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Authors: Azahara Martínez-García[1], Isabel Oller[1], Martin Vincent[2], Viviana Rubiolo[2], Jacent K. Asiimwe[3], Charles Muyanja[4], Kevin G. McGuigan[5], Pilar Fernández-Ibáñez[6*], María Inmaculada Polo-López[1*]

Affiliations:

[1]CIEMAT-Plataforma Solar de Almería-CIEMAT, Carretera de Senés Km 4, Tabernas (Almería), Spain.

[2]Ecosystem Environmental Services S.A., Sant Andreu de Llavaneres, Barcelona, Spain

[3]Kyambogo University, Department of Human Nutrition and Home Economics, Kampala-Uganda.

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

[5]Dept. of Physiology and Medical Physics, RCSI University of Medicine and Health Sciences, Dublin D02 YN77, Ireland.

[6]Nanotechnology and Integrated BioEngineering Centre, School of Engineering, University of Ulster, Newtownabbey, Northern Ireland, United Kingdom.

***CORRESPONDING AUTHORS:**

Dr. M. Inmaculada Polo López

CIEMAT-Plataforma Solar de Almería. P.O. Box 22, 04200 Tabernas, Almería, Spain Phone: + 34 950 387900, E-mail: mpolo@psa.es

Dr. Pilar Fernández-Ibáñez

NIBEC, School of Engineering, University of Ulster, Newtownabbey, Northern Ireland, United Kingdom. Phone: +44 2890368979, E-mail: p.fernandez@ulster.ac.uk

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ABSTRACT

Two large reactors designed for solar water disinfection (SODIS) of harvested rainwater (HRW) were built and tested in Spain (controlled conditions) and Uganda (field testing). Both reactors use V-trough aluminium mirrors and UV-transparent poly(methyl-methacrylate) (PMMA) photo-reactor tubes of diameters, 100 mm and 200 mm, for treating 90L and 140L per batch, respectively. No differences in terms of treatment performances was obtained between both solar reactors. Complete disinfection of synthetic HRW spiked with a consortium of waterborne pathogens (*E. coli, S. enteritidis*, *E. faecalis* and MS2 coliphage) was achieved under natural sunlight, obtaining > 5-log reduction values (LRV) of all bacteria for a maximum solar UVA dose of 270 kJ/m^2 or 120 minutes of solar exposure. A 5-LRV for MS2 virus was also achieved with a maximum of up to 620 kJ/m^2 of UVA dose or 300 min of solar exposure. Accelerated and natural aging of the PMMA material was also investigated, showing that the material is highly transparent in the UVB (from 7 to 75%) and UVA (87%) and photostable, with not significant change in UV-B&A transmittance for 9 months under extreme conditions of solar radiation, humidity and temperature. Results for the reactors in the field, in two rural primary schools in Uganda over 1 year, demonstrated excellent performances with complete reductions of the bacterial load in natural HRW to undetectable levels of *E. coli*, *E. faecalis* and Total coliforms, meeting Ugandan national standards for potable water. A cost analysis, materials selection and solar resources needed have been carried out to determine the affordability and feasibility of this technology. Results of this analysis demonstrated the potential capability of the 140L solar V-trough reactor for treating HRW, with an estimated cost of €0.0012 per litre.

Keywords: solar water disinfection; photo-reactor; waterborne; poly(methyl-methacrylate); transmittance.

1. INTRODUCTION

Scarce natural fresh-water resources are currently one of the main health and environmental concerns worldwide. The 2019 United Nations report on progress towards Sustainable Development Goal 6 (SDG6 – Clean Water and Sanitation) [1], indicates that even though the percentage of global population (71%), with access to safely managed drinking water services, has increased compared with 2015 (61%), billions of people remain without access to safe water and rely on inadequate sanitation facilities. This appalling situation is likely to deteriorate further in the near future due to growing demand for fresh water sources, increased pollution of existing water sources and the effects of climate change, (i.e. raising the frequency and severity of droughts and floods), as well as increasing in the number of people relying on river basin water sources.

