UNIVERSITY OF MEDICINE AND HEALTH SCIENCES

Royal College of Surgeons in Ireland

repository@rcsi.com

Evaluation of Solar Disinfection of E. coli Under Sub-Saharan Field Conditions Using a 25 Litre Borosilicate Glass Batch Reactor Fitted with a Compound Parabolic Collector.

AUTHOR(S)

R Nalwanga, B Quilty, C Muyanja, P Fernández Ibáñez, Kevin G. McGuigan

CITATION

Nalwanga, R; Quilty, B; Muyanja, C; Ibáñez, P Fernández; McGuigan, Kevin G. (2014): Evaluation of Solar Disinfection of E. coli Under Sub-Saharan Field Conditions Using a 25 Litre Borosilicate Glass Batch Reactor Fitted with a Compound Parabolic Collector.. Royal College of Surgeons in Ireland. Journal contribution. https://hdl.handle.net/10779/rcsi.10792544.v1

HANDLE

10779/rcsi.10792544.v1

LICENCE

CC BY-NC-ND 4.0

This work is made available under the above open licence by RCSI and has been printed from https://repository.rcsi.com. For more information please contact repository@rcsi.com

URL

https://repository.rcsi.com/articles/journal_contribution/Evaluation_of_Solar_Disinfection_of_E_coli_Under_Sub-Saharan_Field_Conditions_Using_a_25_Litre_Borosilicate_Glass_Batch_Reactor_Fitted_with_a_Compound_Parabolic_Collector_/10792544/1

Evaluation of Solar Disinfection of *E. coli* Under Sub-Saharan Field Conditions Using a 25 Litre Borosilicate Glass Batch Reactor Fitted with a Compound Parabolic Collector

R. Nalwanga[1, 2], B. Quilty[2], C. Muyanja[3], P. Fernandez-Ibañez[4], K.G. McGuigan[1*]

[1]Dept. of Physiology & Medical Physics, Royal College of Surgeons in Ireland, Dublin, Ireland

[2]School of Biotechnology, Dublin City University, Dublin, Ireland

[3]School of Food Technology and Nutrition Makerere University , Kampala, Uganda

[4]Plataforma Solar de Almería – CIEMAT, P.O. Box 22, 07200 Tabernas, Almería, Spain.

Keywords: Solar disinfection (SODIS); enhancement technologies, compound parabolic collector (CPC); point of use water treatment

***Corresponding Author:** Kevin G. McGuigan. Dept. of Physiology and Medical Physics, The Royal College of Surgeons in Ireland, 123 St. Stephen's Green, Dublin 2, Ireland.

Phone: +353 1 4022207, E-mail: kmcguigan@rcsi.ie

Abstract

The bacterial inactivation efficacy of a solar water disinfection (SODIS) reactor consisting of a 25L borosilicate glass tube fitted with a compound parabolic collector (BGTR-CPC) was assessed under equatorial weather conditions in Uganda. The SODIS BGTR-CPC was tested over a 17-month period in Sub-Saharan conditions in Kampala, Uganda. The BGTR-CPC was filled with natural water from a nearby protected well. A wild strain of *Escherichia coli* isolated from local natural water was added to the reactor to give a starting population of between 10^5 and 10^7 CFU/100ml. This spiked water was exposed to natural sunlight. Satisfactory bacterial inactivation ($\log_{10}$ reduction values >6 units or inactivation to below the limit of detection (<1 CFU/100ml.)) was observed for 11 of 13 experiments. Rainfall and overcast/cloudy conditions were factors on both of the occasions when incomplete inactivation was observed. In conclusion, the use of CPC SODIS technology is suitable for treating drinking water both at household level and institutional level in Sub-Saharan and other similar tropical climates if careful consideration of the cloud cover and rainfall is taken into account.

1. Introduction

In many parts of the world households rely on untreated drinking water leaving them at great risk from waterborne disease. Solar disinfection (SODIS) is a point-of-use household water treatment which can be used to treat drinking water in those parts of the world where suitable levels of sunshine are available. SODIS usually involves exposing water in 1.5 to 2 L transparent bottles to sunlight for a minimum of 6 hrs and has been found to be effective against a range of waterborne pathogens including: *Salmonella typhimurium; Shigella dysenteriae; Escherichia coli (E. coli); Vibrio cholera* and *Pseudomonas aeuriginosa* (Berney *et al*., 2006; Kehoe *et al*., 2001; Smith *et al*., 2000; McGuigan *et al*., 1998). However, one disadvantage of SODIS remains the small treatment volume and the labour intensive nature of filling several bottles in order to treat an adequate volume. Other concerns relate to the possible release of genotoxic photoproducts into the water after prolonged use of plastic bottles. Despite experimental evidence to the contrary (Schmid *et al.*, 2008, Reed 2004, Ubomba-Jaswa *et al.,* 2010), many people have remained unconvinced about the safety of plastic SODIS bottles.

In addition to the practical restrictions mentioned earlier, in terms of solar collection, a major limitation of standard SODIS bottles is that usually they are only illuminated on the upper side that faces the sun. The bottles are often of irregular shape which makes it difficult for the sunlight to penetrate inside. The material from which they are made is PET, which absorbs sunlight in the UV-B range, the most damaging part of the available solar spectrum for microorganisms. Therefore, to improve the disinfection efficiency, other materials should be desirable for these solar reactor systems.

Efforts to improve the disinfection of water using solar energy include; 1) maximising the received solar energy dose, 2) enhancing the disinfection efficacy against resistant waterborne pathogens; 3) increasing the output volume of treated water; 4) reducing user dependence (work effort) associated with reactor systems; and 5) using cheap and robust materials for low-cost disinfection systems.

Research to develop low-cost solar reactors to enhance the efficacy of solar water disinfection has been carried out in the last decade (McGuigan *et al*. 2012, Marques *et al*., 2013). Some flow reactors have focused on increasing the optical inactivation component of sunlight inactivation using solar collectors and reflectors, while others have focused on increasing the thermal component of the solar

spectrum (Li *et al*. 2013). The most important criterion for good solar photo-reactor performance is the increase of output volume of treated water within a given solar exposure. To address these objectives one must take into account the collection of solar light (using either CPC solar mirrors or other low-cost reflectors which increase the solar light collection) into the photo-reactor must be efficient for large volumes of water. Therefore water turbidity is critical. If the water is sufficiently transparent (turbidity < 10 NTU) the optical reactor path length (i.e. diameter of the photo-reactor cross-section) can be increased up to 10 cm (Ubomba-Jaswa *et al*., 2010, Marques *et al*., 2013). If the water is not very transparent, then the required reactor diameter must be reduced to a few cm and the large volume requirement will be accomplished by connection of several photo-reactor modules.

