Short Communication

Effect of source water quality on solar disinfection rate under multiple experimental conditions

M. Mansoor Ahammed and Shilpa Dave

ABSTRACT

Water samples from four different sources of varying physico-chemical and microbial quality with their naturally occurring microorganisms were exposed to sunlight in polyethylene terephthalate bottles under similar conditions. Up to 3-$\log_{10}$ reduction of total coliforms (TC) was observed during a 6-h exposure period under weak/moderate radiation conditions (<600 W/m^2). Complete inactivation of TC was not achieved in 6 h of exposure for waters with larger initial TC such as river water (1×10^3 most probable number [MPN]/100 mL) and treated municipal wastewater (2×10^5 MPN/100 mL) under these conditions. Heterotrophic bacteria showed lower inactivation rates than did TC. The inactivation rate for spiked *Escherichia coli* was faster than for naturally occurring coliforms. Further tests with compound parabolic collectors showed that complete inactivation of naturally occurring TC could be achieved within 6 h of exposure for all the natural waters tested. The results of the study thus indicate the need to use naturally occurring organisms in testing the effectiveness of solar disinfection, and the importance of source quality on the inactivation rates of microorganisms.

Key words | household water treatment, solar disinfection, source water quality, total coliforms

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INTRODUCTION

One of the most promising household water treatment technologies is solar disinfection. In solar disinfection, microbiologically contaminated water stored in transparent polyethylene terephthalate (PET) bottles or glass bottles is exposed to sunlight for at least 6 h. Solar disinfection has been demonstrated to be effective against a range of microorganisms (Berney *et al*. 2006; McGuigan *et al*. 2012). While the impact of water quality parameters, such as turbidity and pH, on solar disinfection is well known, recent studies have suggested that different organic and inorganic species also have effects on solar disinfection. Since natural water contains a range of organic and inorganic species, tests need to be conducted to assess the suitability of solar disinfection for treatment of water from different sources. Only a few studies have addressed this (Martin-Dominguez *et al*. 2005; Rincon & Pulgarin 2007). Some of these studies with natural waters employed test waters with spiked organisms because of the initial low concentration of test organisms (Rincon & Pulgarin 2007; Ubomba-Jaswa *et al*. 2010).

One of the limitations of solar disinfection is the long exposure period, often in excess of one day, required to achieve complete inactivation of different microorganisms (SANDEC 2011). Use of compound parabolic collectors (CPCs) is generally adopted to accelerate the disinfection rate (Polo-Lopez *et al*. 2011). The objective of the present study was to compare solar inactivation of naturally occurring microorganisms in four different water sources of varying characteristics. Tests were also conducted to compare inactivation rates of naturally occurring organisms to seeded organisms in natural waters. In addition, the efficacy of CPCs in enhancing the solar inactivation rate of naturally occurring organisms was investigated.

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MATERIALS AND METHODS

Materials

Commercially available two-litre transparent PET bottles of circular cross section (diameter 9 cm) were used in all tests. CPCs with a concentration factor of 1 were constructed (Figure 1(a)). Highly reflective aluminium composite panel sheet was used to make the reflectors which were supported by polyurethane foam at their base (Figure 1(b)). The CPCs were fixed to a support system which could accommodate nine bottles at a time (Figure 1 (c)). It was inclined at 21° (equal to the local latitude) to maximize solar radiation. Water samples from four different sources, as follows, were used in the tests: dug well (pH 6.8 ± 0.3; turbidity 3.4 ± 0.4 nephelometric turbidity units [NTU]; conductivity 750 ± 60 μS/cm; total coliforms [TC] 45 ± 11 most probable number [MPN]/100 mL; heterotrophic plate count [HPC] $9.0 \pm 3.3 \times 10^3$ colony-forming units [CFU]/ml; dissolved oxygen [DO] 3.5 ± 0.4 mg/L); river water (pH 7.8 ± 0.2; turbidity 23.6 ± 1.3 NTU; conductivity 540 ± 40 μS/cm; TC $1.1 \pm 0.4 \times 10^3$ MPN/100 mL; HPC $1.3 \pm 0.7 \times 10^4$ CFU/mL; DO 6.3 ± 1.2 mg/L); roof-harvested rainwater (pH 7.1 ± 0.2; turbidity 5.8 ± 0.3 NTU; conductivity 110 ± 9 μS/cm; TC 110 ± 30 MPN/100 mL; HPC $8.0 \pm 2.2 \times 10^3$ CFU/mL; DO 5.7 ± 0.8 mg/L) and treated municipal wastewater (pH 8.0 ± 0.1; turbidity 34.0 ± 1.3 NTU; conductivity 660 ± 65 μS/cm; TC $1.7 \pm 0.9 \times 10^5$ MPN/100 mL; HPC $4.5 \pm 1.3 \times 10^5$ CFU/mL; DO 2.3 ± 0.1 mg/L). Dug well water, rainwater and river water are the common water sources in developing countries. Treated wastewater was included in the study to investigate whether complete inactivation can be achieved for the high levels of organisms present in it.