The lack of sanitation and access to safe water is associated with increased risks of contracting infectious waterborne diseases such as diarrhoea, cholera, hepatitis, dysentery, etc [2]. This is the main cause of morbidity and mortality in the elderly population and children under five, according to World Health Organization [3]. Provision of safe drinking water not only prevents waterborne and other infectious diseases but also leads to improved nutritional status and growth outcomes for children under 5 years old [4]. Low-income areas are in particular, dramatically affected by this issue. In these settings, surface waters such as lakes, rivers, open wells and dams are the main water sources for drinking but are often faecally contaminated.

Harvested rainwater (HRW) is an emerging alternative source of fresh water which has been used in recent decades in Sub-Saharan Africa to mitigate this situation [5]. Most HRW systems consist of a collection tank connected to a catchment roof area. A number of chemical and microbial contaminants have been identified in harvested rainwater [6] rendering it non-potable according to most national guidelines. Nevertheless, in many areas of the world, HRW is frequently used for drinking in the absence of better alternatives [7]. In such settings water treatment techniques must be put in place. Due to the lack of centralised treatment solutions, household water treatment interventions are usually practiced by the users or by non-governmental organizations (NGOs). Therefore, such treatments must be easy to use, install and maintain, while being accessible and affordable.

While chlorination, filtration and boiling are the most frequently used treatments, solar water disinfection (SODIS) can be used to treat small volumes of water in regions of high solar irradiation. Typical SODIS practice involves filling 1-2L PET (polyethylene terephthalate) containers with available water and placing them in full sunshine for a minimum of 6 hours. During solar exposure, UV radiation damages the microbial cells until they are completely non-viable. Damage is caused by i) UVB radiation which is absorbed by bacterial DNA preventing its replication and/or generating mutations [8], and ii) UVA radiation reaching various endogenous or exogenous chromophores altering the electron transport chain which induces the creation of Reactive Oxygen Species (ROS) [9]. These ROS species cause oxidative stress that produces, inter alia, pyrimidine dimers, peroxidation of proteins and lipids or DNA rupture [10], which prevent normal cellular function.

SODIS is recognised as a zero-cost intervention that has been extensively investigated over the past 30 years. SODIS is recognized by the WHO as a suitable household water treatment and safe storage technique [11]. Hundreds of articles have demonstrated that solar disinfection is an effective technique for killing a variety of resistant waterborne pathogens and to provide safer water [12]. However, a number of obstacles to widespread SODIS use remain. Foremost amongst these is the small batch volume of treated water that one can deliver using 1-2L PET bottles. In addition, SODIS compliance in the field remains a challenge due loss of bottles during exposure and the tedious workload associated with refilling and exposing the bottles [13]. Consequently, research on solar containers to increase the output treated water and ease the water access has been identified as key to promote use of SODIS in the field. Another critical drawback is its strong dependence on availability of strong sunlight to deliver safer water, especially when inactivating resistant pathogenic species [14]. Thus, improving the efficiency of the SODIS process is of paramount importance in order to deliver safe drinking water.

Recent publications reported some reactor prototypes designed to improve SODIS efficacy. Factors including design and material costs were considered. The inclusion of Compound Parabolic Collectors (CPC) improved the inactivation of several pathogens including *E. coli*, *E. faecalis*, oocyst of *Cryptosporidium parvum*, etc. in clear and turbid waters below 30 NTU [15-18]. In the field, the efficacy of solar CPC reactors was also demonstrated in sub-Saharan Africa [19]. Nevertheless, the cost of these designs is still unaffordable for many communities in low-income countries. Simpler geometries, like V-trough mirrors, permit lowering the cost of the solar reactor manufacturing with quite good disinfection performance even at large scale of around 100 litres per day [Martinez-Garcia, 2020].