There are limitations of solar disinfection when it is scaled-up through the use of large batch volumes or continuous flow recirculation reactors (Ubomba-Jaswa *et al*., 2010). Flow through systems have a negative effect on inactivation of bacteria as at a given time point there needs to be maximum exposure of bacteria to UV to ensure inactivation as compared to having bacteria exposed to several sub-lethal doses over a long period of time. When the water containing bacteria remains static under solar light it is constantly illuminated and hence the required uninterrupted UV dose is achieved and complete inactivation to below the detection level takes place. With continuous flow systems, the lethal dose will be deposited to the bacteria but in an intermittent manner and may not produce complete inactivation (Ubomba-Jaswa, 2009). This statement has important implications for those attempting to scale-up solar systems through the use of pumped, re-circulatory, continuous flow reactors. If the operational parameters are set such that the microbial pathogens are repeatedly exposed to sub-lethal doses of solar radiation followed by a period within which the cells have an opportunity to recover or repair, complete inactivation may not be achieved.

In order to address these challenges, a 25L volume borosilicate glass tube reactor fitted with a compound parabolic collector (BGTR-CPC) was developed by Ubomba-Jaswa and co-workers (2010) for solar treating drinking water. The CPC works by redistributing the incident sunlight over the entire outer surface of the reactor so that no portion of the reactor remains un-illuminated. While some previous research has looked at the possibility of using CPC reactors for solar remediation of microbiological contaminants in water (Duffy *et al*. 2004, Mcloughlan *et al*. 2004, Sciacca *et al*. 2011), no research has been carried out on its efficacy under real field conditions in Sub-Saharan African

Tropical regions. The aim of this study was therefore to assess the efficacy of the BGTR-CPC over an extended period of 17 months under local weather conditions in Uganda which is a tropical country with two rainy and two dry seasons in the year. If this research proved successful it could be used as proof of concept with wider geographical applications throughout Sub-Saharan Africa and the tropics in other continents.

2. Methodology

2.1 Source of *E. coli*

In this study *E. coli* was used as the indicator micro-because of its widespread use as an indicator of faecal pollution of water. *E. coli* UG-KST 001 was isolated from a protected well located in Kikonyi, a heavily populated slum 2km away from Makerere University in Kampala, Uganda. Untreated water sample (100 ml.) was filtered through 0.45-µm pore-size and 47-mm-diameter Whatman cellulose nitrate membrane filter (GN-6 Metricel Grid, Gelman Sciences Inc. USA). Filters were placed onto Chromocult Agar (CCA) plates and pre-incubated at ambient temperature for 4 hrs to aid bacterial resuscitation. The plates were then incubated at 37°C for 24 hrs. Presumptive *E. coli* colonies deep blue in colour and were confirmed with Indole production, Methyl red (MR), Voges-Proskauer (V-P) and Citrate tests (IMViC biochemical tests). Confirmed *E. coli* colonies were stabbed in Mueller-Hinton and kept at room temperature for further experiments.

2.2 *E. coli* inoculum preparation

E. coli obtained from Mueller-Hinton agar was streaked onto Nutrient Agar and incubated at 37°C for 24 hrs. A single colony was then used to inoculate sterile nutrient broth (Conda Pronadisa 1340) and was incubated at 37°C for 18 to 20 hrs. Cells were harvested by centrifugation at 8000x*g* for 10 min. The pellet was resuspended in 5 ml. of quater strength Ringers solution. Centrifugation and resuspension steps were repeated three times to remove all traces of the growth medium. The cell suspension was used to inoculate the reactor to give an initial concentration of *E. coli.* ranging from 10^5-10^7 CFU/100ml.

2.3 Water

In order to carry out the experiments under natural conditions and to avoid weakening of bacterial cells due to unfavourable osmotic environmental conditions, unautoclaved natural well-water was used (McGuigan *et al*., 2012). Water was collected from the Kikonyi well near Makerere University in Kampala on the day before the experiment and kept at ambient temperature overnight. The water was analysed for *E. coli,* pH, temperature and total dissolved solids (TDS).

2.4 Solar enhanced Compound Parabollic Borosilicate Glass Tube Batch Reactor (BGTR-CPC)

The BGTR-CPC SODIS reactor previously described by Ubomba-Jaswa *et al.* (2010) was used in this study. It was constructed by placing a glass tube at the linear focus of a compound parabolic collector (CPC) positioned with the axis of the tube and CPC aligned alon the North-South direction to recieve maximum solar radiation during the experiment. The borosilicate glass tube was fitted with an outlet valve in the bottom (for taking samples during experiments, and for emptying the treated volume after use) and a removable glass port at the top which facilitated filling the reactor. Untreated water was poured into the unit through the top of the tank. Once the tank was filled with water, the top was sealed using four Allen screws.

After the required exposure time, treated water was removed using the exit valve at the bottom. The CPC collector was made of highly reflective anodised aluminium (specular reflectivity in the UV-A spectrum is 92%). The glass tube had an internal diameter of 20 cm and an external diameter of 22cm. The concentration factor (CF) of the CPC was 1.0. The CPC collects both direct and diffuse UV-A so the tube is homogeneously illuminated even on cloudy days. All experiments were performed under natural solar radiation on a platform located at 0°20'15"N 32°33'51"E, the Makerere University, Kampala Uganda. The CPC was mounted on a frame elevated at 20° from the horizontal. Although the exposure is almost on the equator (Latitude 0°20'15"N) the elevation angle of the reactor was not reduced because some inclination was required to facilitate maximal filling and ease of emptying the reactor.

Experiments occurred on a monthly basis for a period of 17 months encompassing two dry and two wet seasons. Typically one experiment was conducted in each month and tests started at 10:00 am and finished at 5:00 pm local time. Samples were taken at hourly intervals.

2.5 Enumeration of *E. coli*

Enumeration of *E. coli* was conducted using the standard plate count method for the first 3 hrs of each experiment. Volumes of 0.1 ml. of the appropriately diluted sample were spread on chromocult agar (CCA) plates in triplicate and incubated at 37°C for 24 hrs. For all samples taken after 3 hrs, 100ml. water was filtered through 0.45 µm-pore-size and 47mm diameter Whatman cellulose nitrate membrane filters (GN-6 Metricel Grid, Gelman Sciences Inc. USA. The filters were placed onto CCA plates and incubated at 37°C for 24 hrs in a Paqualab 25 incubation kit. In both methods, deep blue colonies were counted as *E. coli*. Control samples were kept in the dark until the end of the experiment. The possibility of regrowth after treatment was also investigated by keeping part of the last sample at room temperature under dark conditions for 24 hrs, 100ml. of sample was then filtered and plated onto chromocult Agar at 37°C for 24 hrs. The numbers of typical colonies were counted to calculate the number of *E. coli*/100ml. water.

