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Capability of 19-L polycarbonate plastic water cooler containers for efficient solar water disinfection (SODIS): Field case studies in India, Bahrain and Spain

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Abstract

The small treated volume (typically ~2 L) associated with polyethylene terephthalate (PET) bottles that are most frequently used in solar water disinfection (SODIS), is a major obstacle to uptake of this water treatment technology in resource-poor environments. In order to address this problem we have conducted a series of experiments in Spain, Bahrain and India, to assess the efficacy of large volume (19 L) transparent plastic (polycarbonate) water cooler/dispenser containers (WDCs) as SODIS reactors to inactivate *Escherichia coli* and *Enterococcus faecalis*, under strong natural sunlight. Reduction values of 6 $\log_{10}$ units (LRV = 6.0) have been observed using WDCs in each location. Additional comparisons between 2-L PET bottles and 19-L indicate that WDCs provide bacterial inactivation similar in both systems. SODIS disinfection experiments in turbid water (100 NTU) in both reactors showed very good inactivation efficiency. LRVs of 6 were obtained for *E. coli* in both WDC and 2-L PET bottles, and in the case of *E. faecalis* LRV = 5 and 6 were observed in Spain and Bahrain, respectively. These studies demonstrate that under conditions of strong sunlight and mild temperature, 19 L water dispenser containers can be used to provide adequate volumes of SODIS treated water for households or larger community applications such as schools or clinics in the developing world.

Keywords: SODIS; PET bottle; Water dispenser container; *E. coli*; *E. faecalis*

1. Introduction

In developing countries, numerous people are without any access to safe drinking water. Since water is required to maintain life, people often have no alternative but to use contaminated drinking water despite the associated risk

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of waterborne disease. According to WHO/UNICEF Joint Monitoring Programme (JMP) for Water Supply and Sanitation, as of 2014, 748 million people lack access to an improved drinking water source and 547 million of these will not have gained access by 2015 if the trends remain unchanged (WHO/UNICEF, 2014). Furthermore, the progress achieved was mostly in urban areas. Indeed 90% of the population, who are still without access to improved drinking water sources, are poor, marginalized, and live in rural areas (WHO/UNICEF, 2014). This lack of access to adequate and safe drinking water sources is detrimental to health as waterborne diseases, in particular diarrhea, occur after consumption of unsafe and contaminated drinking water. Globally each year there are approximately 1.7 billion cases of diarrhea and of these 760,000 children under-five years of age die as a result (WHO/UNICEF, 2014).

A number of methods are used to improve the quality of contaminated drinking water at household level in developing countries, such as boiling, filtration, flocculation or chlorination. However each treatment is associated with its own disadvantages such as taste, poor microbicidal efficacy or high cost. In many developing countries which have high solar irradiance, the use of solar radiation for water disinfection could be an appropriate technology for reducing pathogen load in water. Solar disinfection (SODIS) of drinking water is a World Health Organisation (WHO) approved point-of-use household water treatment technology which is both practical and low-cost (WHO/UNICEF, 2011). To reduce childhood morbidity and mortality, SODIS is a viable and affordable option for provision of safe water in regions which receive ample sunlight throughout the year. It only requires that water is stored in transparent containers (usually PET plastic bottles) which are exposed to direct sunlight for a minimum period of 6 h under clear sky conditions in which time waterborne pathogens are inactivated, making the water safe to drink (Conroy et al., 1996; Wegelin et al., 1994; Nalwanga et al., 2014).

The efficiency of this water treatment technique has been widely proven against different groups of microorganism such as bacteria (*Escherichia coli*, *Enterococcus* sp., *Salmonella* sp., *Vibrio* sp., etc.), fungi (*Fusarium* sp., *Candida albicans*, etc.), viruses (Bacteriophage f2, Rotavirus, Polio virus, Norovirus, etc.), protozoa (*Cryptosporidium parvum*, *Giardia*, *Entamoeba*, etc.) and helminths (*Ascaris*) (McGuigan et al., 2012). Pathogenic waterborne bacteria and pathogen indicators are the main target in studies of SODIS efficacy. Due to the entirety of its genome mapping and its status as a faecal indicator organism, the Gram negative bacteria *E. coli* is the most frequently studied species.

On the other hand, recent research has focused on the study of other enteric pathogens such as the Gram positive microorganisms *Enterococcus* sp. This bacterium poses a threat to health and is often associated with nosocomial infections (Klein, 2003; Łuczkiewicz et al., 2010). Intestinal enterococci have been used in testing contaminated water as an indicator of faecal pathogens that survive longer than *E. coli* (or thermotolerant coliforms) (WHO, 2011) Furthermore, recent contributions have shown the higher resistance of *Enterococcus faecalis* to solar photochemical treatments compared to *E. coli* demonstrating that this strain is more appropriate for validating the effectiveness of solar processes (Rodríguez-Chueca et al., 2014).

Bacterial disinfection by solar radiation is usually attributed to the synergistic effect of solar ultra-violet (UV) light and mild heating of the water by infrared spectrum (McGuigan et al., 1998; Berney et al., 2006a). The total solar spectrum reaching the Earth's surface includes wavelengths ranging from UV-B (280 nm) to infrared (1000 μm). Among these wavelengths, the most harmful for cells are in the near UV region (UV-B from 280 to 320 nm and UV-A from 320 to 400 nm), nevertheless only 4–5% of solar UV is UV-B. Cells are damaged by light absorption phenomena through biomolecules like chromophores which lead to the generation of reactive oxygen species (ROS), e.g. peroxyradicals ($HO_2^{\bullet}$), hydrogen peroxide (H_2O_2), and hydroxyl radicals ($^{\bullet}OH$). Furthermore, intracellular $^{\bullet}OH$ radical formation can be attributed to the Fenton and Haber–Weiss reactions, due to the presence of intracellular iron and hydrogen peroxide (Imlay, 2008). ROS can lead to lipid peroxidation, pyrimidine dimer formation and even DNA lesions. When ROS react with DNA, single strand breaks (SSBs) are generated as well as nucleic base modification which may be lethal and/or mutagenic. Oxidation of proteins and membrane damage is also induced (Miller et al., 1999). The disrupting of the sequence of normal cellular functions by solar disinfection has been also reported in literature using flow cytometry (Berney et al., 2006b). Adenosine triphosphate (ATP) synthesis and efflux pump activity in the cell cease shortly after the start of exposure. These are followed by a gradual loss of membrane potential and a reduction in glucose uptake ending in the loss of cultivability (Berney et al., 2006b). Regarding the influence of temperature, differences in bacterial inactivation rates at temperatures varying from 12 to 40 °C have been found to be negligible.