Another way to improve the design of a SODIS reactor is to increment its capacity to transmit the solar radiation that inactivates the microorganisms in water, i.e. namely the UVA and UVB regions of the solar spectrum. According to previous modelling and research on this (Castro et al., validation 2018), the material of the photoreactor and its diameter are the most critical aspects on the good transmission of solar radiation to the water inside the reactor. Potential candidates for SODIS reactor materials must have mechanical and chemical stability, being light, resilient, have a high UV-transmittance and photostability, with additional reasonable cost and commercial availability. Among them, PET (polyethylene-ethylene-terephtalathe), polycarbonates (PC), borosilicate, quartz, methacrylate are investigated. PET is the most widely used because proceeds from reusable drinking plastic bottles and is accessible to the wide population at zero cost, but their resilience is poor, the transmittance is low in the UVA and UVB, and they are recommended to dispose after 6 months [Review Kevin, etc.]. PC containers have also low transmittance in the UVA, around 30% [Keogh et al., 2010] while other methacrylate materials transmit below 20% in the UVA. Borosilicate and quartz, while have good optical properties, are simply not viable for this application based on their weight, fragility and cost. The recent development of modified methacrylate materials for food industry and biotechnology (photo-bioreactors) have permitted to identify new polymeric materials that offer excellent properties from chemical and mechanical point of view while they have also great UV-transmission performance, this is the case of modified PMMA (poly(methyl-methacrylate)), selected as novel SODIS reactor material [21].

This article aims to demonstrate that an easily-manufactured and low-cost solar reactor can be used at community level to provide safer water from HRW. In this research two solar reactors, with water treatment capacities of 140 L and 90 L, were specifically designed to optimise SODIS and were assessed for disinfection of HRW under natural sunlight in two countries (Spain and Uganda) which experience high solar irradiance. A V-trough mirror was used due to its high efficiency for SODIS application [20]; a commercial modified PMMA was selected as a novel UV-transparent material for the photo-reactor and its photostability was evaluated. A preliminary assessment of the capability of both reactors was conducted in Spain under controlled conditions using synthetic rainwater spiked with a consortium of waterborne pathogens. Field validation was carried out in Uganda, using real harvested rainwater in two rural primary schools in the rural district of Makondo.

The main novelty of this contribution is therefore the assessment of a novel large scale SODIS reactors based on the selection of UV-transparent materials, which is a unique contribution with new and promising results. The key scientific value of this article is the testing of the large reactor using natural sunlight and real harvested contaminated rainwater in the field for low-income communities. Moreover, this study helps to understand the advantages and cost implications of large-scale solar disinfection systems for end-users in low-income areas.

2. MATERIALS AND METHODS

2.1. Solar photo-reactors

Two solar photo-reactors designed and constructed by Ecosystem Environmental Services S.A. (Barcelona, Spain) have been tested. The 140L-V trough reactor consists of 3 transparent tubes (140 cm length, 5mm thickness, 200 mm diameter) and a total volume of 140L (illuminated volume 135 L, irradiated surface 1.8 m^2). The 90L-V trough reactor consists of 8 tubes (140 cm length, 5mm thickness, 100 mm diameter) with a total volume of 90L (illuminated volume 87.5

L, irradiated surface 2.4 m^2). The tubes are made of UV-transparent PMMA (GEHR Plastics Inc., Germany) and are located at the linear focus of an anodized aluminium V-shaped mirror (Fig. 1a, Fig. SI1-2). This modified PMMA is a highly transparent thermoplastic polymer obtained from the polymerization of methyl-methacrylate. The physico-chemical properties of this material are summarised in Table SI1. -The tubes are connected in parallel by transparent communicating pipes which minimise the presence of dark-zones and are supported by a fixed platform inclined at 33° (140L-V trough) and 8° (90L-V trough), equal to the latitudes of the final locations in South Africa and Uganda, respectively, where the reactors will be operating. This is design criteria for static solar collectors to maximise the annual solar income in these reactors. For validation purposes this article shows Ugandan field results, while the South African field trials have been recently published [21].

The reactors have been designed to be gravity fed from a HRW tank and to operate as static water batches exposed to sunshine for several hours. An outlet valve located at the bottom of the reactors was used for both taking samples and emptying the reactors after use. With this design, electrical pumps are avoided and uninterrupted illumination of the water is guaranteed during the treatment, which has been reported to improve SODIS efficacy [16].

