sunlight conditions.

Table 3 | Comparison of k -values (h^{-1}) for various container types under different weather conditions

Microbial parameters	Weak sunlight			Moderate sunlight			Strong sunlight		
	Refl.	Absp.	Trans.	Refl.	Absp.	Trans.	Refl.	Absp.	Trans.
TC	0.094	0.072	0.078	0.13	0.11	0.099	0.178	0.2	0.15
Mean (S.D.)	(0.0087)	(0.009)	(0.023)	(0.02)	(0.012)	(0.009)	(0.022)	(0.02)	(0.04)
FC	0.125*	0.106	0.114	0.151	0.14	0.125	0.214	0.237	0.18
Mean (S.D.)	(0.018)	(0.02)	(0.018)	(0.018)	(0.024)	(0.038)	(0.059)	(0.07)	(0.1)
<i>E. coli</i>	0.12	0.1	0.1*	0.157	0.13	0.128	0.21	0.246	0.17
Mean (S.D.)	(0.027)	(0.031)	(0.032)	(0.022)	(0.03)	(0.042)	(0.042)	(0.039)	(0.08)
HPC	0.08	0.08 [†]	0.085*	0.11 [†]	0.075	0.088	0.13	0.11*	0.125
Mean (S.D.)	(0.04)	(0.052)	(0.05)	(0.03)	(0.015)	(0.041)	(0.06)	(0.06)	(0.041)

* $R^2 = 0.87-0.89$.† $R^2 = 0.85-0.87$.Note: S.D. Standard Deviation for $n = 3-5$.

2–3 h except for *E. coli*. In case of strong sunlight, SODIS efficiency improved by 25% with a radiation difference of three times with weak sunlight conditions. The second important difference is that of best backing surface which is absorptive due to thermal effects because of maximum temperature difference at late hours although reflective containers are effective for first half of exposure time as shown in Figure 5b. This proves the thermal effects although inactivation difference is not very significant. Transmissive containers shows poor performance where by both effects of radiation and temperature are not concentrated as compared to reflective or absorptive types.

The microbial inactivation followed first-order kinetics, based on log-linear plots. Table 3 presents the quick comparison of all four microbial parameters among three weather conditions with various container types. Among different container types, reflective container showed the best results for all microbial parameters at weak sunlight conditions while absorptive containers seems to be best at strong sunlight conditions due to synergistic thermal effects. The calculated ' k ' values for *E. coli* are not in accordance with the recent findings (Wegelin *et al.* 1994; Rijal & Fujioka 2003) mainly due to the different experimental conditions involved and also it contradicts the reported decay constant for TC (Dan *et al.* 1997). One main reason could be the use of rainwater as source water in this study. ' k ' values for TC under strong sunlight conditions, however, were in accordance with the findings of Sommer *et al.* i.e. about $0.2-0.3 \text{ h}^{-1}$ (Sommer *et al.* 1997).

The better results of absorptive type PET bottles under strong weather conditions are also in accordance with the previous findings (Sommer *et al.* 1997). The temperature enhancement observed in absorptive type due to black-backing was mainly due to the strong sunlight intensity, which means that synergetic interaction between thermal and optical effects that occurred due to high temperature, above 50°C , will not occur under weak and moderate sunlight intensities. Therefore, the absorptive type PET bottles should be the best choice only when the sunlight irradiance is higher than at least $500-600 \text{ W/m}^2$. For irradiance less than these values, reflective type backing should be used for the best performance of SODIS.

RADIATION EFFECTS BY USING REFLECTIVE CONTAINERS UNDER ALL WEATHER CONDITIONS

Figure 6 shows the comparison based on sunlight intensities by using reflective containers. Results are shown for the mean calculated values while error bars are shown based on the repetitions of the experiments when about 3–5 samples are analyzed for several points. SODIS exhibited three stages of treatment depending upon the sunlight intensity with middle stage being critical. Initial lag period showed persistent nature of non-fecal organisms against sunlight effects for about couple of hours at weak and moderate weather conditions or most probably against UV attacks at low wavelengths. Organic matter, however, showed