However, when temperature rises above 45 °C bactericidal action doubles, due to the strong synergy between UV radiation and thermal effect (McGuigan et al., 1998; Wegelin et al., 1994).

When examining factors influencing the decision whether or not to adopt SODIS one disadvantage frequently offered by potential users is the small batch unit volume of SODIS treated water provided by the plastic PET bottles that are most frequently used. Typically these plastic SODIS bottles have volumes between 0.5 L and 2.0 L. This limitation on the batch treatment volume is circumvented by using/treating several bottles simultaneously. However, this increases the time and labour routinely associated with procuring, cleaning, filling and treating the bottles. If we are to address obstacles to uptake of SODIS represented by the treated batch volume restriction, then it is incumbent upon SODIS researchers to identify a larger volume container that is readily available, low-cost and suitable for solar water disinfection.

In this study, plastic water dispenser containers (WDC) of 19 L volume are tested as candidate containers suitable for SODIS under real sunlight conditions in three very different locations (Spain, India, and Bahrain). A single WDC could provide treated water for many more users than a standard 2-L bottle can. They are readily available in most developing world peri-urban environments as containers used in office water dispensers and water coolers. Furthermore, in some developing countries they are discarded after one use rather than recycled and re-used, as is standard practice in the developed world.

The main goal of this work is to determine experimentally if WDCs can be used for solar water disinfection. This objective is achieved by demonstrating SODIS of 19 L-WDCs is effective under natural sunlight conditions across several geographical locations in Europe and Asia, specifically Spain, Bahrain and India. The disinfection efficacy of both 19 L WDC and 2 L PET plastic containers is compared on the basis of *E. coli* and *E. faecalis* inactivation. Experiments with turbid water (100 NTU) were also carried out in the 19 L_WDC with *E. coli* and *E. faecalis* to determine the feasibility of this container for field SODIS implementation with real turbid waters.

2. Materials and methods

2.1. Study location

Experiments were performed over the summer of 2013 in three different locations that experience high annual solar irradiances. Fig. 1 shows these locations which are the Plataforma Solar de Almería (PSA) in Southeast of Spain, RCSI-Medical University of Bahrain (RCSI-MUB) in Manama, Bahrain and the National Environmental Engineering Research Institute (NEERI) in Nagpur, Maharashtra State, India. The exact location of the experiments and variations in technique between sites are provided in Table 1.

2.2. Solar reactors

Two different types of reactors were used and these are displayed in Fig. 1. Polycarbonate WDC reactors of volume 19-L were used while PET containers used had a total volume of 1-L (India), 1.5-L (Bahrain) or 2-L (Spain). Dimensions of both reactors are described in Table 1 for each location and the dimensions are as shown in Fig. 2a. Experiments were carried out in triplicate for both reactors.

The absorbance spectrum of containers wall materials was measured after the experiments (Fig. 2b). 2 cm × 3 cm sections of each kind of reactor were cut and absorbance measured using a UV–Visible spectrophotometer (PG Instruments Ltd., T-60-U). Dark control samples of each experiment were kept in the dark (samples wrapped with aluminium foil) at constant lab temperature (25 °C) to re-plate them at the end of the experiment. Thermal studies were carried out with wrapped PET and WDC containers, under sunlight exposure for permitting the water temperature to increase at same velocity than SODIS samples but preventing the sunlight exposure as the WDC and PET containers were wrapped with opaque foil. This test permitted monitoring the thermal inactivation of bacteria in water due solely to the action of solar heating.

2.3. Bacterial strain, enumeration and quantification

E. coli and *E. faecalis* were used as microbial indicators of the inactivation efficiency of solar water disinfection. The strains used are described in Table 1. Different strains of bacteria were used in each location. In Bahrain both *E. coli* and *E. faecalis* were wild-type clinical bacteria while in Spain *E. coli* K-12 ATCC23631 and *E. faecalis* CECT 5154 were used and in India *E. coli* ATCC 25922. The experiments were carried out using different strains and bacteria types, including wild types, to validate the capacity of WDC containers for SODIS disinfection under more realistic field conditions.

The same enumeration and quantification methods were used in all experiments at the three locations of this work. These methods have been described elsewhere (Ubomba-Jaswa et al., 2010; McGuigan et al., 1998). Each strain was inoculated from stocks in 14 mL of Luria broth nutrient medium (Miller's LB Broth, Sigma–Aldrich, USA) and incubated at 37 °C at constant agitation under aerobic conditions. After 18 h the bacteria were in the stationary phase with a concentration of 10^9 CFU mL^{-1}. Bacterial suspensions were centrifuged at 800*g* for 10 min and then the pellet was re-suspended in 14 mL PBS (Phosphate Buffer Saline). Appropriated dilution was made directly into the reactor water to achieve an initial bacteria concentration of 10^6 CFU mL^{-1}.

Standard plate count method was used to enumerate the cells during the solar test (Ubomba-Jaswa, 2010). Standard plate count was carried out using a 10-fold serial dilution of the most concentrated samples in PBS and volumes of 20 µL in triplicate were added on Luria agar (Sigma–Aldrich, USA) for *E. coli* enumeration supplemented with Sodium Dodecyl Sulphate (SDS, Riedel-de Häen, Germany) which is an inhibitor of gram-positive bacteria; and Slanetz & Bartley agar (SB, Scharlab, Spain) for *E. faecalis*. When bacterial concentration was low enough to be enumerated in drops of 20 µL, 50–250–500 µL aliquots of samples were spread on the same agar dishes to reach a DL of 2 CFU mL^{-1}. Colonies were counted after 24 h of incubation at 37 °C.