In determining the log reduction values, numbers of *E. coli* were expressed as $\log_{10}$ number of organisms/100ml. water. The number of log reductions was determined by subtracting the log of the number of cells remaining from the log of the initial number of cells. Inactivation curves were constructed by plotting the number of *E. coli* as $\log_{10}$ (N_t) against time. Where N_t = number of cells at time t.

2.6 Measurement of environmental conditions

Solar UV irradiance was measured with a global UVA+B radiometer (Solartech, USA). The temperature, pH and TDS of samples were measured using a calibrated pH/TDS meter (model HI 9813-6N, Hanna Instruments, S.L., Eibar, Spain).

Observations of weather conditions were recorded at each sampling. In this experiment, the experimental day was described as sunny, intermittent sunny/cloudy or cloudy/overcast. A sunny day was defined as zero cloud cover with strong sunshine for at least three quarters of the day and with

the remainder having not more than 1/4 cloud cover (2 octa) and no rain. We defined an intermittently sunny/cloudy day as having between 1/4 and 1/4 cloud cover (2 octa – 4 octa) for more than 4 hrs. We defined a cloudy/overcast day as having at least ½ cloud cover (4 octa) throughout the experiment.

2.7 Data analysis

All samples were analysed in triplicate. Mean values and standard deviations were determined using Excel. One-way analysis of variance (ANOVA, Origin v7.0300, OriginLab Corp., Northampton, USA) was used to determine the significant differences between means.

3. Results

Uganda typically has two rainy and two dry seasons per calendar year, however, the timing of these is no longer reliable due to the effects of climate change. For the period of this study April, May, August, September, October, November and December were rainy (wet) months (rainy season) while January, February, March, June and July were dry months (dry seasons). However, in between the rainy or dry seasons some days could be sunny or cloudy rainy. Data were recorded on 13 occasions over a 17 month period from May 2011 to September 2012. Data were not collected for the months of June 2011, August 2011, October 2011 and October 2012.

3.1 Characteristics of untreated natural water

The characteristics of the untreated water used in all the experiments are described in Table 1. The temperature and pH of the source water did not vary significantly ($p>0.05$) for the duration of the investigation. The temperature ranged from 22°C – 27°C and the pH from 6.0 – 7.7. The level of total dissolved solids varied significantly ($p = 0.001$) with the season ranging from 26 – 63 mg l^{-1} in the rainy season and from 8 – 25 mg l^{-1} in the dry season. The levels of *E. coli* in the untreated water also

varied from month to month and higher numbers were detected during the rainy season and corresponded with higher levels of dissolved solids.

3.2 Response of *E. coli* to solar disinfection using the CPC

The response of *E. coli* to solar disinfection using the CPC was monitored over a 17 month period from May 2011 to September 2012. None of the control samples, incubated in the absence of light, showed any significant difference ($p>0.05$) in cell numbers from the starting inoculum size. This implied that there was neither growth nor inactivation under dark storage. Furthermore, none of the samples that were taken at the end of experiments and stored for 24 hrs in the dark showed any significant change ($p>0.05$) in cell numbers indicating that there was no re-growth of *E. coli* after treatment.

The results obtained on 13 occasions during this period are described in Figure 2 which shows the starting population, final population after 7 hrs solar exposure and the $\log_{10}$-unit removal values (LRV) for all experiments. It is evident from this figure that the starting bacterial inoculum varied between 10^5 and 10^7 CFU/100ml. Complete inactivation to below the detection limit (< 1 CFU/100ml) was achieved for all 6 exposures conducted under strong sunlight conditions. If satisfactory disinfection is defined as one which produces either a LRV ≥ 6.0, as recommended by the US EPA (1987), or inactivation to below the Ugandan National Bureau of Standards guidelines (UNBS 2008) for safe drinking water (< 1 CFU/100ml), then successful disinfection of the 25 litre batch volume was achieved in 11 of the 13 experimental investigations. Only experiments conducted in Sept 2011 (LRV = 4.5) and April 2012 (LRV = 3.0) failed to produce satisfactory disinfection levels. The former was conducted under intermittently sunny/cloudy conditions and the latter under cloudy overcast skies, both exposures experienced periods of rain or drizzle.

Representative data for Sunny (a), Intermittently Sunny/Cloudy (b) and completely Overcast/Cloudy (c and d) months during the study period are presented in Figure 3. An absence of data at any time point before the end of exposure (7 hrs) indicates the bacterial population is below the limit of detection (1

CFU/100ml.). In Sept 2012, complete inactivation was achieved within 7 hours. No colonies were obtained from the samples taken after 7 hrs exposure indicating the population at this time was below the limit of detection (1 CFU/100ml.). Satisfactory inactivation of the bacteria was achieved for the sunny (a) and intermittently sunny/cloudy (b) conditions. LRVs of 7-log units are observed within 6 and 7 hrs for the Sept 2012 (sunny) and Aug 2012 (intermittently sunny/cloudy) conditions, respectively.

In the case of the overcast/cloudy months while the inactivation of the bacteria was unsatisfactory in April 2012, a satisfactory response in March 2012 was attributed to the higher levels of UV detected. The April 2012 exposure was conducted under such rainy/overcast conditions that we suspected complete inactivation would not be achieved during the 7 hrs duration of the experiment. Consequently the experiment was extended to the following day and the results of this two-day exposure are provided in Figure 4. Despite improved cloud and sunshine conditions on Day 2 full inactivation was not achieved with final concentration remaining at 10^4 CFU/100ml. Figure 5 shows the maximum water temperatures achieved in the BGTR-CPC reactor for each experiment.

4 Discussion

In the current study, *E. coli* was the organism of choice because it is widely used as a faecal indicator and is known to be resistant to sunlight compared to other bacteria such as *Salmonella typhi*, *Shigella flexneri* and *Pseudomonas aeruginosa* (Wegelin *et al*., 1994). Since the control and t_0 concentrations were not significantly different, the observed inactivation of *E. coli* in all the experiments was as a result of SODIS treatment and there was no re-growth of *E. coli* after treatment in all experiments.

These experiments formed part of a larger research programme (The “Water is Life –Amazzi Bulamu” project, see www.waterislife.ie) funded by the Irish government. Work committments for the Uganda based graduate researcher (RN) on other work-packages within this project resulted in the BGTR-CPC experiments having to take place in the fourth week of each calendar month. Consequently

given the preparation time required for each experiment (one day to prepare the inoculum, one day to conduct the exposure and 1 day to analyse the results), there was no possibility of waiting for optimal weather conditions. Instead each experiment started on roughly the same day (± 1 day) of each month, regardless of weather conditions. As shown above, season does not guarantee the daily weather conditions or the number of hours (days) of exposure for full treatment. However, as one might expect, the chances of experiencing a cloudy day are higher in a wet season than in a dry season.

