

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

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### CITATION

Keogh, Michael B.; Castro-Alf  rez, M; Polo-L  pez, M I.; Calderero, I Fern  ndez; Al-Eryani, Y A.; Joseph-Titus, C; et al. (2015): Capability of 19-litre polycarbonate plastic water cooler containers for efficient solar water disinfection (SODIS): field case studies in India, Bahrain and Spain.. Royal College of Surgeons in Ireland. Journal contribution. <https://hdl.handle.net/10779/rcsi.10792520.v1>

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**Capability of 19-litre 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 litres) 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 the developing world. 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 litres) 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<sub>10</sub> 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 7.2 and 7.8 were obtained for *E. coli* in WDC and 2-L PET bottles, respectively, and in the case of *E. faecalis* LRV = 5.7 and 7.9 were observed. These studies demonstrate that under conditions of strong sunlight and mild temperature, 19 litre 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.

## Key words

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 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 and UNICEF, 2014). Furthermore, the progress achieved was mostly in urban areas. Indeed 90% of the population, who is still without access to improved drinking water sources, are poor, marginalized, and live in rural areas (WHO and 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 and UNICEF, 2013).

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 parts of the developing world 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 Organization (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 hours 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).

The efficiency of this water treatment technique has been widely proven against different groups of microorganism such as bacteria (*E. 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 *Escherichia coli* is the most frequently studied species. On the other hand, recent research has focussed 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; Łuczkiwicz *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 *E. faecalis* to solar photo-chemical treatments compared to *E. coli* demonstrating that this strain is more appropriate for validating the effectiveness of solar processes (Rodriguez-Chueca *et al.*, 2014).

Bacterial disinfection by solar radiation is usually attributed to the 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  $\mu$ m). 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 ( $\text{HO}_2^\cdot$ ), hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), and hydroxyl radicals ( $^\cdot\text{OH}$ ). Furthermore, intracellular  $^\cdot\text{OH}$  radical formation can be attributed to the Fenton and Haber-Weiss reactions, due to the presence of intracellular iron and hydrogen peroxide (Imlay *et al.* 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 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 litres and 2.0 litres. 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 litres 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-litre 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 parts of the developing world they are frequently 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 water solar water disinfection. This objective is achieved by demonstrating SODIS of 19L-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 19L WDC and 2L PET plastic containers is compared on the basis of *E. coli* and *E. faecalis* inactivation.

## **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. Figure 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 Figure 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 Figure 2(a). Experiments were carried out in triplicate for both reactors.

The absorbance spectrum of containers wall materials was measured after the experiments (Figure 2(b)). 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 test was carried 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 to the mere action of solar mild heating.

### **2.3 Bacterial strain, enumeration and quantification**

*Escherichia coli* and *Enterococcus 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 hours the bacteria were in the stationary phase with a concentration of  $10^9$  CFU·mL<sup>-1</sup>. Bacterial suspensions were centrifuged at 800 xg for 10 minutes 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<sup>-1</sup>.

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 serial 10-fold dilution of the most concentrated samples in PBS and volumes of 20  $\mu$  L in triplicate were added on Luria agar (Sigma-Aldrich, USA) for *E. coli* enumeration supplemented with Sodium Dodecyl Sulfate (SDS, Riedel-de H  en, 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  $\mu$  L, 50-250-500  $\mu$  L aliquots of samples were spread on the same agar dishes to reach a DL of 2 CFU mL<sup>-1</sup>. Colonies were counted after 24 hours 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 hours at room temperature (~25 °C). Then, 100 mL of sample was analysed to determine bacterial regrowth following the filtration method. Samples of 100mL were filtered through 47 mm diameter 0.45  $\mu$ m pore size cellulose nitrate filters (Sartorius AG, Germany). The filter was then 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<sup>-1</sup>. 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<sup>-1</sup>).

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 hours. Appropriate dilutions were carried out to achieve an initial turbidity of 100 NTU in WDC containers, PET bottles and 200mL-glass bottle for thermal control.

### **1.5. 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  $\mu\text{V/W}$  per  $\text{m}^2$ . The pyranometer provides data in terms of incident  $\text{W.m}^{-2}$ , 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 .