For those experiments carried out in Spain, the membrane filtration method was used to assess bacterial regrowth. For this, a volume of 200 mL of sample was collected at the end of the experiment and kept in dark for 24 h at room temperature (∼25 °C). Then, 100 mL of

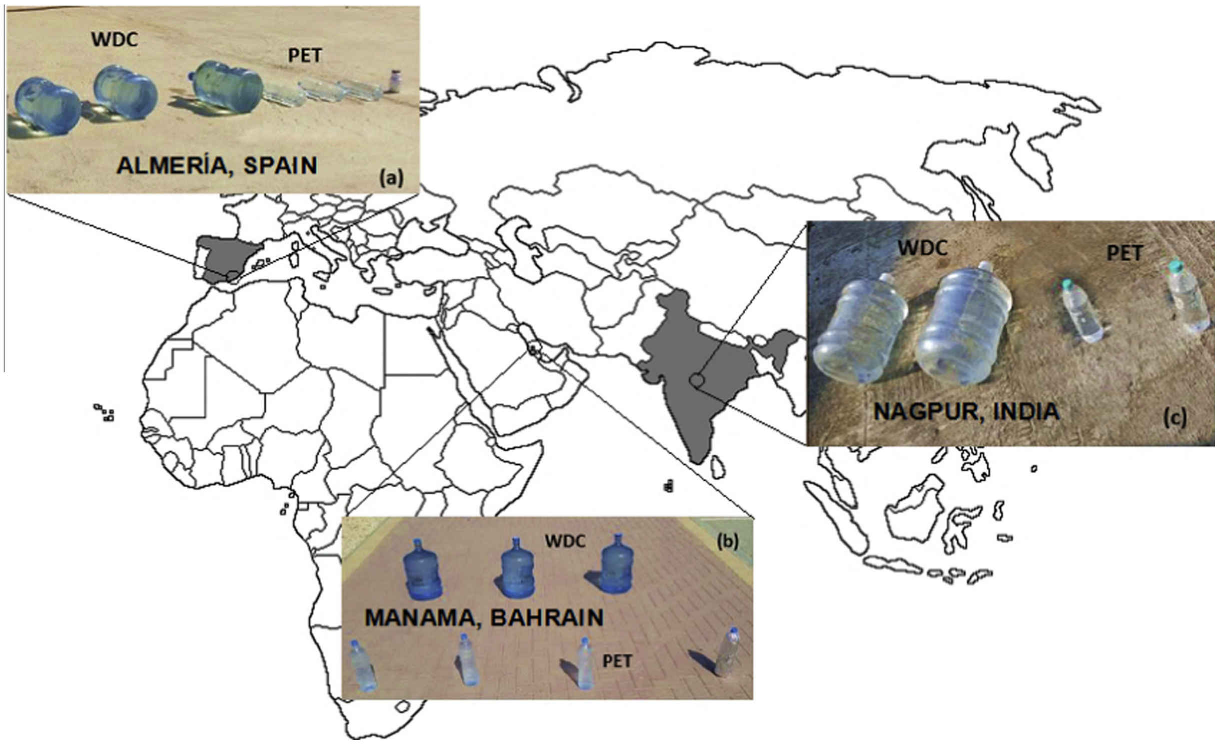

Fig. 1. Photographs of the PET plastic and WDC SODIS reactors comparison experiments in (a) Almería, Spain; (b) Manama, Bahrain; (c) Nagpur, India.

Table 1
Experimental arrangements for Spain, Bahrain and India solar exposures.

Location of experiments	Institute	Plataforma Solar de Almería	RCSI Medical University of Bahrain	National Environmental Engineering Research Institute
	Location	Almería, Spain	Manama, Bahrain	Nagpur, India
	Coordinates	37.0°N, 2.3°W	26.2°N, 50.5°E	21.1°N, 79.0°E
Water Dispenser Container (WDC)	Filled vol. (L)	19	19	19
	Height (cm)	48	48	48
	Diameter (cm)	27	26	25.5
	Wall thickness (mm)	1.4	1.4	1.0
	Material (cm)	Polycarbonate	Polycarbonate	Polycarbonate
	Orientation	Resting on its side	Standing on base	Resting on side
	Replication[b]	3	3	3
Polyethylene terephthalate bottle	Filled vol. (L)	2	1.5	1
	Height (cm)	29	32	27
	Diameter (cm)	8.5	8	7.5
	Wall thickness (mm)	0.5	0.5	0.4
	Material	PET	PET	PET
	Orientation	Resting on side	Standing on base	Standing on base
	Replication[b]	3	3	3
Bacterial strains	*E. coli*	K-12 ATCC 23631	Wild-type clinical	ATCC 25922
	E. faecalis	CECT 5154	Wild-type clinical	–
Source of water		Natural well[a]	Mineral water	Mineral water

[a] See Table 2 for chemical profile of the natural well water used in Spain.
[b] Number of replicates/duplicates exposed simultaneously in each batch.

sample was analysed to determine bacterial regrowth following the filtration method. Samples of 100 mL were filtered through 47 mm diameter 0.45 μm pore size cellulose nitrate filters (Sartorius AG, Germany). The filter was then

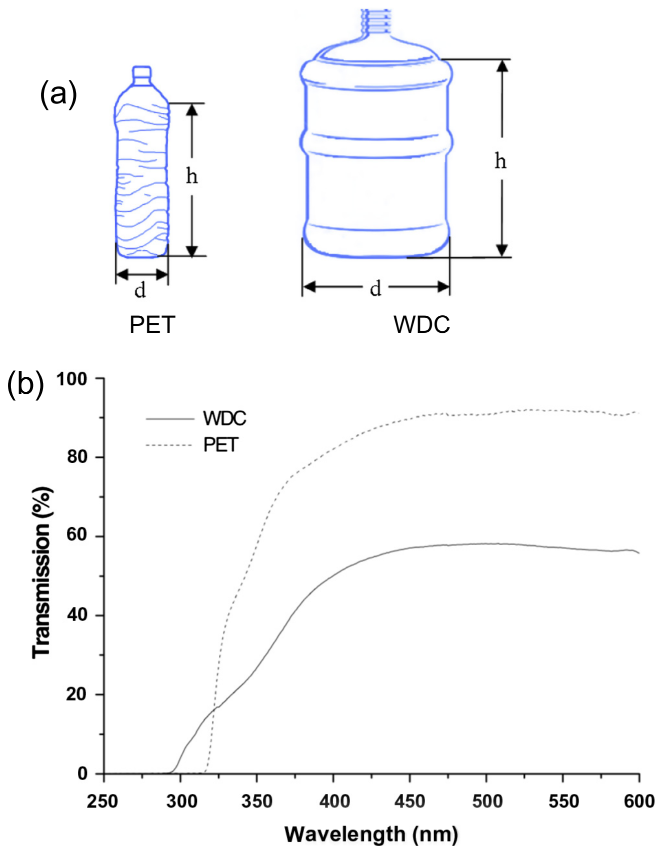

Fig. 2. Measure of the dimensions of the PET plastic and WDC SODIS reactors (a). UV/vis transmission spectra of the WDC and PET container materials used in the Spanish experiments (b).