Compared to other enhanced SODIS technologies for example methacrylate and PET bottles, the borosilicate glass reactor has the best transmission properties for the microbicidal UVA and UVB (Ubomba-Jaswa *et al*., 2010). A 2.5L borosilicate glass tube reactor of 2.5L volume was found to achieve full inactivation of *E. coli* K-12 under both sunny and partially sunny in only 3 hrs exposure (Ubomba-Jaswa *et al*., 2010). However, in this current study the 25L borosilicate glass tube reactor required 6-7 hrs on continously sunny days to achieve complete inactivation of the bacteria. This difference in exposure time of required to achieve complete inactivation of *E. coli* can be attributed to a number of factors. The current research used a borosilicate glass tube reactor of 25L which is 10 times larger in terms of volume than that used by Ubomba-Jaswa *et al*. (2009). The diameter of the current CPC tube used is 20cm and so solar radiation has a longer path-length to traverse than in the smaller CPC tube of 5cm diameter that was used in Ubomba-Jaswa *et al*.(2009).

In this study, a wild strain of *E. coli* isolated from protected natural well water located in a heavily populated slum was used. Ubomba-Jaswa *et al*.(2009) used a laboratory strain (*E. coli* K-12). Wild strains of *E. coli* are known to be more resistant to treatment than laboratory strains like *E. coli* K-12 and therefore they are more suitable for testing treatment efficiencies than laboratory strains (Quek and HU, 2008). Comparing the results reported here with the first testing of a CPC-25l methacrylate reactor (Ubomba-Jaswa *et al.*, 2010), we observe similar treatment times to attain the detection limit starting at similar initial concentrations of *E. coli*. Although in the former study the water was only well water with no dissolved solids (maximum dissolved organic carbon in the water was 5 mg l^{-1}), very low turbidity (1.5 NTU), and with spiked bacteria from the Spanish collection of cultures (Ubomba-Jaswa *et al.*, 2010). These collection strains have been shown to be more sensitive to any disinfection

method than wild species isolated from real contaminated water sources (Agulló-Barceló *et al*., 2013). In the present study, the real contaminated water presents with a complex chemical matrix, a moderate level of TDS and naturally ocurring bacteria, as explained in the experimental section.

A lower efficiency on the solar disinfection for real contaminated waters as compared with ideal conditions of distilled water and well water spiked with culture strain collection bacteria was also reported with a similar design CPC-25l-solar reactor in a recent study carried out at PSA in Southern Spain (Bichai *et al.*, 2012). The authors assessed the efficiency of solar disinfection to reduce microbial contamination in solar-treated real wastewater effluents from a municipal wastewater treatment plant which was subsequently used for irrigation of horticultural crops. They reported solar disinfection results of 20 litres of real wastewater effluents with *E. coli* bacterial decrease from concentrations of $>10^3$-10^4 CFU/ml to <2 CFU/ml. (detection limit of that study) within 4 hrs of solar exposure using the same reactor under clear sunny conditions in the South of Spain. They reported that the required exposure times for disinfecting similar levels of *E. coli* in distiled water (1h), well water (1.5h) and simulated effluents of wastewater (3h) were shorter than for real contaminated wastewaters (4h) (Bichai *et al*., 2012). It should be noted that complete inactivation was achieved even when high starting inoculum sizes of the order of 10^7 CFU/100ml. were used. Such starting populations would be consistent with wastewater treatment (Kitis 2004).

Despite the fact that the synergistic effect of temperature and UVA has been reported to play a key role in SODIS inactivation of bacteria (Kehoe *et al*., 2001, Ubomba-Jaswa *et al*. 2010) this was not observed in the current study. The main reason for this is that the thermal inertia associated with the large volume of water is such that water temperature increased slowly during solar exposures compared with those reported for smaller volumes of up to 2.5L. None of the current experiments in achieved maximum water temperatures near the 45°C that has been reported necessary for a synergistic effect (Joyce *et al.* 1996). However, since the irradiated collector surface of the 25L CPC is ~2 times that of the 2.5L CPC reactor used by Ubomba-Jaswa *et al.* (2010), a 25L CPC would require nearly 5 times longer continous solar exposure to attain 45°C from 20°C compared to the time required for the smaller volume reactor. Consequently, given the disparity between volume and illuminated area, it is not surprising that the maximum water temperature achieved at any point in the studies was only 38°C (December 2011) for the 25L reactor.

Total dissolved solids (TDS) have also been reported to have an effect on bacterial inactivation for several SODIS enhancement reactors (Kehoe *et al.,* 2001). Curtis *et al.* (1992) suggested that natural organic matter may facilitate faster solar disinfection as it acts as photo-sensitizer. Ubomba-Jaswa *et al*. (2009) also noted that the higher the turbidity, the higher the maximum water temperature attained since the organic matter absorbs heat (Kehoe *et al*., 2001). On the other hand, increased turbidity reduces solar light penetration (Joyce *et al*., 1996, Kehoe *et al.*, 2001) which is very important in treating microbes in water. Therefore, the advantage of increased temperature as a result of increased turbidity to facilitate increased synergicistic effect between UVA and temperature to inactivate bacteria is thus not enough to compensate for the reduction of solar penetration through turbid water (Kehoe *et al*., 2001).

Conclusion:

Complete and satisfactory bacterial inactivation was achieved using the 25L BGTR-CPC SODIS reactor under conditions of strong continuous sunlight or of intermittently sunny/cloudy conditions. However, completely overcast conditions accompanied by periods of rainfall may result in incomplete inactivation (LRV = 3.0) even after 2 days exposure. The exposure time required to obtain fully treated water (safe drinking water) with use of the CPC does not depend on seasons but on daily weather conditions. The use of CPC SODIS reactor technology is suitable for treating drinking water both at household level and institutional level in Sub-Saharan Africa and other similar tropical climates if careful consideration of the cloud cover and rainfall is taken into account.

Acknowledgement

This work forms part of a large-scale research project 'Water is life: *Amazzi Bulamu'* which is a multi-disciplinary collaboration of various academic institutes, NGOs and stakeholders in Ireland and Uganda (**www.waterislife.ie**). Funding was provided by the Irish Aid/HEA Programme for Strategic Cooperation and is gratefully acknowledged. Financial support by the Access to Research Infrastructures activity FP7-SFERA (Grant number 228296) is also gratefully acknowledged. In

addition, the authors are grateful to Mr. Atuihire Colins, Ms Eugene Manda, Ms.Stella Byakika, the Medical Missionaries of Mary and the Makondo community, for their cooperation, support and input. 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.