Equation 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  $(t_n - t_{n-1})$ .



$$\text{Dose} = \sum_n \overline{UV}_{n-1} \cdot (t_n - t_{n-1}) \quad \text{Eq. (1)}$$

## 2.6. Solar experiments

All experiments were carried out under completely sunny days for 5-6 hours. In Spain and India, at the start of the experiments (~10:00 a.m. local time) the UVA irradiance was around 20 W·m<sup>-2</sup> and it increased during the experiment up to a maximum irradiance value around 50 W·m<sup>-2</sup> after 4.0 - 4.5 hours 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<sup>-2</sup> after 2 hours.

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 homogenization in dark, initial samples (t = 0min) 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

**(I have to adapt the discussion to new figures and think if we are gonne include dadta of 100 NTU got in Spain)**

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 6 (LRV = 6). In

the case of experiments in Spain with clear well water (experiment 1 in the Table 3), the initial concentration of bacteria was 1 log lower than in the others, so the Table 3 shows the LRV = 5 instead of LRV = 6. The log-reduction value of each bacterium after 5 hours exposure under sunlight (5h LRV) is also shown.

## SPAIN

Real sunlight SODIS inactivation curves for *E. coli* and *E. faecalis* suspended in natural well-water and exposed within WDC and PET reactors in Southern Spain are presented in Figure 3a and 3b respectively. In the figures, both detection limits described previously are represented. The variation of water temperature (°C) with time during the experiment and solar irradiances ( $\text{W}\cdot\text{m}^{-2}$ ) 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 = 6.9 and 6.4 were obtained for *E. coli* in PET bottles and WDC containers respectively (Fig. 3a). In the case of *E. faecalis*, lower inactivation rates than *E. coli* were observed, as LRVs = 5.1 and 4.4 were obtained for PET and WDC reactors, respectively. None achieved, in this case, the detection limit of 1 CFU·100mL<sup>-1</sup> (Fig. 3b). pH remained almost constant throughout the solar experiments at 7.5 and dissolved oxygen decreased from 6.8 to 6.2 mg·L<sup>-1</sup> in WDC reactors and from 6.9 to 5.5 mg·L<sup>-1</sup> 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 Figure 4a and 4b, respectively. In this case, both bacterial species were inactivated to below the detection limit of 1 CFU/100mL in PET bottles while in the WDC containers it was not achieved. However LRVs of at least 6 log units are achieved in the WDCs. pH remained almost constant throughout the experiment at 7.5 and dissolved oxygen decreased from 7 to 6 mg·L<sup>-1</sup> in WDC reactors and from 7 to 5.7 mg·L<sup>-1</sup> 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 21 CFU/100mL 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 hours were observed. 45 CFU/100mL and 4 CFU/100mL were measured for WDC and PET reactors, respectively. In turbid experiments, no bacterial regrowth was detected in any case.

## 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 Figure 5. Temperature and irradiance were similar for *E. coli* and *E. faecalis* results, although they 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. Temperature in *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 experiments at 7 in both reactors. No DO measurements were made in Bahrain.

Inactivation of *E. coli* after SODIS treatment achieved the detection limit of 1667 CFU/100mL in both reactors. Inactivation rate was higher in PET bottles that required  $630 \text{ kJ}\cdot\text{m}^{-2}$  (in 4 hours) to reach the DL1 while in WDC reactors  $790 \text{ kJ}\cdot\text{m}^{-2}$  (6 hours) was needed. In the case of *E. faecalis*, an intermediate doses of  $750 \text{ kJ}\cdot\text{m}^{-2}$  (5 hours) was required to achieved the DL1 of 1667CFU/100mL.

## INDIA

Figure 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 reduced below the DL after 6 hours of treatment ( $890 \text{ kJ}\cdot\text{m}^{-2}$ ) 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 2L PET bottles), the 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)  $\geq 6.0$ , or a final treated faecal bacterial population of at least 0CFU/100mL faecal coliforms, as recommended by the US EPA (1987). In the Spanish set of experiments, the WDC reactor achieves satisfactory disinfection in all but

one experiment, with the exception being the ONTU *E. faecalis* experiment, where a LRV of only 5.5, rather than 6.0 was attained after 5 hours exposure. However it should be noted that for this experiment the *E. faecalis* population 24 hours after the start of the exposure was observed to be below DL2 ( $<1$  CFU/100mL.). Continued reduction of viable bacterial populations after SODIS exposure has completed has been reported elsewhere in previous studies (Ubomba-Jaswa *et al.* 2009, Giannakis, PhD Thesis 2014 “Solar disinfection of secondary effluent and the subsequent bacterial regrowth: considerations, limitations and environmental perspectives” Polytechnical University of Catalonia, Spain ). For the Bahrain and India experiments similar end populations are achieved in WDC and PET containers at the end of the 6 hr 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 hours in Spain and 6 hours 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, Asimwe 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 hours 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). In Spain DL1 is achieved with a dose of  $300\text{kJ}\cdot\text{m}^{-2}$  (*E. coli*) in well water, in Bahrain the dose is between 600 and  $700\text{kJ}\cdot\text{m}^{-2}$  in deionized water, and in India, the required dose is  $900\text{kJ}\cdot\text{m}^{-2}$  also in deionized water. From Figure 1 and Table 1 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.