Table 2
Average physical and chemical characteristics of natural well water used in Spain.

Natural well water (PSA location, Spain)			
Cl^-	561.8 mg L^{-1}	K^+	3.7 mg L^{-1}
NO_3^-	53.9 mg L^{-1}	Na^+	387.8 mg L^{-1}
NO_2^-	1.3 mg L^{-1}	Mg^{2+}	87.1 mg L^{-1}
SO_4^{2-}	500.0 mg L^{-1}	Ca^{2+}	139.3 mg L^{-1}
pH	7.57	DOC	1.7 mg L^{-1}
Conductivity	3.215 mS cm^{-1}	TC	89.6 mg L^{-1}
Bacteria	0 CFU mL^{-1}	IC	87.9 mg L^{-1}
Tubidity	0.2 NTU	HCO_3^-	495.0 mg L^{-1}

DOC = dissolved organic carbon.
TC = total carbon.
IC = inorganic carbon.

aseptically placed on a Petri dish with its corresponding agar medium (Luria agar plus SDS or SB) and incubated at 37 °C overnight and colonies count at the following day.

2.4. Water

Mineral water (commercial bottled available on each place) was used for all PET bottle experiments in Bahrain and India, to have standard drinking water conditions in the absence of faecal bacteria. Experiments in Spain were carried out using water collected from a depth of approximately 200 m from a bore-hole well located on the PSA site. Physico-chemical characteristics of the well water are shown in Table 2. Naturally occurring organisms in well water were determined by standard plate count techniques using LB agar before spiking with the indicator bacterial suspensions and they were found to be lower than the DL, i.e. 2 CFU mL^{-1}. Turbidity of the natural well water was measured using a turbidity meter (Hach 2100N, Hach, Hach Company, Laveland, Colorado, USA) and it was found to be approx. 0.2 NTU. Ion concentrations were evaluated using ion chromatography (IC) with a Dionex DX-600 (Dionex Corporation, Sunnyvale, California, USA) system for anions and a Dionex DX-120 system for cations. Dissolved organic carbon (DOC) and total carbon (TC) were analysed using a Shimadzu TOC-5050 (Shimadzu Corporation, Kyoto, Japan). The presence of iron in the water samples was determined by UV-spectrophotometry using the ISO 6332 to measure the total iron concentration. We did not find any iron in the well water (detection limit 0.05 mg L^{-1}).

For experiments with turbid water, carried out in Spain, 100 NTU turbid solutions were prepared. Kaolin powder (Millipore Corporation, Germany) was used as received from the manufacturer and used for preparation of turbid solution. 10 g of kaolin was added to 1000 mL of distilled sterile water to achieve a concentrated stock of 10.000 NTU. This solution was kept in constant agitation at 400 rpm during 24 h. Appropriate dilutions were carried out to achieve an initial turbidity of 100 NTU in WDC containers, PET bottles and 200 mL-glass bottle for thermal control.

2.5. Measurement of radiation, temperature, pH and dissolved oxygen

Temperature, pH (pH 25+Crison Instruments, S.A. Alella, Barcelona) and dissolved oxygen (DO) (Oxi 45+Crison Instruments, S.A. Alella, Barcelona) were measured during the experiments in Spain. UV-A radiation was measured with a global UV-A pyranometer (295–385 nm, Model CUV4, Kipp & Zonen, Netherlands) with a typical sensitivity of 264 μV/W per m^2. The pyranometer provides data in terms of incident W m^{-2}, like the solar radiant energy rate incident on a surface per unit area.

Incident UVA levels were measured in India using a UVA meter (International light technologies model-ILT 1700 with detector UVA detector model SED 033/UVA/TD), while in Bahrain UV data was obtained from the Meteorological Directorate, Ministry of Transportation, Kingdom of Bahrain.

Eq. (1) was used to calculate the total UV energy dose received per unit of illuminated surface where t_n is the experimental time for n-sample and $\overline{UV}_{n-1}$ is the average solar ultraviolet radiation measured during the period $(t_n - t_{n-1})$.

$$\text{Dose} = \sum_{n} \overline{\text{UV}}_{n-1} \cdot (t_n - t_{n-1}) \qquad (1)$$

2.6. Solar experiments

All experiments were carried out under completely sunny days for 5–6 h. In Spain and India, at the start of the experiments (~10:00 a.m. local time) the UVA irradiance was around 20 W·m^{-2} and it increased during the experiment up to a maximum irradiance value around 50 W·m^{-2} after 4.0–4.5 h of solar exposure. In Bahrain, the initial solar UV irradiance was higher than for the other locations, and increased to a maximum of 50 W m^{-2} after 2 h.

Reactors were filled with water in dark conditions. Kaolin solution was added to the reactors when turbidity experiments were carried out. Suspensions of *E. coli* and *E. faecalis* were added to the water. In Spain, the inactivation of *E. coli* and *E. faecalis* were evaluated simultaneously (i.e. mixed cultures); while in studies in Bahrain both strains were individually investigated. In India only *E. coli* was evaluated. After agitation for homogenisation in dark, initial samples ($t = 0$ min) were taken and the reactors were exposed to sunlight. Samples were taken regularly throughout each experiment to measure the variation of the cell density in the reactors and analysed as previously mentioned. Temperature, pH and dissolved oxygen were measured throughout the experiments. Simultaneously, 'control' bottles for thermal assays were kept inside the laboratory and outside under the same operational conditions but in darkness.

The first samples from each experiment were kept in the laboratory in the dark and at ambient temperature (~22 °C) and analysed again at the end of the experiment as a 'control' sample following the same method described above for microbial enumeration. In all experiments, similar bacterial concentration was observed in the 'control' sample and initial sample (data not shown) indicating that any inactivation observed in these experiments is due to the effect of solar disinfection.