References

1. Agulló-Barceló, M., Polo-López, M.I., Lucena, F., Jofre J., Fernandez-Ibañez P. 2013. Solar Advanced Oxidation Processes as disinfection tertiary treatments for real wastewater: implications for water reclamation. Appl. Catal. B: Environ. 136–137, 341– 350.
2. Berney, M., Weinelnmann, H.U., Simonetti, A., Egli, T. 2006. Efficacy of solar disinfection of *Escherichia coli, Shigella flexneri, Salmonella Typhimurium* and *Vibrio cholera*. J. Appl. Microbiol. 101, 828–836.
3. Bichai, F., Polo-Lopez, M.I., Fernández-Ibañez, P. 2012. Solar disinfection of wastewater to reduce contamination of lettuce crops by E. coli in reclaimed water irrigation. Water Research 40, 6040-6050.
4. Buchanan, R. E. and Gibbons, N. E. (eds), 1974. Bergey's manual of determinative Bacteriology. 8th ed. Baltimore: The Williams and Wilkins.
5. Curtis, T. P., Mara, D. D., Silva, S. S., 1992. Influence of pH, oxygen, and humic substances on ability of sunlight to damage fecal coliforms in waste stabilization pond water. Appl. Environ. Microbiol. 58, 1335-1343.
6. Duffy EF, Al Touati F, Kehoe SC, McLoughlin OA, Gill L, Gernjak W, Oller I, Maldonado MI, Malato S, Cassidy J, Reed RH, McGuigan KG., 2004. A novel TiO_2-assisted solar photocatalytic batch-process disinfection reactor for the treatment of biological and chemical contaminants in domestic drinking water in developing countries. *Solar Energy*, 77(5):649-655.
7. Joyce, T.M., McGuigan, K.G., Elmore-Meegan, M., Conroy, R.M., 1996. Inactivation of fecal bacteria in drinking water by solar heating. Appl. Environ. Microbiol.62, 399–402.

8. Kehoe, S.C., Joyce, T.M., Ibrahim, P., Gillespie, J.B., Shahar R.A., McGuigan K.G., 2001. Effect of agitation, turbidity, aluminium foil reflectors and container volume on the inactivation efficiency of batch process solar disinfectors. Water Research 35, 1061–1065.
9. Kitis, M., 2004. Disinfection of wastewater with peracetic acid: a review. Environmental International, 30, 47– 55
10. Li, X; Dai, YJ; Li, Y; Wang, RZ. 2013. Comparative study on two novel intermediate temperature CPC solar collectors with the U-shape evacuated tubular absorber. Solar Energy, 93, 220-234
11. Marques, A.R., de Cassia-Oliveira Gomes, F. Pontes Fonseca, M.P., Soares Parreira, J., Pinheiro Santos, V., 2013. Efficiency of PET reactors in solar water disinfection for use in southeastern Brazil. Solar Energy 87, 158–167.
12. McGuigan, K.G., Conroy, R.N., Mosler, H.J., Preez, M. Du., Ubomba-Jaswa, E., FernandezIbanez, P., 2012. Solar water disinfection (SODIS): A review from benchtop to rooftop. J. Hazard. Mater. 235– 236, 29– 46.
13. McGuigan, K.G., Joyce, T.M., Conroy, R.M., Gillespie, J.B., Meegan, M.E., 1998. Solar disinfection of drinking water contained in transparent plastic bottles: characterizing the bacterial inactivation process. J. Appl. Microbiol. 84, 1138–1148.
14. McLoughlin OA, Kehoe SC, McGuigan KG, Duffy EF, Al Touati F, Gernjak W, Oller I, Malato S, Gill LW., 2004. Solar disinfection of contaminated water: a comparison of three small-scale reactors. *Solar Energy*, 77(5):657-664.
15. Meera, V., Ahammed, M. M., 2008. Solar disinfection for household treatment of roof-harvested rainwater. Water Sci. Technol. 8, 153–160.
16. Navntoft, C., Ubomba-Jaswa, E., McGuigan, K.G., Fernández-Ibáñez, P., 2008. Effectiveness of solar disinfection using batch reactors with non-imaging aluminium reflectors under real conditions: Natural well-water and solar light. J. Photochem. Photobiol. B: Biol. 9, 155–161.
17. Quek, P. H., Hu, J., 2008. Indicators for photoreactivation and dark repair studies following ultraviolet. J. Indust. Microbiol.Biotechnol. 35(6), 533-54.
18. Reed, R.H., 2004. The inactivation of microbes by sunlight: solar disinfection as a water treatment process, Adv. Appl. Microbiol. 54, 333–365.

19. Schmid, P., Kohler, M., Meierhofer, R., Luzi, S., Wegelin, M., 2008. Does the reuse of PET bottles during solar water disinfection pose a health risk due to the migration of plasticisers and other chemicals into the water? Water Research 42, 5054–5060.
20. Sciacca, F ; Rengifo-Herrera, JA; Wethe, J ; Pulgarin, C. 2011. Solar disinfection of wild *Salmonella* sp. in natural water with a 18 L CPC photoreactor: Detrimental effect of non-sterile storage of treated water. Solar Energy, 85, 1399-1408.
21. Smith, R.J., Kehoe, S.C., McGuigan, K.G., Barer, M.R., 2000. Effects of simulated solar disinfection of water on infectivity of *Salmonella typhimurium*, Lett. Appl. Microbiol. 3, 284–288.
22. Ubomba-Jaswa, E., Navntoft, C., Polo-Lopez, M.I., Fernández-Ibanez, P., McGuigan, K. G., 2010. Investigating the microbial inactivation efficiency of a 25 litre batch solar disinfection (SODIS) reactor enhanced with a compound parabolic collector (CPC) for household use. J. Chem. Technol. Biotechnol. 85, 1028–1037.
23. Ugandan National Bureau of Standards. 2008-2009 Drinking (potable) Water Specification, Uganda National Bureau of Standards, Reference number US 201:
24. US EPA, 1987. Guide Standard and Protocol for Testing Microbiological Water Purifiers. Washington, DC: United, States Environmental Protection Agency.
25. Wegelin, M., Canonica, A., Alder, A., Suter, M., Bucheli, T.D., Haefliger, O.P., Zenobi, R., McGuigan, K.G., Kelly, M.T., Ibrahim, P., Larroque, M. 2001. Does sunlight change the material and content of PET bottles? J. Water SRT – Aqua 50, 125–135.
26. Wegelin, M., Canonica, S., Mechsner, K., Fleischmann, T., Pesaro, F., Metzler, A., 1994. Solar water disinfection: scope of the process and analysis of radiation experiments. Aqua 43, 154-169.
27. World Health Organization. 2008. Guidelines for Drinking-water Quality. World Health Organization, Geneva. ISBN 978 92 4 154815 1
28. World Health Organization. 2011. Evaluating household water treatment options: health-based targets and microbiological performance specifications. ISBN 978 92 4 154822 9.