In Figure 7 it is observed that PET material transmits more UV over the range of 300nm-350nm than WDC polycarbonate material so this may explain some of the observed advantage in SODIS inactivation. Transmission for samples retrieved from the WDC and PET bottles used in Spain are presented in Figure 7 and these are consistent with spectra reported by Fisher *et al.* (2012).

The increased resistance of *Enterococcus* spp. to SODIS compared to *E. coli* is clearly observed for the inactivation curves shown in Figures 3-5. This has been previously reported by Fisher *et al.* in SODIS (Fisher, 2012) and by others in photolytic and photocatalytic water disinfection (Rodriguez-Chueca 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 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 2L PET bottles and 19L 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 remain the most economically viable 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 ( $€1.4 \times 10^{-3}/L$ ) lifetime of a standard plastic SODIS container while WDC containers is ( $€1.9 \times 10^{-3}/L$ ).

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 grandparents may be bringing up AIDS orphans. Preliminary feedback from the pilot study suggests that the 19L WDCs are smaller in volume (and consequently lower in mass) than the 25L 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 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) *et al.* 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 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  $\geq 30$  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 (0.8cm) 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 and co-workers (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 so 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 2-3L bottles, the news that 19L 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 19L polycarbonate WDC and 2L PET SODIS reactors were conducted in Spain, Bahrain and India. Results demonstrate that under conditions of strong natural sunlight 19L WDC reactors are only slightly less bactericidally effective than 2L 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.

## **Acknowledgements**

MBK and KMcG were funded by the European Commission (SFERA - Solar Facilities for the European Research Area project'.contract no. 228296). Research Travel for KMcG and CM was funded by the Short Term Study Mission Programme of 3U Global Health (contract no. 3UGH-STSM-2012-2). The authors have no proprietary, professional, financial, or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review of, this work.. KMcG would like to thank Dr Maria Boyle for artwork used in the graphical abstract.

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## Table Captions

**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 <sup>§</sup>	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 <sup>§</sup>	3	3	3
Bacterial strains	<i>E. coli</i>	K-12 ATCC 23631	Wild-type clinical	ATCC 25922
	<i>E. faecalis</i>	CECT 5154	Wild-type clinical	-
Source of water		Natural well*	Mineral water	Mineral water

\*See Table 2 for chemical profile of the natural well water used in Spain.

<sup>§</sup>Number of replicates/duplicates exposed simultaneously in each batch

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

Natural well water (PSA location, Spain)			
<b>Cl<sup>-</sup></b>	561.8 mg·L <sup>-1</sup>	<b>K<sup>+</sup></b>	3.7 mg·L <sup>-1</sup>
<b>NO<sub>3</sub><sup>-</sup></b>	53.9 mg·L <sup>-1</sup>	<b>Na<sup>+</sup></b>	387.8 mg·L <sup>-1</sup>
<b>NO<sub>2</sub><sup>-</sup></b>	1.3 mg·L <sup>-1</sup>	<b>Mg<sup>2+</sup></b>	87.1 mg·L <sup>-1</sup>
<b>SO<sub>4</sub><sup>2-</sup></b>	500.0 mg·L <sup>-1</sup>	<b>Ca<sup>2+</sup></b>	139.3 mg·L <sup>-1</sup>
<b>pH</b>	7.57	<b>DOC</b>	1.7 mg·L <sup>-1</sup>
<b>Conductivity</b>	3.215 mS·cm <sup>-1</sup>	<b>TC</b>	89.6 mg·L <sup>-1</sup>
<b>Bacteria</b>	0 CFU·mL <sup>-1</sup>	<b>IC</b>	87.9 mg·L <sup>-1</sup>
<b>Turbidity</b>	0.2 NTU	<b>HCO<sub>3</sub><sup>-</sup></b>	