1.1. Solar disinfection tests under controlled conditions

Preliminary SODIS tests were carried out simultaneously with both reactors from October 31st to November 22nd 2018 under real outdoor conditions for 5 hours (11:00 to 16:00 local time) each day at Plataforma Solar de Almeria (Almeria, South East of Spain, 37º84´ N, 2º34 W) (Fig. 1b,c).

Reactors were filled with synthetic harvested rainwater (SHRW) and suspensions of each microorganism were spiked to achieve ca. 10^6 CFU/mL for each bacterium and ca. 10^5 particles forming unit (PFU)/mL for MS2. After a dark homogenization by agitation, first sample (t = 0 min) was taken out and the reactors were exposed to natural solar radiation. Along the treatment time (5 h), samples were taken regularly and the concentration of each microbial target analysed. Dark samples were also kept in the lab at room temperature (25 °C) and analysed at the end of each experiment for viability control purposes. Results of the dark controls showed that the microorganism concentrations remained stable (data not shown). Four replicates were carried out for testing solar inactivation of both bacteria and MS2. Results were highly reproducible (P value < 0.05). Statistical analysis was performed using ANOVA excel (Microsoft office 2016) and OriginPro 2015. The average values of microbial concentration at each time point were plotted in graphs with standard deviation as error bars. Samples were retested for regrowth of all bacteria at 24 and 48 h after completion, although recovery of bacteria was not observed anytime the reduction reached the detection limit (DL).

UV radiation was measured with a pyranometer (Kipp & Zonen CUV-5 (280-400 nm)) that provides data in terms of the solar radiant energy rate incident on a surface per unit of area (W/m^2). Inactivation data were plotted as a function of delivered solar-UVA dose (Eq. 1).

$$Dose_{UV}\left(W \cdot h/_{m^2}\right) = \sum_{n} \overline{UV}_{n-1}(W/m^2) \cdot \Delta t_{n-1}(h) \qquad \text{Eq. 1}$$

where UV is the average value of UVA radiation received (W/m^2), and *Δt* is the amount of time the reactor is exposed to solar radiation

1.2. Solar disinfection tests in Uganda

For field testing, the reactors were installed at two primary schools: Arise & Shine (31.419648, S0.496382°) and Kabuyoga (31.4392507, S0.499342°) both in Ndagwe subcounty, Makondo, Lwengo district, in Southern Uganda (Fig. 1d,e). These schools had previously participated in a SODIS project (Water is Life (WIL) 2010-2013. [22]) using the standard 2-L PET bottle procedure and were selected for this study since they displayed excellent compliance with the previous WIL guidelines. In addition, this area is characterized by the presence of HRW tanks as source of collecting and storing fresh-water. Rainfall pattern is bimodal with two rainy seasons (March-May and September-December) and an average annual rain fall of 1100-1200 mm with 100-110 rainy days [Lwengo District Local Government Statistical Abstract 2018-2019. Url; https://lwengo.go.ug]

Each reactor was connected to a 10,000L closed ferro-concrete HRW tank with netted inlet to sieve out large debris. HRW tanks were provided by the project to ensure a sufficient supply of rainwater for disinfection. The tanks were positioned up-hill from the reactors to allow gravity-filling of the reactors. Water was treated in the reactor for at least six hours and drained into a collection tank from which users could draw treated water for drinking.

The testing period lasted from January to November 2019, where 200 mL samples were collected every month from each school in clean sterile glassware. Two types of samples were collected: i) rainwater from the tank (non-treated sample) and ii) treated rainwater from the reactor after exposure to sunlight for 6 hours (SODIS treated sample). The samples were transported on ice from the field to the School of Food Technology, Nutrition and Bio-engineering at Makerere University in Kampala for microbial analysis. Samples were processed within a maximum of 6 hours after collection. Each rainwater sample was analysed in triplicate and results are shown as the averaged value with the corresponding standard deviation as error.