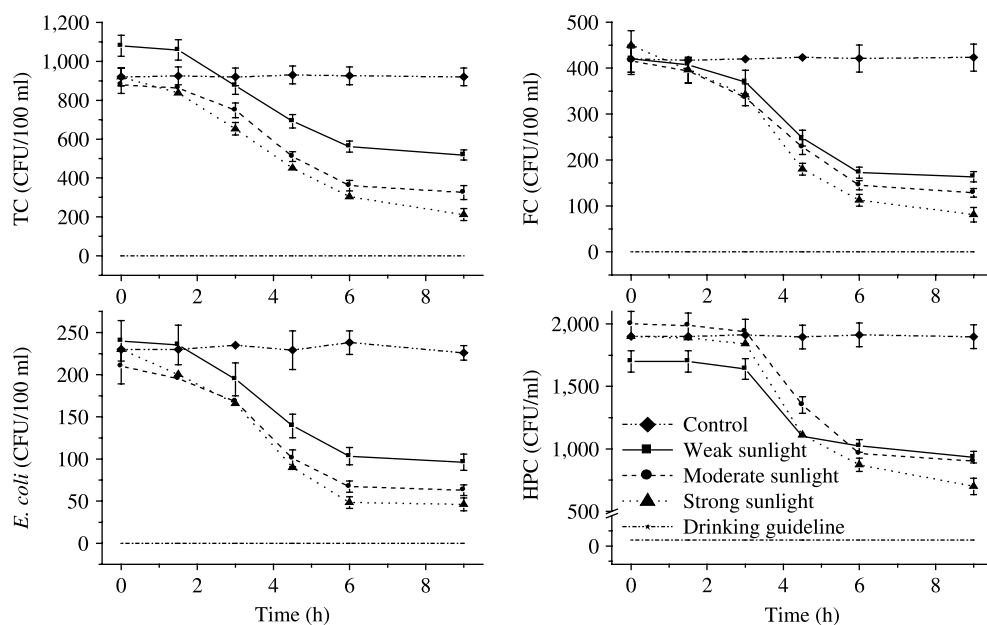


Figure 6 | Microbial inactivation under different weather conditions using only reflective containers.

prolonged resistance even at strong sunlight or against full UV range as is obvious from HPC results.

SODIS effects are critical during middle stage at peak radiations for mild or cold weathers but for hot weather SODIS is even effective in afternoon periods except for *E. coli*. SODIS proved to be ineffective for complete disinfection even at strong sunlight radiations, however, direct correlation of radiation and inactivation is observed and TC removal increased from 50 to 80% with a three fold increase in sunlight radiation. Furthermore, inactivation difference of TC and FC or *E. coli* decreased from about 10% under weak sunlight to about 3% for strong sunlight intensities proved lethal thermal effects for fecal organism. No parameter met the potable guideline values, 0 CFU/100 ml for TC, FC and *E. coli* and 10 CFU/ml for HPC, however, the relative removal of indicator microorganism was $HPC < TC < FC/E. coli$.

Microbial inactivation is directly related with sunlight intensity, which is very obvious because of the strong optical effects of short wavelength components of sunlight in the solar UV (300–400 nm) especially those in the UVB range (300–320 nm). Because UVB 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

conducted experiments. All the results showed the same tendency signifying a close relationship between sunlight intensity and time required to inactivate microorganisms. Temperature measured inside the bottles leads to the conclusion that it is not a predominant factor in the elimination of microorganisms, and it is mainly radiations 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).

THE EFFECTS OF INITIAL PH AND TURBIDITY VALUES

Among number of operating parameters affecting SODIS, the effects of only two basic physicochemical parameters including pH and turbidity were evaluated. All rainwater samples were kept undisturbed with an air space in reflective PET bottles for air circulation to achieve aeration (Reed 1997). After having set the initial values, pH and turbidity values along with DO and EC were measured at regular time intervals of 2 h throughout the exposure time (results are not shown) and these measured values almost remained constant with little or no difference.