DOC = Dissolved Organic Carbon

TC = Total carbon

IC= Inorganic Carbon

**Table 3.** Summary and comparison of all results obtained for SODIS experiments. ‘*LRV = 6*’ is the time required to achieve a 6-log reduction. ‘*5h LRV*’ is the logarithmic reduction value (LRV) achieved after 5 hours of solar exposure. NA = Not Attained

Experiment	Turbidity (NTU)	Location	<i>E. coli</i>				<i>E. faecalis</i>			
			LRV = 6 (min)		5h LRV		LRV = 6 (min)		5h LRV	
			WDC	PET	WDC	PET	WDC	PET	WDC	PET
1	0	Spain	250§	220§	6.4	6.9	NA§	290§	4.4	5.1
2	100	Spain	250	200	7.2	7.8	NA	250	5.7	7.9
3	0	Bahrain	NA	NA	3.8	5.1	-	-	-	-
4	0	Bahrain	-	-	-	-	NA	NA	5.0	5.1
5	0	India	NA	NA	3.8	5.0	-	-	-	-

§ Time required to achieve a log reduction value of 5 instead of 6.

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

Container	PET	WDC
Volume (L)	2.0	20.0
Cost (€)	0.50	6.40
Lifetime (months)	6	6
Cost per Litre treated (€) over recommended lifetime	$1.4 \times 10^{-3}$	$1.7 \times 10^{-3}$

## Figure Captions

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

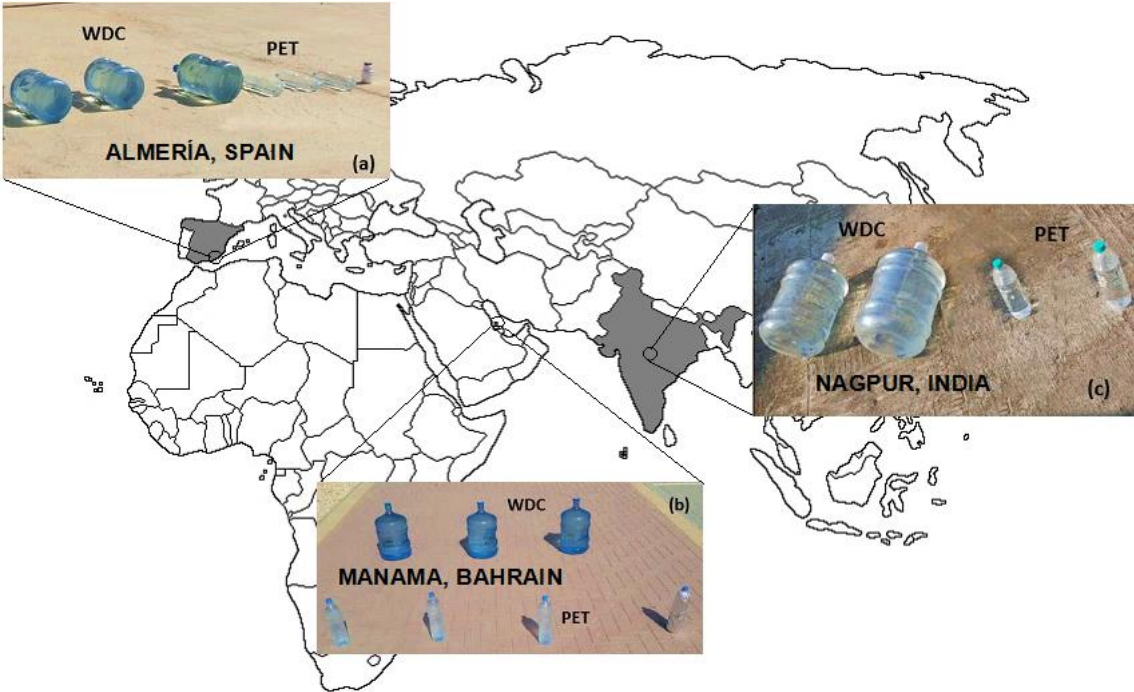
**Figure 2.** Measure of the dimensions of the PET plastic and WDC SODIS reactors (a). UV/vis transmission spectra of the WDC and PET container materials used in the Spanish experiments (b).

**Figure 3.** Comparisons in Southeast Spain of SODIS inactivation efficacy of populations of (a) *E. coli* and (b) *E. faecalis* populations in 19-litre WDC (-■-) and 2-litre PET (-●-) reactors filled with 0 NTU natural well water. DL1 = detection limit of the standard plate count. DL2 = detection limit of the membrane filtration method.