In the seeded tests, *Escherichia coli* (ATCC No. 4157) concentrate was added to natural water samples to obtain the desired initial concentration. The concentration of TC was estimated by a multiple-tube fermentation method. Enumeration of viable *E. coli* was conducted by plate count test using MacConkey agar. Heterotrophic bacteria were enumerated using the pour plate method with plate count agar. All the tests were conducted in accordance with the techniques described by Standard Methods (APHA/AWWA/WEF 1998).

Experimental procedure

Three sets of experiments were carried out in the present study. The first experiment was aimed at comparing the solar disinfection rates of naturally occurring microorganisms in different test waters. In the second experiment, inactivation of seeded *E. coli* in different test waters was studied. In this test, water samples were sterilized by autoclaving before spiking with *E. coli* to an initial concentration of ~ 10^6 CFU/mL. Initial DO of 6 mg/L was used in this test for all the samples. This was achieved by aerating the water samples prior to solar exposure. For the third experiment, solar disinfection rates were compared for samples of river water and roof-harvested rainwater with their naturally occurring microorganisms in PET bottles, either placed on CPCs or not placed on CPCs. Standard solar disinfection procedure was followed in all the tests (SANDEC 2011). The bottles were exposed to sunlight in duplicate on the rooftop during January–February 2011 from 09:30 onwards for 6 h. Control bottles indicated a

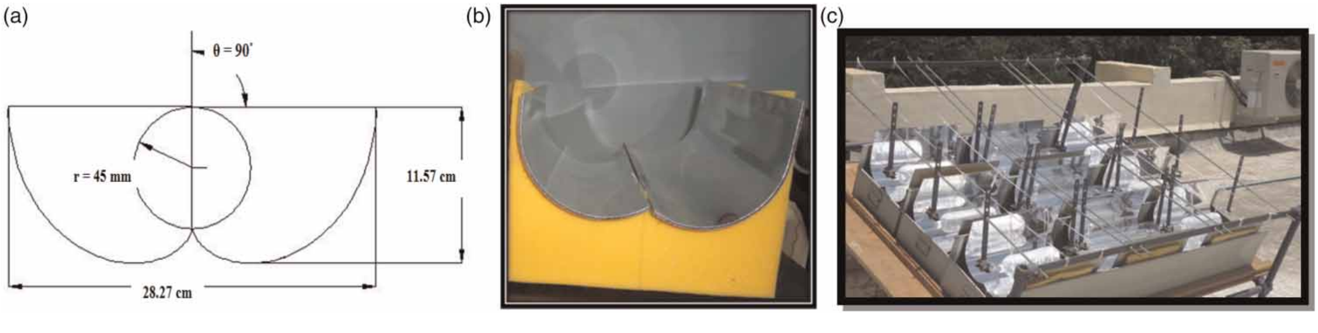

Figure 1 | Details of the CPC system: (a) dimensions, (b) single CPC, (c) support system for the CPCs.

maximum microbial reduction of 0.2 $\log_{10}$ for different waters tested after 6 h. Global solar intensity was measured (in W/m^2) using a pyranometer with spectral range of 300–3000 nm. Water and ambient temperatures were recorded using a digital thermometer at regular intervals (15–30 min). DO was measured by a DO meter (Elico, India) just before exposure to sunlight and also at the end of the exposure period.