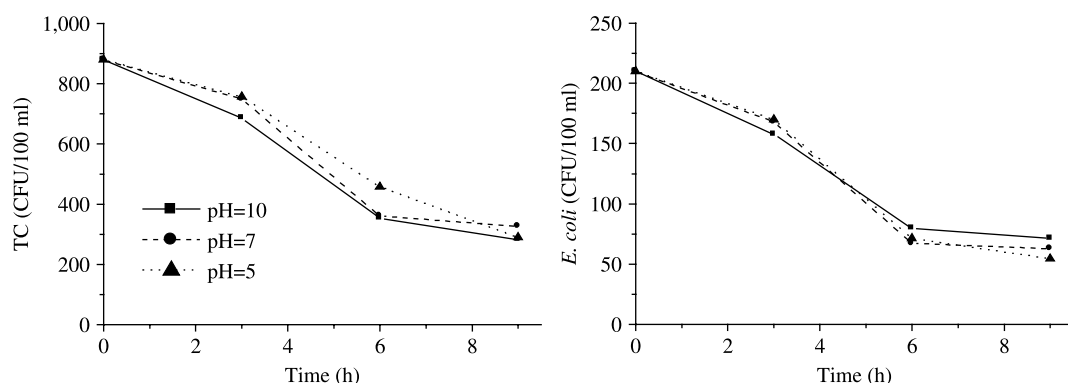


Figure 7 | Microbial changes at different initial pH values.

Figure 7 shows the microbial changes for different initial pH values. Almost 3–5 repetitions were realized with mean values in graphs and corresponding standard deviations for each case as mentioned in Table 4. Three pH values were chosen representing acidic, neutral and basic conditions using diluted HCl and NaOH for pH adjustment and comparison is performed at moderate sunlight.

Rainwater with acidic pH offered better efficiency for SODIS for all microbial parameters except for TC showing non-fecal organisms are not affected much by pH. These findings differed from previous studies showing no effects of initial pH values on *E. coli* inactivation rates (Rincon & Pulgarin 2004). For quick comparison of all four microbial parameters among different initial pH values, 'k' values are presented in Table 4. Rainwater with acidic pH has higher 'k' value, although not significant for TC.

Microbes are sensitive to the hydrogen ion concentration but most bacteria grow best around neutral pH

Table 4 | Comparison of k-values (h^{-1}) for different initial pH values

Microbial parameters	pH values		
	10	7	5
TC	0.136	0.124	0.128
Mean (S.D.)	(0.028)	(0.022)	(0.02)
FC	0.151	0.145	0.184
Mean (S.D.)	(0.023)	(0.019)	(0.03)
<i>E. coli</i>	0.131	0.151	0.165
Mean (S.D.)	(0.026)	(0.024)	(0.02)
HPC	0.088*	0.091	0.13*
Mean (S.D.)	(0.029)	(0.031)	(0.06)

* $R^2 = 0.87-0.89$.

values (6.5–7.0). Low pH may be beneficial from the standpoint of protein nutrition but it may increase inactivation rate by presenting a significant additional stress to the cell, for example by requiring it to expend energy maintaining pH homeostasis, thus accelerating the depletion of Adenosine triphosphate (ATP), the main energy storage and transfer molecule in the cell, and/or reducing equivalents. Biosynthetic reaction comes to halt as a consequence of ATP depletion and there is a loss of cell's ability to maintain its 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 radical, superoxide radical anion, hydrogen peroxide, and singlet oxygen, and/or repair damaged Deoxyribonucleic Acid (DNA), facilitating more rapid photoinactivation. ROS damage external structures of microorganisms, such as cell membranes.

There is no health-based guideline for pH and Annual Report of the National Health and Medical Research Council in 1996 indicates that the consumption of food or beverages with low (2.5) or high pH (11) does not result in adverse health effects. The taste of water at pH of 5 is also not bad and it is at least much better than commercially available beverages with much less pH values.

Also, the efficiency of SODIS was compared with different turbidity values as shown in Figure 8. Once again, experiments were repeated and the corresponding standard deviations are mentioned in Table 5. Rainwater collected from underground storage tank had turbidity less

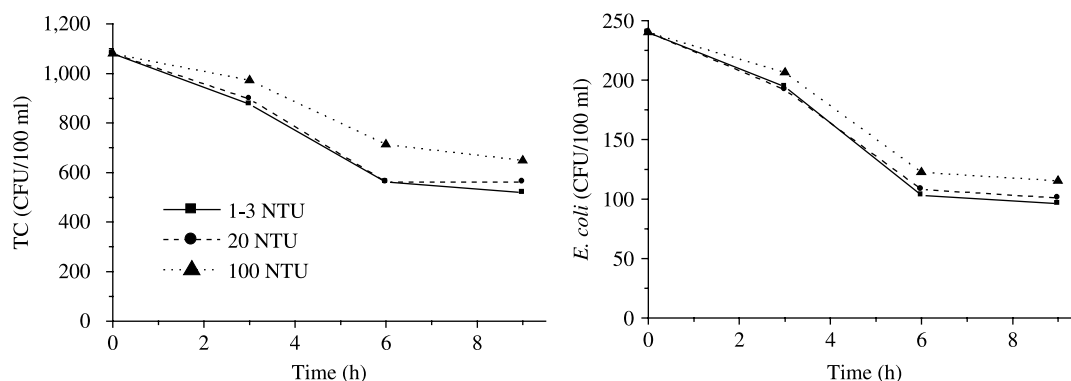


Figure 8 | Microbial changes at different initial turbidity values.

than 5 NTU and for comparison purposes higher values were adjusted by adding kaolin. Undisturbed, reflective containers were used under weak sunlight conditions.