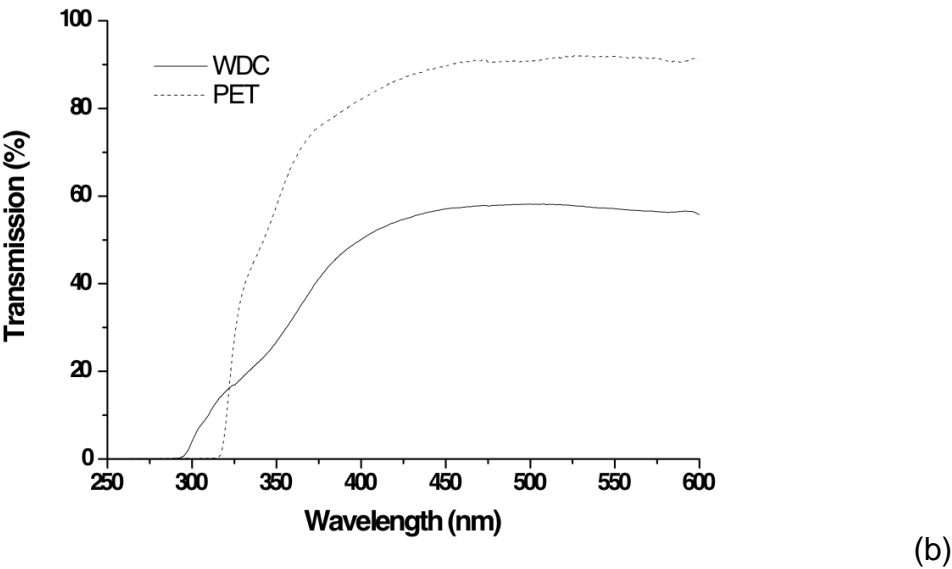
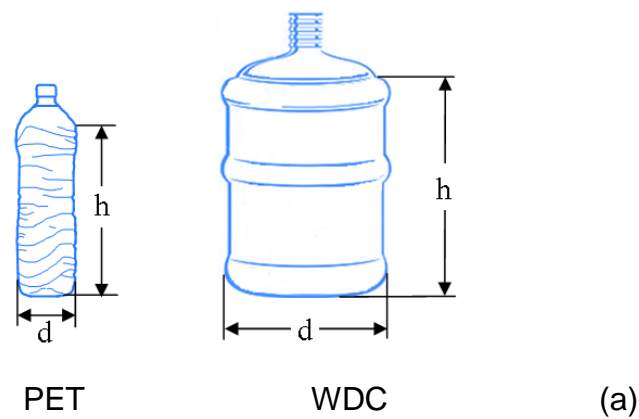
**Figure 4.** Comparisons in Bahrain of SODIS inactivation efficacy of populations of (a) *E. coli* and (b) *E. faecalis* populations in 19-litre WDC (-■-) and 1.5-litre PET (-●-) reactors filled with 0 NTU de-ionised water. DL1 = detection limit of the standard plate count. DL2 = detection limit of the membrane filtration method.

**Figure 5.** Comparisons in central India of SODIS inactivation efficacy of populations of *E. coli* populations in 19-litre WDC (-■-) and 1-litre PET (-●-) reactors filled with 0 NTU de-ionised water. DL1 = detection limit of the standard plate count. DL2 = detection limit of the membrane filtration method.