Table 1. Physico-chemical and microbial quality of untreated natural water collected from Kikonyi protected well.

Exposure Date (MM/YY)	*E. coli* conc. CFU/100ml	Temp. (^oC)	pH	Total Dissolved Solids (mg l^{-1})	Season (Rainy/Dry)
05/11	136 ± 11	23.0	7.6	32	Rainy
07/11	117 ± 5	23.5	6.3	19	Dry
09/11	174 ± 30	25.0	6.8	40	Rainy
11/11	11 ± 2	23.0	6.8	47	Rainy
12/11	>300	23.8	6.0	55	Rainy
01/12	136 ± 14	27.0	6.4	12	Dry
02/12	190 ± 23	23.0	7.3	10	Dry
03/12	56 ± 15	22.1	5.8	21	Dry
04/12	230 ± 23	25.0	6.0	37	Rainy
06/12	91 ± 13	22.0	7.6	25	Dry
07/12	126 ± 6	22.0	6.0	8	Dry
08/12	>300	23.0	6.9	63	Rainy
09/12	105 ± 5	23.0	7.7	26	Rainy

Figure Captions:

Figure 1. The 25L volume borosilicate glass tube reactor fitted with a compound parabolic collector (BGTR-CPC) of concentration factor CF=1.

Figure 2. Summary of the bacterial inactivation efficacy of the BGTR-CPC over the study period.

Figure 3. A comparison of bacterial inactivation (-) and incident UVA+B (-) for a representative sample of Sunny (a), Intermittently Sunny/Cloudy (b) and completely Overcast/Cloudy (c and d) months during the study period. An absence of data at any time point indicates the bacterial population is below the limit of detection (1 CFU/100ml.)

Figure 4. Bacterial inactivation (-) and incident UVA+B (-) over two consecutive days within a completely cloudy/overcast period in April 2012.

Figure 5. Maximum water temperature achieved in CPC during each exposure.

Figure 1

Figure 2

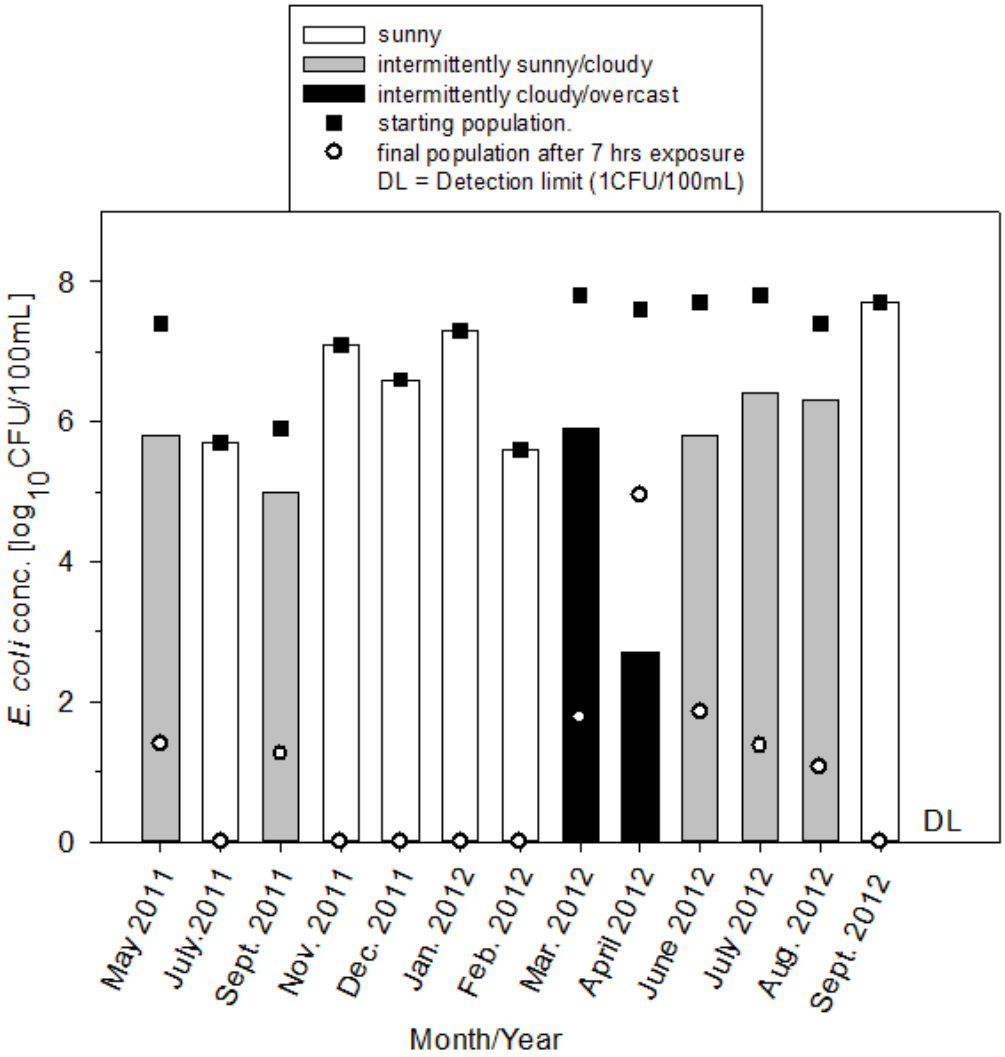

sunny
intermittently sunny/cloudy
intermittently cloudy/overcast
starting population.
final population after 7 hrs exposure
DL = Detection limit (1CFU/100mL)
E. coli conc. [log10CFU/100mL]
0
2
4
6
8
DL
May 2011
July 2011
Sept. 2011
Nov. 2011
Dec. 2011
Jan. 2012
Feb. 2012
Mar. 2012
April 2012
June 2012
July 2012
Aug. 2012
Sept. 2012
Month/Year