All experiments and operational conditions were carried out in triplicate. No significant differences were found in the triplicate sample results or the triplicate reactors. The average of these results is represented for each point of the graphs and the standard deviation is shown as the error bars. Data obtained in the studies were analysed using the one way ANOVA analysis tool (Origin v7.0300, OriginLab Corp., Northampton, USA). The results of triplicates of each experiment revealed that there are no significant differences ($P < 0.05$, Confidence > 95%) in culturable bacterial population of the samples.

3. Results

Results of the solar exposure experiments in Spain, Bahrain and India are summarised in Table 3. This table shows the time required to achieve a log-reduction value of at least 4 (LRV ⩾ 4). This value is a pre-requisite of quality for drinking water established by the World health Organisation in its Harmonised Testing Protocol within the International Scheme to Evaluate Household Water Treatment Technologies (WHO, 2014). Table 3 also shows the calculated accumulated UV dose for every location at the exposure time when the DL was achieved for each experiment.

3.1. Spain

Real sunlight SODIS inactivation curves for *E. coli* and *E. faecalis* suspended in 0 NTU natural well-water and exposed within WDC and PET reactors in Southern Spain are presented in Fig. 3a and b respectively. Both figures show that the detection limit was reached in all cases, for the two types of bacteria in both SODIS containers. The variation of water temperature (°C) with time during the experiment and solar irradiances (W m^{-2}) were equal for the *E. coli* and *E. faecalis* results since both species were exposed simultaneously in mixed cultures within the same reactors. Water temperature varied from 23 °C to 41.8 °C in WDC containers while in PET bottles a constant average of 2 °C higher values were measured. LRVs = 4.6 and 4.4 for *E. coli* in PET bottles and WDC containers, reaching the detection limit (2 CFU mL^{-1}) in 2 h and 2.5 h respectively (Fig. 3a). In the case of *E. faecalis*, different inactivation curve shapes (longer shoulder than for *E. coli*) and lower inactivation rates than *E. coli* were observed, although LRVs = 4.6 and 4.3 were similar, for PET and WDC reactors, respectively reaching also the detection

Table 3
Summary and comparison of all results obtained for SODIS experiments. '*LRV ⩾ 4*' is the time required (expressed in hours) required to achieve a minimum required Log reduction of bacteria equal or higher than 4-log according to the Harmonised Testing Protocol of WHO (WHO, 2014).

Experiment	Turbidity (NTU)	Location	*E. coli* Minimum required reduction LRV ⩾ 4 (h) // UV-dose (kJm^{-2})		*E. faecalis* Minimum required reduction LRV ⩾ 4 (h)	
			WDC	PET	WDC	PET
1	0	Spain	2.5 // 250	2 // 200	4 // 435	4 // 435
2	100	Spain	3 // 300	2.5 // 240	4.5 // 500	4.5 // 500
3	0	Bahrain	5 // 730	3.5 // 560	4.5 // 680	4.5 // 680
4	0	India	5 // 750	4.5 // 665	–	–

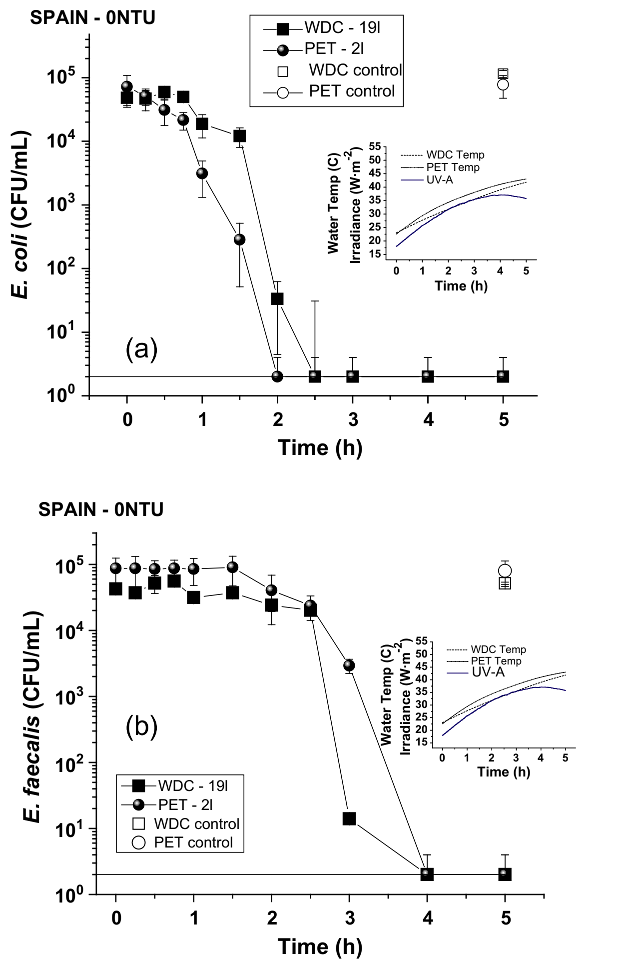

Fig. 3. Comparisons in Southeast Spain of SODIS inactivation efficacy of populations of (a) *E. coli* and (b) *E. faecalis* populations in 19-L WDC (-■-) and 2-L PET (-●-) reactors filled with 0 NTU natural well water.