Figure 1



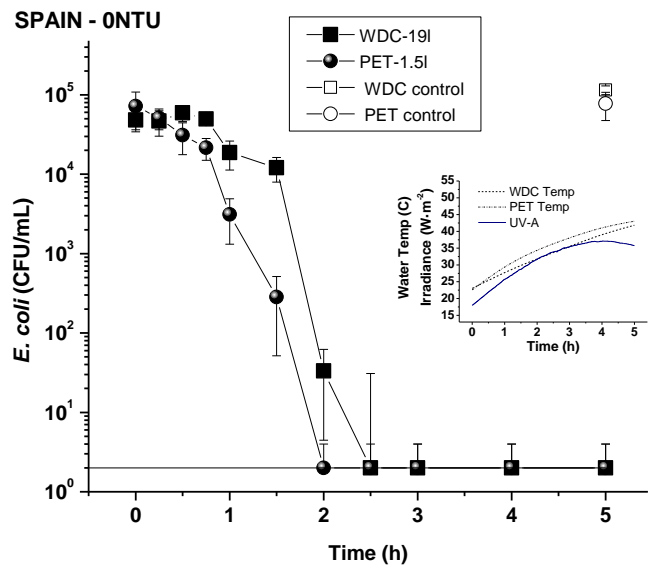
New Figure 2



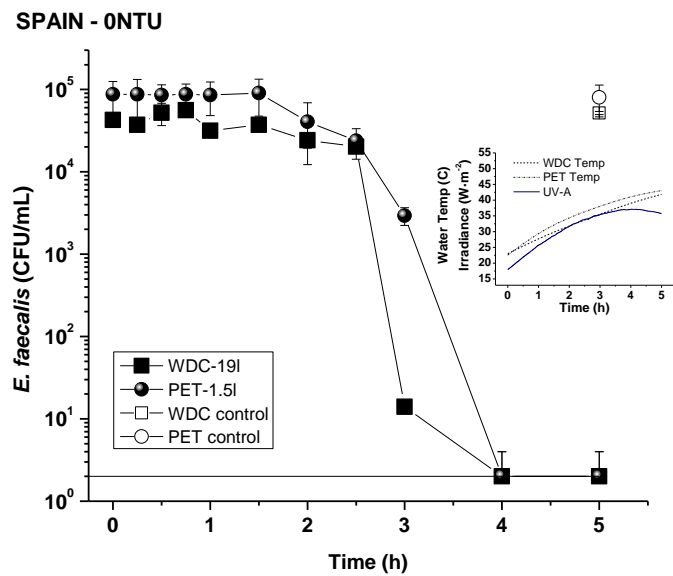


New Figure 3

a)

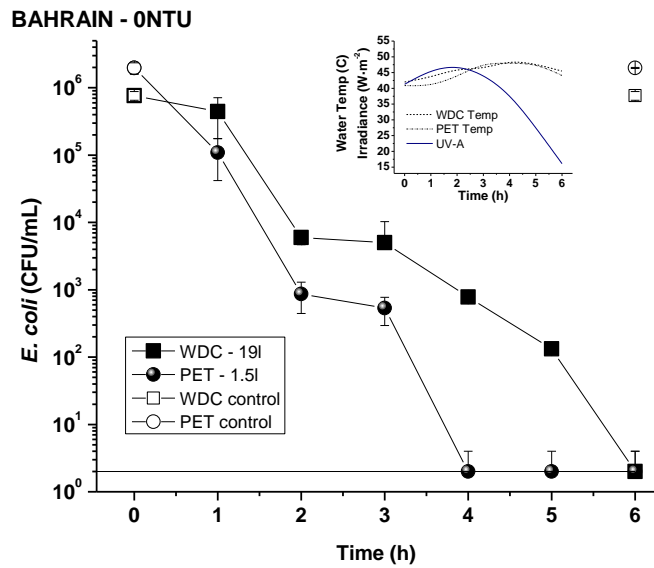


b)

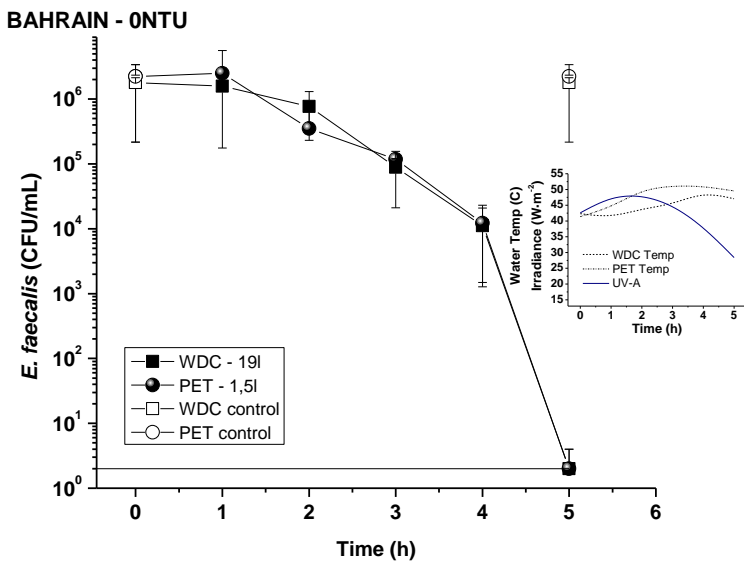


New Figure 4

a)



b)



New Figure 5