RESULTS AND DISCUSSION

Disinfection of naturally occurring microorganisms

Figure 2 presents the variation in concentration of TC and HPC bacteria in different water samples along with the intensity of solar radiation on a day with weak/moderate solar radiation with a mean value of 512 W/m^2 (Figure 2(b)). Similar tests were conducted on two more days with mean solar intensity values of 543 and 562 W/m^2. The results on all three days followed similar trends. Complete inactivation of TC was observed within 4.5 h of solar exposure for dug well water and roof-harvested rainwater whereas 6.0 h of exposure was not sufficient for complete inactivation of TC in the case of river water and treated municipal wastewater, presumably due to high initial concentration of coliforms present in these two water samples (Figure 2). During this test, the average water temperature observed during the 6-h exposure period in four different water samples varied in the range of 36.5–38.2 °C, with river water exhibiting the highest average temperature (Figure 2(a)). The maximum water temperature during the exposure did not exceed 40.5 °C in any of the samples tested. It is known that synergistic action of UV radiation and temperature generally occurs at temperature above 45 °C (Berney *et al.* 2006).

Figure 2(c) shows that complete inactivation of TC did not occur in the case of treated municipal wastewater and river water. About 3-$\log_{10}$ reduction was observed for treated wastewater during the 6-h exposure period, while a lower reduction of 2.3 $\log_{10}$ occurred in the case of river water. This difference could possibly be attributed to the variation in characteristics such as turbidity, and different dissolved species, as well the initial TC count. It may be noted that the initial concentration of TC in treated

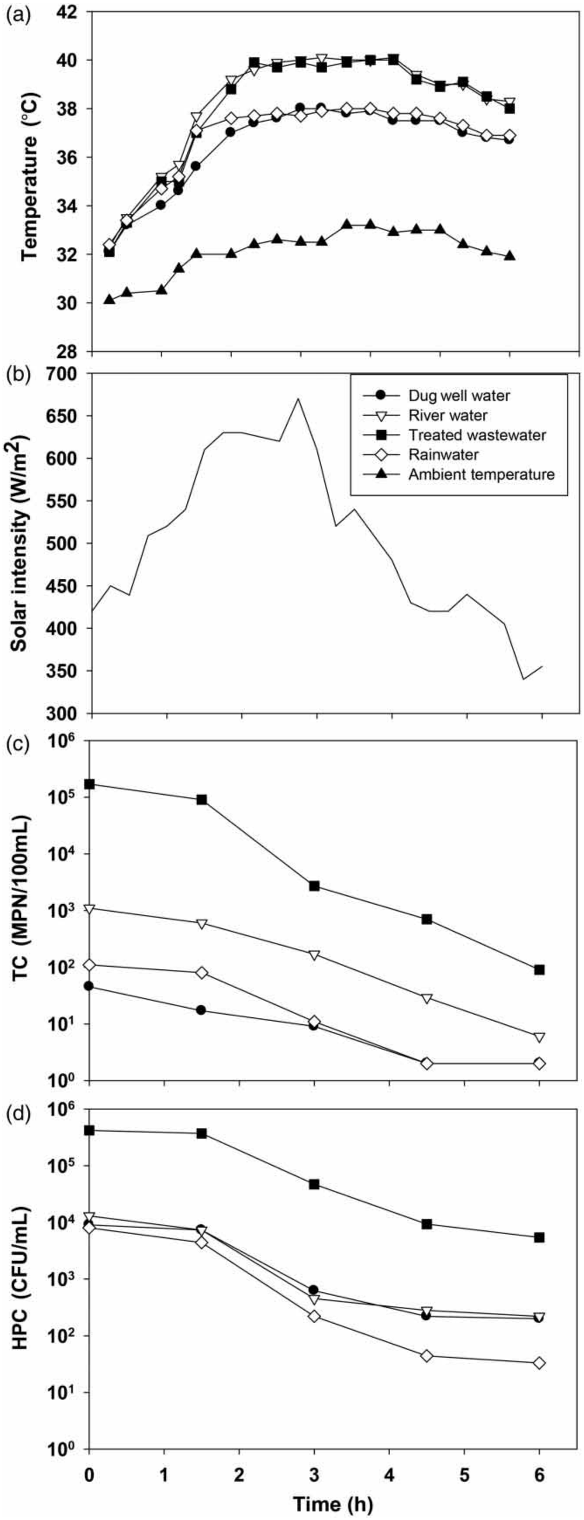

Figure 2 | Inactivation of TC and HPC bacteria in different water samples tested. The mean solar intensity in this test was 512 W/m^2. Each point in the TC and HPC curves represents the average of two values. Total coliform concentration <2 MPN/100 mL was plotted as 2 MPN/100 mL.

wastewater was about 100-fold greater than that in river water. It has been reported that the rate of disinfection is higher for a larger initial concentration than for smaller concentration (Rincon & Pulgarin 2007), though a low bacterial load requires less time to reach the detection limit as observed in the case of dug well water and roof-harvested rainwater (Figure 2(c)).