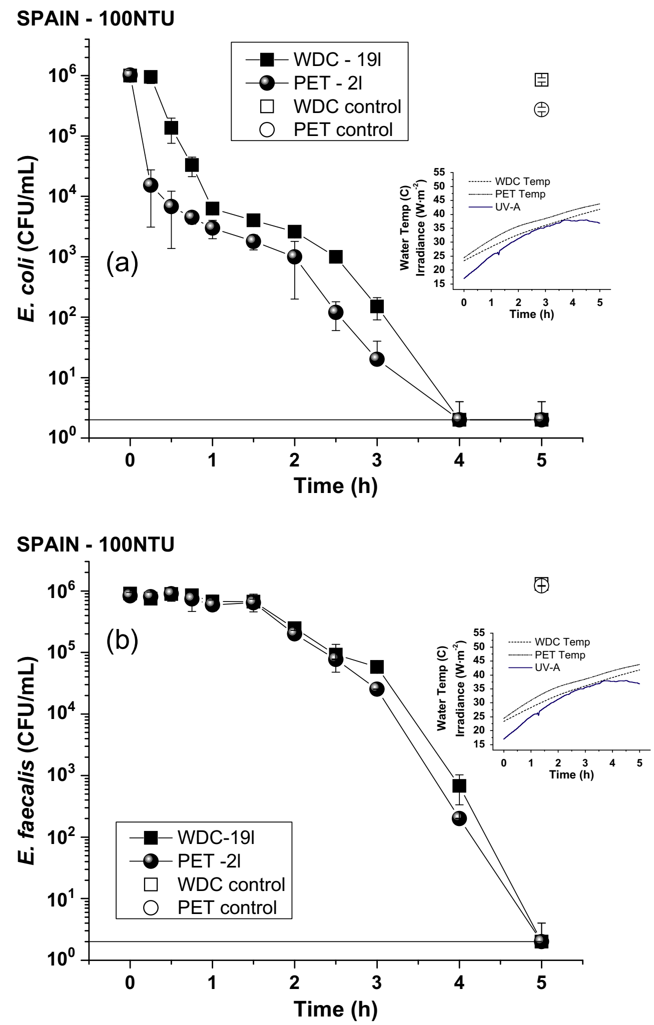

Fig. 4. Comparisons in Southeast Spain of SODIS inactivation efficacy of populations of (a) *E. coli* and (b) *E. faecalis* populations in 19-L WDC (-■-) and 2-L PET (-●-) reactors filled with 100 NTU natural well water.

limit (Fig. 3b). pH remained constant throughout the solar experiments at 7.5 and dissolved oxygen decreased from 6.8 to 6.2 mg L^{-1} in WDC reactors and from 6.9 to 5.5 mg L^{-1} in PET bottles tests.

The inactivation rate of *E. coli* and *E. faecalis* under real sunlight SODIS reactors (WDC and PET) for 100 NTU solutions are shown in Fig. 4a and b, respectively. In this case, both bacterial species were inactivated to below the detection limit of 2 CFU mL^{-1} in PET bottles and WDC containers. However achieving LRVs higher than 4 required 0.5 h longer exposure than when the water samples were clear (0 NTU). pH remained constant throughout the experiment at 7.5 and dissolved oxygen decreased from 7 to 6 mg L^{-1} in WDC reactors and from 7 to 5.7 mg L^{-1} in PET bottles tests. Temperature in turbid experiments was similar to those measured in 0 NTU experiments, i.e. from 22 °C to 44 °C achieving a maximum temperature of 44 °C in PET bottles and 42 °C in WDC containers.

Regrowth was monitored in the Spanish experiments. It was found that after 24 h, *E. coli* was under the detection limit in the case of WDC and 2 CFU/mL were observed in PET results. In the case of *E. faecalis*, where DL was not achieved during the solar exposure in all reactors, lower bacterial concentrations after 24 h were observed. In turbid experiments, no bacterial regrowth was detected in any case.

3.2. Bahrain

Inactivation curves for *E. coli* and *E. faecalis* suspended in 0 NTU de-ionised water and exposed separately to strong natural sunlight within WDC and PET reactors in Bahrain are presented in Fig. 5. Temperature and irradiance were similar for *E. coli* and *E. faecalis* results, although they were carried out on different days. For *E. coli* experiments, the temperature was similar in both reactors and it achieved a maximum of 48.9 °C and 48.1 °C in WDC and PET reactors, respectively. Water temperature in the *E. faecalis* experiment was 2.5 °C higher in PET bottles than in WDC reactors and the maximum values were 51.2 °C and 49.2 °C in PET and WDC reactors, respectively. pH values were constant during the

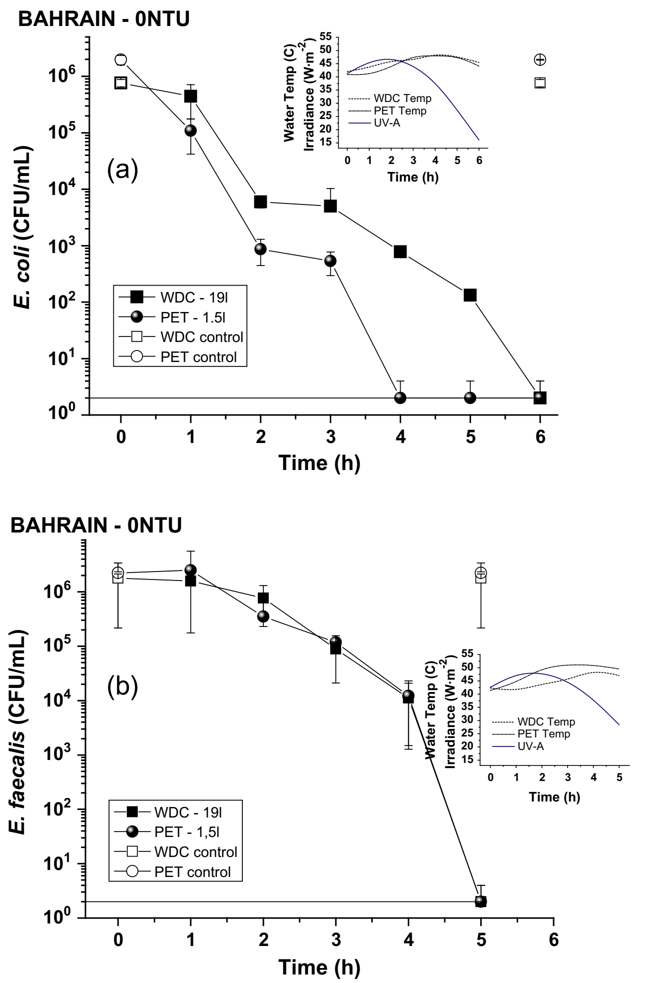

Fig. 5. Comparisons in Bahrain of SODIS inactivation efficacy of populations of (a) *E. coli* and (b) *E. faecalis* populations in 19-L WDC (-■-) and 1.5-L PET (-●-) reactors filled with 0 NTU de-ionised water.

experiments at 7 in both reactors. No DO measurements were made in Bahrain.

Inactivation of *E. coli* after SODIS treatment achieved the detection limit in both reactors. The inactivation rate was higher in PET bottles requiring 630 kJ m^{-2} (in 4 h) to reach the DL while in WDC reactors 790 kJ m^{-2} (6 h) was required. In the case of *E. faecalis,* an intermediate doses of 750 kJ m^{-2} (5 h) was required to achieved the DL.