Samples with low turbidity showed better results although this difference is insignificant up to may be 20 NTU. However, SODIS showed poor performance for all microbial parameters at higher turbidity due to the loss of UV due to scattering & absorption by particles. 'k' values for higher turbidities are less as compared with low turbidity values for all microbial parameters as shown in Table 5.

High turbid water may show substantial temperature increase due to absorption of solar radiation by suspended particles and hence it may help in higher disinfection efficiency (Joyce *et al.* 1996). The contrary results, however, showed that rainwater failed to reach temperatures high enough for better disinfection efficiency under weak

weather conditions. Higher turbidity may also result in microbial re-growth if appropriate sunlight irradiance and hence moderate temperatures are not reached.

In all experiments, PET bottles were kept undisturbed with an air space of about 15% of bottle volume. For comparison purposes based on sample volume and bottles conditions, two more PET bottles; one full with no air space kept undisturbed and other one spaced with regular shaking were used. Temperature effects are negligible due to weak sunlight and only optical inactivation is effective. Comparing both spaced bottles, SODIS showed better performance for bottles without shaking, contrary to the recent findings (Rijal & Fujioka 2003).

MICROBIAL RE-GROWTH

Another factor that was needed to be considered was that of microbial re-growth or reactivation of microorganisms if water is to be kept for several hours after exposure. Undisturbed reflective containers were used at weak and moderate sunlight with different initial turbidity values at neutral pH and different initial pH values at low turbidity, respectively. Rainwater is stored in dark at room temperature for one week after exposure and microbial changes are observed for TC and *E. coli* as shown in Figure 9. Experimental repetitions were realized only for few critical samples for about 3–5 times and the results are presented based on the mean average values of each point and the error bars are shown based on the difference of different values at each point.

Table 5 | Comparison of k-values (h^{-1}) for different initial turbidity values

Microbial parameters	Turbidity values, NTU		
	2–3	20	100
TC	0.088	0.081*	0.06
Mean (S.D.)	(0.008)	(0.008)	(0.01)
FC	0.12*	0.116*	0.1
Mean (S.D.)	(0.02)	(0.018)	(0.01)
<i>E. coli</i>	0.113	0.106	0.09
Mean (S.D.)	(0.029)	(0.04)	(0.018)
HPC	0.076*	0.086*	0.067†
Mean (S.D.)	(0.036)	(0.03)	(0.038)

* $R^2 = 0.87-0.89$.

† $R^2 = 0.80-0.85$.