Figure 2(d) presents the reduction of HPC with time. The pattern of inactivation rates of TC and HPC in the same water sources shows that heterotrophic bacteria are much more resistant to solar inactivation than TC. Greater resistance of HPC to solar inactivation has been reported by previous researchers as well (Meera & Ahammed 2008; Amin & Han 2009).

Inactivation of *E. coli* in natural waters

Figure 3 shows inactivation of spiked *E. coli* in different natural waters. Complete inactivation of *E. coli* did not occur in any of the test waters due to high initial count, and rate of inactivation varied widely between different water samples. A larger reduction of >4 $\log_{10}$ occurred in the case of dug well water and rainwater during 6 h of exposure. In the case of river water and treated wastewater, a lower *E. coli* reduction of ~3 $\log_{10}$ was observed (Figure 3). Tests conducted on another two days with mean solar intensity values of 534 and 587 W/m^2 showed similar trends.

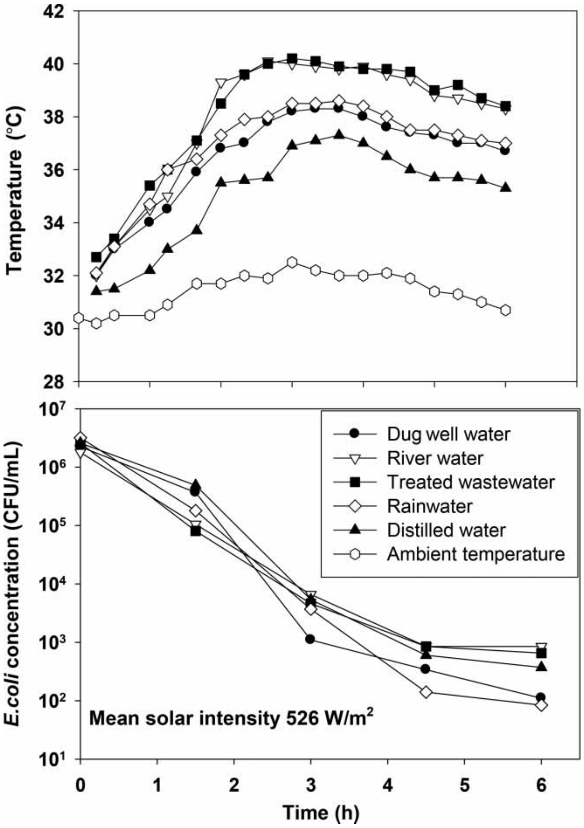

Figure 3 | Inactivation of spiked *E. coli* in different natural waters. Each data point represents average of two samples.

A lower disinfection rate was observed in experiments with distilled water compared with samples obtained from the dug well water and the harvested rainwater. This may be explained on the basis of the differences in water characteristics. While distilled water had a turbidity ~ 0 NTU, the dug well water and harvested rainwater had average turbidity values 3.4 and 5.8 NTU, respectively. This resulted in different mean temperature values in the water samples. The mean temperatures were 1.4 and 1.8 °C higher in dug well water and harvested rainwater, respectively, than in distilled water during solar exposure. Scattering and absorption of light by the turbid agents, leading to trapping of heat within the bottle results in increased water temperature (Meera & Ahammed 2008; Ubomba-Jaswa *et al*. 2010). Though these temperature differences were not substantial, they might have contributed to the increased inactivation rates. While a synergy between thermal and optical action is generally expected above 45 °C (Berney *et al*. 2006), smaller increases in temperature have been shown to increase inactivation rates of microorganisms in the range of 25–45 °C (Heaselgrave *et al*. 2006). Though a larger mean temperature was observed for the other two water samples (river water and treated wastewater) also (Figure 3), *E. coli* inactivation rates were lower than that in distilled water. It may be noted that these two water samples had relatively high average turbidity values (23.6 and 34.0 NTU, respectively), and the advantage due to higher temperature may not be enough to compensate for the reduction of solar penetration through the water samples. In this test, since the initial bacterial concentration and DO level, and solar exposure conditions were kept similar for all the test waters, the observed differences in inactivation behaviour can be primarily attributed to physico-chemical characteristics of the test waters, such as concentration of different dissolved species and turbidity.