3.3. India

Fig. 6 shows inactivation curves for *E. coli* suspended in de-ionised water (0 NTU) and exposed to strong natural sunlight within WDC and PET reactors in Nagpur, India. Temperature was similar in both reactors and the maximum was achieved at the end of the experiment at 43 °C in both reactors, although the average of the water of PET bottles was 2 °C higher than of the WDC reactors. In this experimental study, pH and DO were not monitored.

Similar inactivation rates for *E. coli* in WDC and PET were observed. In PET bottles the bacteria concentration

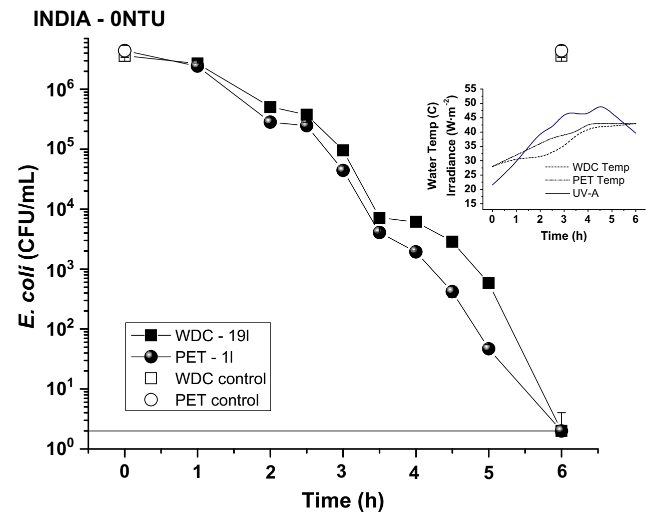

Fig. 6. Comparisons in central India of SODIS inactivation efficacy of populations of *E. coli* populations in 19-L WDC (-■-) and 1-L PET (-●-) reactors filled with 0 NTU de-ionised water.

reduced below the DL after 6 h of treatment (890 kJ m^{-2}) while that achieved in the WDC was within one log_{10} unit for the same time.

4. Discussion

Our results demonstrate that despite the larger thermal mass and thicker container wall (compared with standard 1–2 L PET bottles), the 19 L-WDC containers are effective as SODIS reactors, especially in conditions of strong, sustained sunshine.

In this study we have defined satisfactory disinfection as one which produces either a faecal bacteria population log unit reduction value (LRV) $\geqslant$4.0, or a final treated faecal bacterial population of at least 2 CFU/mL faecal coliforms, as recommended by the Harmonised Test Protocol for Non-Specific Technology within the WHO International Scheme to Evaluate Household Water Treatment Technologies in matter of bacterial contamination in drinking water (WHO, 2014). In the Spanish set of experiments, the WDC reactor achieves satisfactory disinfection from 10^5 to 10^6 CFU/mL down to the DL for *E. coli* and *E. faecalis* for 0 NTU and 100 NTU, although for *E. faecalis* experiments the required exposure is 6 h, while 4 h are necessary to inactivate same bacteria in 0 NTU water. It is also expected that continued reduction in viable bacterial cell count occurs in the post-exposure period. Continued reduction of viable bacterial populations after SODIS exposure has completed has been reported elsewhere in previous studies (Ubomba-Jaswa et al., 2009; Giannakis et al., 2013). For the Bahrain and India experiments similar end populations are achieved in WDC and PET containers at the end of the 6 h exposures. As expected, the PET SODIS reactors achieve LRVs below the limit of detection across all sites for both *E. coli* and *E. faecalis*.

For logistical and operational reasons, the SODIS exposure durations used were 5 h in Spain and 6 h in both Bahrain and India. In practical use in the field, SODIS is seldom exposed for such short durations. The usual practice observed during SODIS studies in Kenya, S. Africa, Zimbabwe, Cambodia and Uganda (McGuigan et al., 2012; Asiimwe, 2014) is that bottles are usually set out for exposure early in the morning and not retrieved for use until the following morning when the next set of bottles are being set out. Consequently actual solar exposure times in the field are likely to be considerably longer than the 5–6 h examined in this comparison study and LRVs achieved for WDC and PET containers are, by extension, likely to be similarly larger than observed in our study.

We note the UVA dose required to achieve DL1 differs across the three experiment locations (see Figs. 3–6, Table 3). In Spain DL is achieved with a dose of 200–250 kJ m^{-2} (*E. coli*) in well water, in Bahrain the dose is between 560 and 730 kJ m^{-2} in deionized water, and in India, the required dose is between 665 and 750 kJ m^{-2} also in deionized water in PET and WDC, respectively. From Fig. 1 and Table 3 it is apparent that the water matrix, container dimensions, wall thickness, orientation and tint of the WDCs vary for each location. In addition the operational ranges of the three different UV sensors employed in Spain, Bahrain and India were not identical. Consequently, as is often the case, exact dosimetric comparisons across sites may not be informative. Instead, the most significant result of this research is the fact that, despite these differences, significant bactericidal log reduction values are observed in each location using WDCs as SODIS reactors. It should be noted that the wild-type clinical isolate bacterial strains used in Bahrain are likely to be more resistant to disinfection than the national collection strains used for the Spanish and Indian experiments.

Transmission spectra for samples retrieved from the WDC and PET bottles used in Spain are presented in Fig. 2b and these are consistent with spectra reported by Fisher et al. (2012). In Fig. 2b it is observed that PET material transmits much more UV radiation over the range of 290 nm-400 nm than WDC polycarbonate material. For the case of PET material, the 40% more radiation is transmitted along the range between 400 and 600 nm compared with the WDC wall. Between 320 and 400 nm, transmittance of PET varied from 0% to 83%; while the most damaging wavelengths between 290 and 320 nm were transmitted by 0–17% by the WDC wall compared with zero transmission of PET in this range. WDC material had transmittance values varying from 17% to 50% in the range of 320–400 nm. These values may also explain some of the observed advantage in SODIS inactivation in WDC due to the presence of more energetic wavelengths inside the container.

The increased resistance of *Enterococcus* spp. to SODIS compared to *E. coli* is clearly observed for the inactivation curves shown in Figs. 3–5. This has been previously reported by Fisher et al. in SODIS (Fisher, 2012) and by others in photolytic and photocatalytic water disinfection (Rodríguez-Chueca et al., 2014).