Figure 3

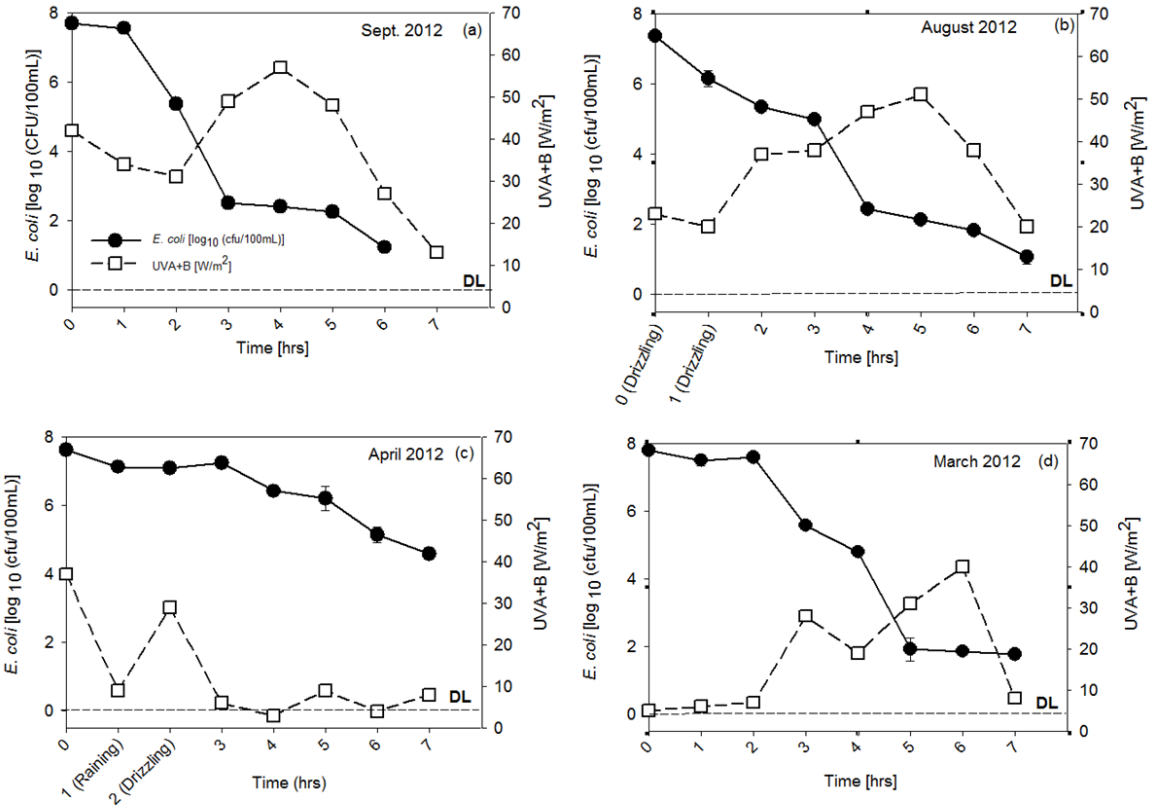

Sept. 2012 (a)
E. coli [log 10 (CFU/100mL)]
UVA+B [W/m2]
E. coli [log10 (cfu/100mL)]
UVA+B [W/m2]
DL
Time [hrs]
August 2012 (b)
E. coli [log 10 (cfu/100mL)]
UVA+B [W/m2]
DL
0 (Drizzling)
1 (Drizzling)
Time [hrs]
April 2012 (c)
E. coli [log 10 (cfu/100mL)]
UVA+B [W/m2]
DL
1 (Raining)
2 (Drizzling)
Time (hrs)
March 2012 (d)
E. coli [log 10 (cfu/100mL)]
UVA+B [W/m2]
DL
Time [hrs]