A comparison of the inactivation rates of spiked *E. coli* (experiment 2) with that of naturally occurring coliforms (experiment 1) in the same test waters indicates the difference in the rate of inactivation for the two types of organisms. For example, in the case of river water, TC reduction was 2.3 $\log_{10}$ units compared to 3.7 $\log_{10}$ reduction for *E. coli,* though the initial concentration of *E. coli* was much larger than that of TC. Though experiments 1 and 2 (Figures 2 and 3, respectively) were conducted on different days, the average solar intensity for these days were close (512 and 526 W/m^2), thus suggesting that the observed differences in inactivation rates were not due to the differences in solar intensity. This indicates that naturally occurring microorganisms are more resistant to solar disinfection than spiked organisms. It is plausible that the organisms in natural waters are adhering to particles, and it is known that particle-adherent microorganisms are more resistant to disinfection processes (Wu *et al.* 2005). The study thus indicates the need for using naturally occurring organisms in testing the effectiveness of solar disinfection process.

Inactivation of TC in CPCs

Figure 4 shows that complete inactivation of TC was achieved in river water with the use of CPC for 6 h even at a low/moderate solar intensity of 546 W/m^2. In the case of rainwater, though complete inactivation of TC was observed in both CPC and PET bottles, it was achieved within 4.5 h in CPC while it took 6.0 h in PET bottles. The test was repeated on two more days with different solar intensity values, and gave similar results. These observations clearly show the effectiveness of CPCs in enhancing the inactivation rates.

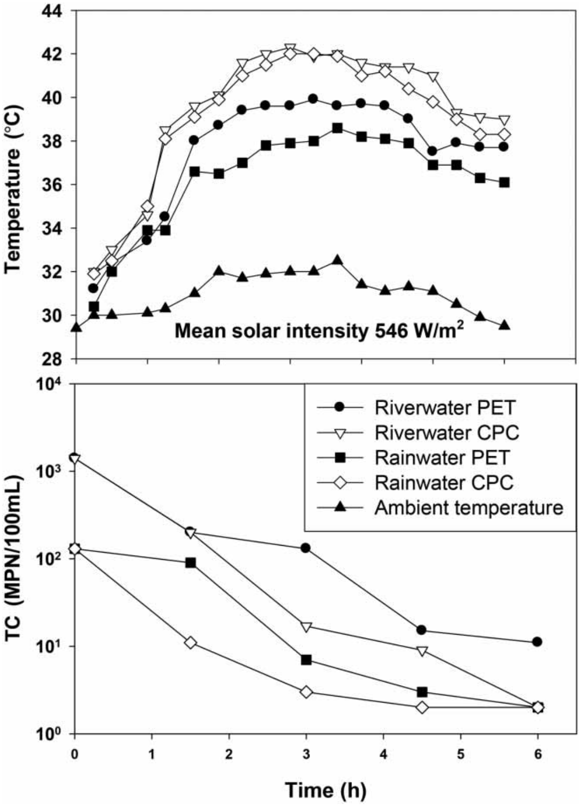

Figure 4 | Comparison of inactivation of TC in river water and rainwater with and without CPC. Each point represents average of two samples. Total coliform concentration of <2 MPN/100 mL was plotted as 2 MPN/100 mL.

CONCLUSIONS

This study demonstrates that source water quality plays important role on the inactivation rates of different indicator organisms during solar disinfection. Exposure for 6 h under weak/moderate radiation conditions (<600 W/m^2) was not enough to achieve complete inactivation of TC in highly contaminated waters with initial concentration greater than 10^3 MPN/100 mL. Lower inactivation rates (up to 1.2 $\log_{10}$ units) were observed for HPC than for TC. The use of CPCs resulted in substantial increase in rate of inactivation (up to 1 $\log_{10}$ unit). The study also indicates the need to use naturally occurring organisms in testing the effectiveness of solar disinfection process.

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