The results presented here were conducted under conditions of uninterrupted, strong, sunlight in Southern Spain, the Arabian Gulf and the Indian sub-continent. While the WDC reactor performance achieved good inactivation results in conditions of strong sunshine this may not be the case under conditions of increased or intermittent cloud-cover. Further studies are required to identify the full range of meteorological conditions for which WDC-based SODIS is effective.

Table 4 illustrates the comparative costs associated with SODIS treatment using PET and WDC reactors. Previous studies have indicated that PET bottles should be replaced after 6 months to avoid risks associated with leaching of chemical photoproducts from the plastic container material into the water (Ubomba-Jaswa et al., 2010). In the absence of any similar studies for polycarbonate, which is the plastic from which all WDCs used in this study, were manufactured, we have assumed a similar safe lifetime. The costs cited for purchase of 2 L PET bottles and 19 L WDC containers are costs incurred in January 2014 for purchase of these items in Uganda. The purchase cost of PET bottles is 0.50€ while WDC containers is 6.40€, therefore the PET bottle remains the most economically viable container option. The PET bottle is most cost-effective when examined on the basis of (i) purchase cost; (ii) cost per litre treated over the recommended 6 month (€1.4×10^{-3}/L) lifetime of a standard plastic SODIS container while WDC containers is (€1.9×10^{-3}/L).

In most social contexts, the principal barrier to the uptake of SODIS technology is probably its simplicity. Therefore it is quite possible that a WDC may be perceived as a more plausible and 'scientific' SODIS reactor than a discarded everyday object such as the PET bottle. There will be, however, material culture and design anthropology considerations to be addressed wherever these are introduced. For example, their bulk and shape may render them unsuitable for use as water collection vessels that can be carried between home and water source. Since we are proposing the use of the WDC and not the accompanying water cooler, dispensing water from unwieldy WDCs within homes (in the absence of a water cooler) may be a task that can only be performed by able bodied adults, which makes them less practicable in developing world situations where housework and childcare is often carried out by siblings who are themselves quite young, or where

Table 4
Comparison of economic cost associated with PET, WDC and CPC SODIS reactor water treatment.

Container	PET	WDC
Volume (L)	2.0	19.0
Cost (€)	0.50	6.40
Lifetime (months)	6	6
Cost per litre treated (€) over recommended lifetime	1.4×10^{-3}	1.7×10^{-3}

grandparents may be bringing up AIDS orphans. Preliminary feedback from a pilot study in Uganda suggests that the 19 L WDCs are smaller in volume (and consequently lower in mass) than the 25 L jerry-cans typically used (predominantly by children in rural Uganda) to transport water from water sources to the home. Since WDCs remain at the homestead and are filled on site before exposure, their bulk and mass was not perceived as problematic. If WDCs are used solely for water treatment, and the treated water is subsequently transferred into other storage containers, there may be new contamination issues to contend with.

Medical anthropologists have noted that that it is necessary to attend to indigenous notions of water purity and indigenous practices of water decontamination when reviewing issues of uptake of technology. At the same time, indigenous notions of water purity and decontamination are frequently inlaid within local and global relationships of power, and may be subject to challenge and contestation. In comprehending the uptake of WDCs in such a scenario, obstacles may range from the very manner in which the technology enters the field (as a 'clinical trial' of sorts? or by policy directive? or at the initiative of a people's movement?), to the larger national and global political economic currents within which daily struggles over water take place. It has previously been observed by du Preez et al. (2010) in a SODIS trial in a South African township that residents were reluctant to adopt the technology since it permitted the state to continue to disregard its duty to provide safe drinking water for all. Thus, questions of likely uptake of the more convenient WDC reactor will need to be framed within a context-specific understanding of how the technology interpolates with the socio-political status quo.

Although SODIS in PET bottles is effective, a number of limitations remain, such as: (i) The volume of water disinfected at a given time is restricted to <3 L, which creates a requirement to have sufficient bottles and time to provide adequate volume of treated water for an average household. (ii) Periods of cloudy weather will require SODIS users to expose bottles for 2 consecutive days in order to inactivate pathogens. (iii) During rainy seasons, an alternative disinfection method has to be used. The use of filtration before solar exposure is also recommended for water that has a turbidity $\geqslant$ 30 NTU (McGuigan et al., 2012).

Other approaches investigated elsewhere have been the use of plastic bags as SODIS reactors. Bag reactors have the advantage that they can easily be transported and stored in large quantities. The area of the SODIS bags is bigger than in PET bottles and the path length for light penetration through the water decreases in this case. This permits a greater absorption of photons within the reactor (Sommer et al., 1997; Walker et al., 2004). More recently, Dunlop et al. (2011) have investigated the use of batch bags for solar water disinfection. They found that complete *E. coli* inactivation (LRV = 6.5) was achieved within 240 min in low-density polyethylene bag reactors.

SODIS use has been proven to confer a protective effect against waterborne disease and in particular dysentery in children under the age of 5 years. In addition, du Preez et al. (2011) reported a small (0.8 cm) but significant benefit in height for Kenyan children using SODIS over a 12 month period, compared with children in the non-intervention group. This benefit was subsequently confirmed by Dangour et al. (2013) in their Cochrane collaboration meta-analysis. Provision of safe water within the home has other benefits in addition to health. Time spent caring for sick family members could be used in income generating activities. Childhood diarrhoea frequently leads to absence from school so there is a concomitant impact on education also. Since water treatment has clear benefits in health, family finances and education, any technological development that can increase uptake to such technologies is to be encouraged. Given that one of the most frequently disadvantages of SODIS identified by users is the low treated volume provided by 2–3 L bottles, the news that 19 L WDCs can be used for SODIS will be an important boost in dissemination and uptake of this household water treatment technology.

5. Conclusions

Comparative studies of the bacterial inactivation efficacy of 19 L polycarbonate WDC and 2 L PET SODIS reactors were conducted in Spain, Bahrain and India. Results demonstrate that under conditions of strong natural sunlight 19 L WDC reactors are only slightly less bactericidally effective than 2 L PET reactors on the basis of log reduction value, cost and cost per litre treated. Water dispenser containers are a viable alternative to PET bottles in situations where strong continuous sunshine is readily available.

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