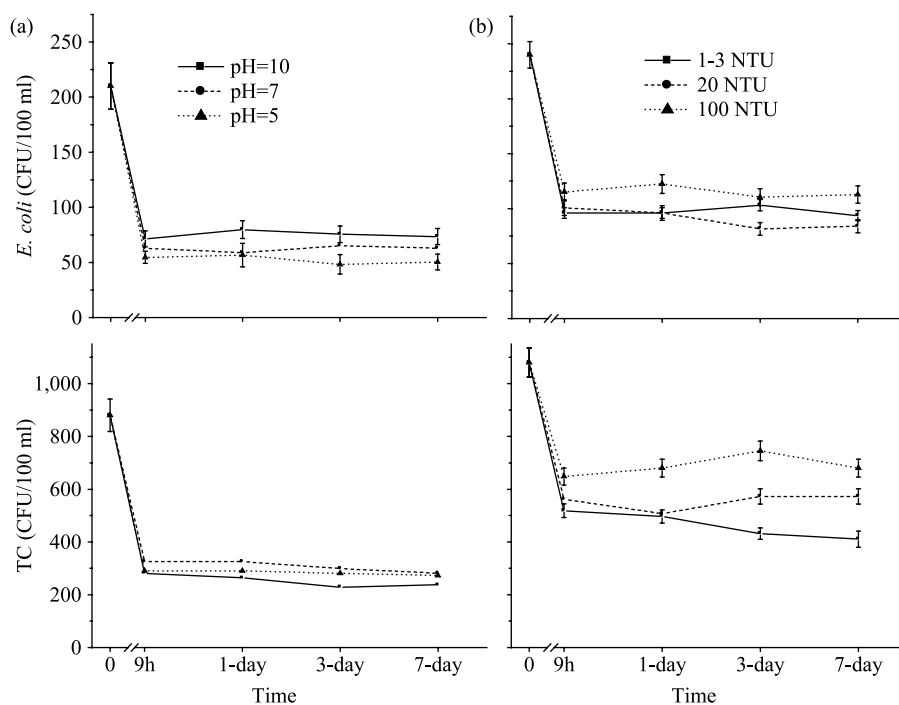


Figure 9 | Microbial re-growths for different initial; (a) pH values under moderate sunlight, and (b) turbidity values under weak sunlight.

Microbial re-growth was not observed after one day except for TC at high turbidity and for *E. coli* at high turbidity and basic pH. Rainwater with acidic or neutral pH and low turbidity up to 20 NTU did not pose any problem of microbial re-growth. *E. coli* re-growth was not observed after one day even for higher turbidity values. This re-growth might be due to the repair of partially damaged microorganisms showing negative/reversal effects of SODIS requiring additional measures to control microbial re-growth.

The presence of TC in stored samples indicates the resistance of this group to stressful conditions produced by attack of UV at higher turbidities. These organisms recover by means of some of the documented cellular repair mechanisms such as photoreactivation etc. (Kim & Sundin 2001).

Finally, using PET bottles for SODIS, may not cause any health risk and traces of the plasticizers, di(2-ethylhexyl) adipate and di(2-ethylhexyl) phthalate, leaching 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 water with regard to the aldehyde, organic photoproduct,

and additive or phthalate concentrations even for water stored up to 3–4 months (Wegelin *et al.* 2001). Hence PET bottles are considered safe and adequate for SODIS.

CONCLUSIONS

SODIS efficiency is evaluated for rainwater disinfection for possible applications in developing countries. The effects of two most important and critical parameters i.e. radiation and temperature were evaluated under different weather conditions. Fecal organisms proved to be more sensitive to optical inactivation under weak sunlight with 50–60% disinfection efficiency which increased to about 80% under strong sunlight due to the synergistic effects of thermal and optical inactivation.

Also, PET bottles with different backing surfaces were used to maximize the effects of radiation and temperature for optimizing SODIS. Under weak and most probably at moderate sunlight intensities, ranging from less than 200 W/m² up to 600–700 W/m², reflective containers are best solutions because of insignificant thermal effects, although incomplete disinfection, while in strong weather,

categorized as sunlight intensity above 700 W/m^2 for at least 8–10 h, absorptive containers are the best choices since thermal or synergistic effects are included.

Disinfection did not improve significantly by changing initial pH and turbidity values, although, SODIS is optimized at acidic pH and less turbidity keeping bottles undisturbed with some air space. Microbial inactivation followed exponential decay after initial lag period and maximum value of first-order reaction rate constant range is less than 0.1 h^{-1} to above 0.2 h^{-1} . The problem of microbial re-growth was also observed for higher pH and turbidities.

SODIS seems to be ineffective for complete disinfection under the investigated experimental conditions even at strong weather conditions and more exposure time is needed especially at moderate weather conditions for efficient SODIS. Another limitation of SODIS is the microbial re-growth which requires more investigations on microbial re-growth and control if water has to be stored for longer times before use. To overcome the SODIS inefficiency and for larger volumes, simple devices for concentrating sunlight radiations and enhanced temperature effects can be used. Research is also needed on other commonly available additives for rapid SODIS under moderate or even at weak sunlight conditions and for routine disinfection in larger and more practical containers. Finally, with maximum possible storage of rainwater in storage tank and using some means to accelerate SODIS process (by using simple devices to concentrate radiation effects by reflection, using very cheap heat resistant bag for enhancing thermal effects, and by using some commonly available food products to achieve low pH), rainwater can be disinfected completely and used for potable purposes. Initial microbiological investigations and SODIS results revealed interesting findings providing the opportunities of future research in the area of RWH systems and SODIS applications for disinfection of stored rainwater to be used as potable supplies in developing countries.

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