Figure 4

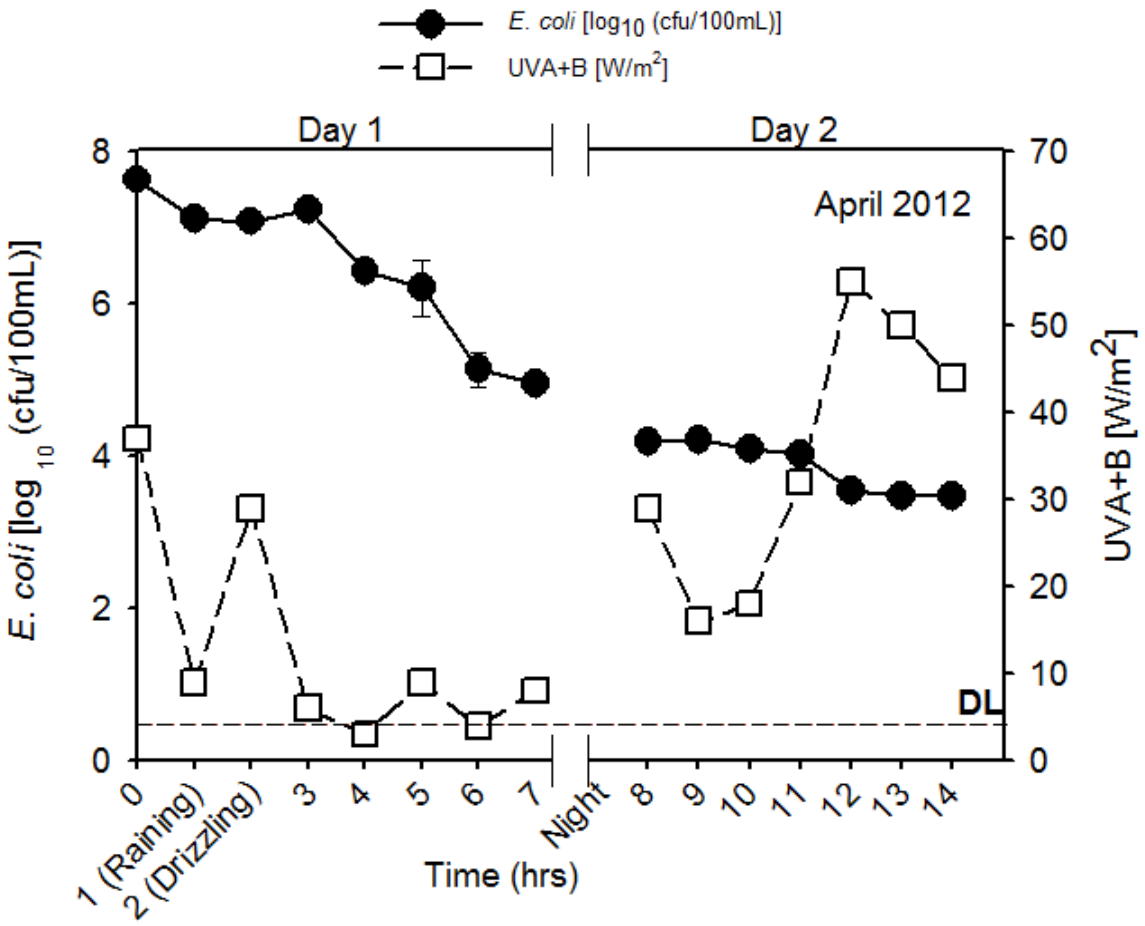
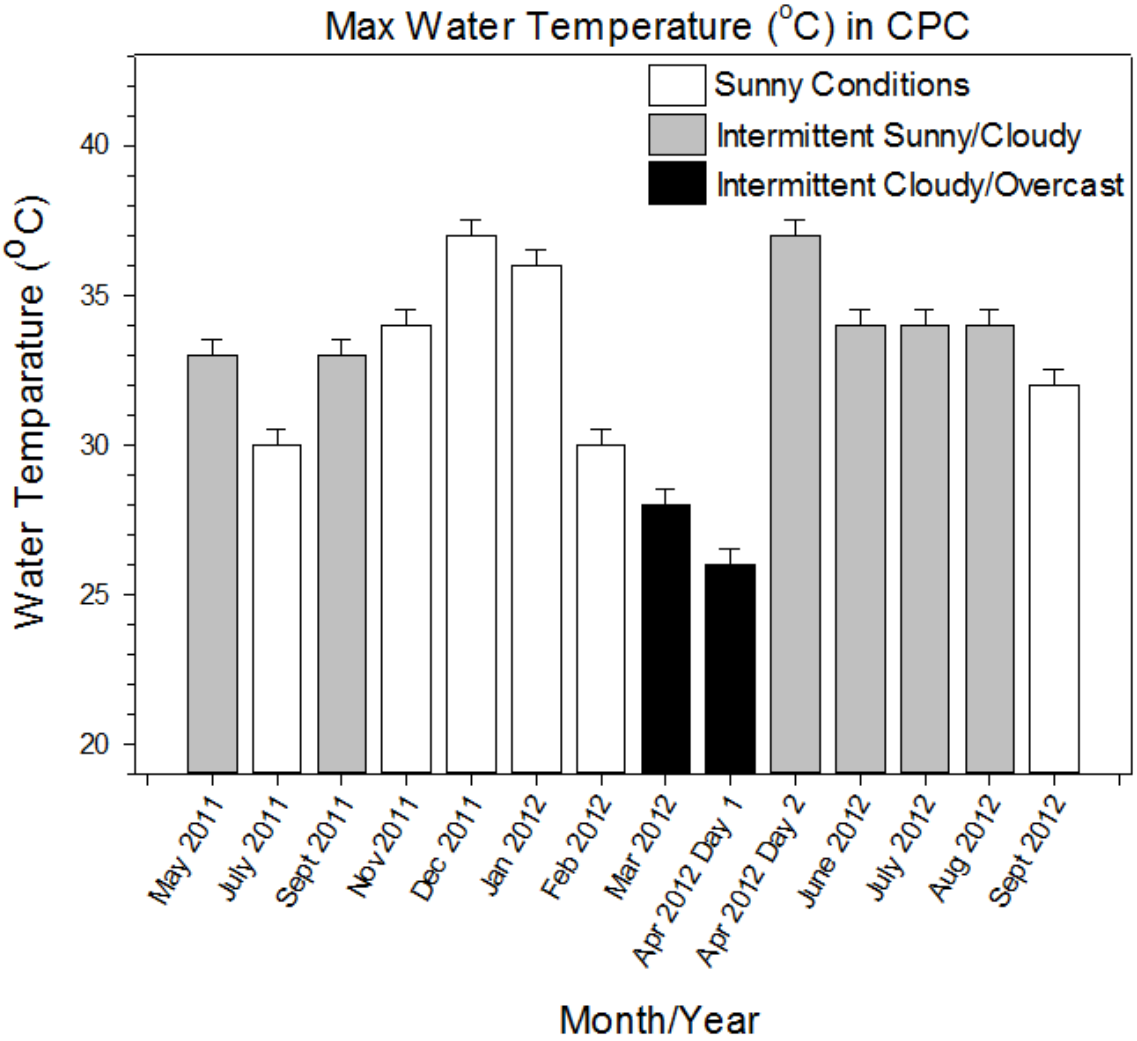
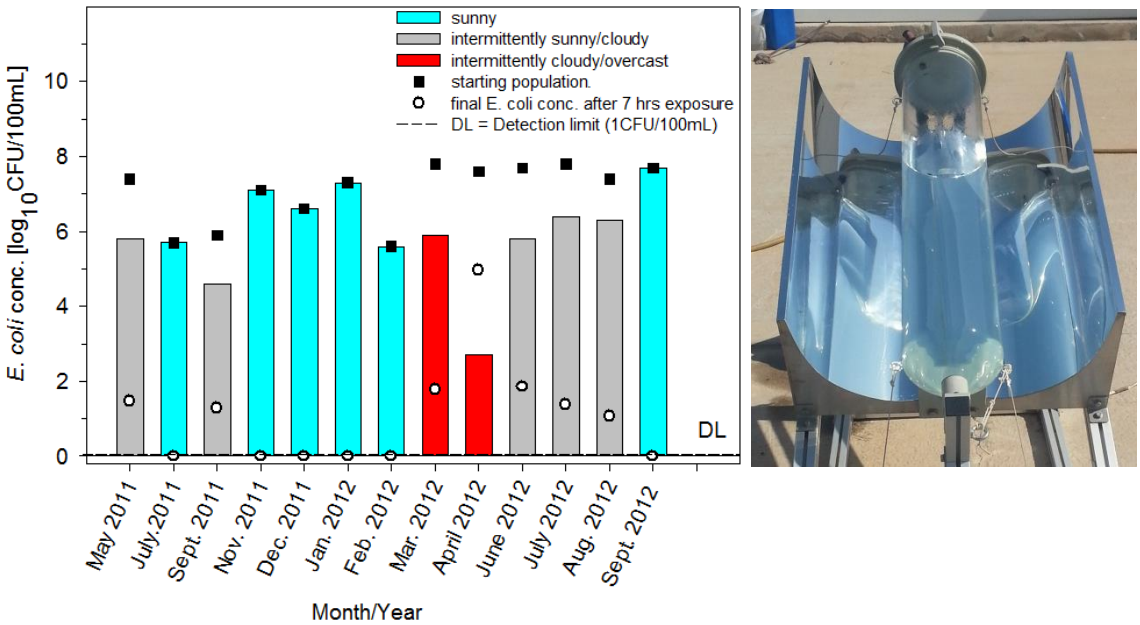

E. coli [log10 (cfu/100mL)]
UVA+B [W/m2]
Day 1
Day 2
April 2012
DL
E. coli [log 10 (cfu/100mL)]
UVA+B [W/m2]
Time (hrs)
1 (Raining)
2 (Drizzling)
Night
0
3
4
5
6
7
8
9
10
11
12
13
14
0
2
4
6
8
0
10
20
30
40
50
60
70

Figure 5


Max Water Temperature (°C) in CPC
Sunny Conditions
Intermittent Sunny/Cloudy
Intermittent Cloudy/Overcast
Water Temparature (°C)
40
35
30
25
20
May 2011
July 2011
Sept 2011
Nov 2011
Dec 2011
Jan 2012
Feb 2012
Mar 2012
Apr 2012 Day 1
Apr 2012 Day 2
June 2012
July 2012
Aug 2012
Sept 2012
Month/Year

Graphical Abstract