1.3. Water Matrix

In Spain, all the experiments were carried out with SHRW for which the reagents and concentrations used were: NaCl (56.1 mg/L), K_2SO_4 (17.4 mg/L), $CaCl_2$ (5.55 mg/L), $MgCl_2$ (5.71 mg/L), NH_4NO_3 (12 mg/L), KH_2PO_4 (0.14 mg/L) and $CaSO_4{\cdot}2H_2O$ (19.7 mg/L). This recipe is lab-made with sterile distilled water and it has been reported elsewhere [20]. The main physico-chemical parameters of SHRW are: pH value of 5.3, Conductivity of 261 µS/cm^2, Turbidity < 0.5 NTU and Total Organic Carbon < 0.1 mg/L.

In Uganda, real rainwater samples collected from HRW tanks were used for testing the reactors. These were analysed following the main parameters included in the Ugandan National Standards Limits. The values recorded was 6.7-6.9 of pH, < 5 NTU of turbidity and 122 mg/L of Total Dissolved Solids (TDS), which meet the national recommended values (pH 6.5-8.5, turbidity < 10 NTU and TDS: 1500 mg/L).

1.4. Microbial enumeration and quantification in SODIS tests in Spain

Three bacterial strains obtained from the Spanish Culture Collection (CECT) were used: *E. coli* K-12 (CECT 4624), *Enterococcus faecalis* (CECT 5143), and *Salmonella sub enteritidis* (CECT 4155). These strains were grown in fresh liquid medium Luria-Bertani Broth (Merck KGaA®, Darmstadt, Germany) for *E. coli* and *E. faecalis*; and Triptone Soya Broth (Merck KGaA®, Darmstadt, Germany) for *S. enteritidis,* incubated at 37 ºC for 18-20 hours to reach stationary phase. Bacterial cultures were then centrifuged at 900xg for 10 minutes at 25 ºC using a Rotine R380 (Hettich Zentrifugen, Germany). The pellets obtained were re-suspended in phosphate buffered saline (PBS) (Sigma-Aldrich®, Germany). Suspensions containing each bacterium were simultaneously diluted directly into the SHRW to reach an initial concentration of 10^6 CFU/mL. Samples were enumerated using the plate count method in different selective media: ENDO Agar (Merck KGaA, Darmstadt, Germany) for *E. coli;* Slanetz Bartley Agar (Scharlau®, Spain) for *E. faecalis* and Salmonella Shigella Agar (Scharlau®, Spain) for *S. enteritidis.* Volumes of 20 µL from water samples and ten-fold dilutions (in PBS) were spread onto each corresponding agar media to reach the detection limits (DL) of 17 CFU/mL. When lower microbial concentrations were expected, 500 µL of water sample were directly spread on each selective media to reduce the DL to 2 CFU/mL. Colonies were counted after incubation of 24-48h at 37 ºC.

MS2 Coliphage (ATCC 15597B1) and the bacterial host *E. coli* C300 171 (ATCC 15597) were obtained from the American Type Culture Collection (ATCC). Aliquots of virus stock solution were added directly into the SHRW to reach an initial concentration of 10^5-10^6 PFU/mL. Stocks of MS2 infective particles and enumeration procedure were prepared using Tryptone Yeast Glusose (TYG) medium containing the following reagents from Sigma-Aldrich: Tryptone (10.0 g/L) Yeast Extract (1.0 g/L), NaCl (8.0 g/L), Glucose (10.0 g/L), $CaCl_2$ (2.94 g/L) and Thiamine (0.1 g/L); additionally, 5 and 15 mg/L of Bacteriological Agar was added to prepare semi-solid and solid agar medium, respectively. The *E. coli* host was cultivated for 6 h in fresh liquid medium

(TYG) at 37 ºC with a rotatory agitation of 90 rpm prior to MS2 enumeration. Infective MS2 particles was enumerated by a double-layer agar method. Briefly, 1 mL of *E. coli* C300 is mixed with 0.1-0.5 mL of sample (or 10-fold dilutions using PBS) and 5 mL of melted semi-solid TYG agar. The mix was then poured on solid TYG agar petri dishes. Solidified plates were incubated upside-down at 37 ºC for 24 hours. The detection limit of this method was 2 PFU/mL.

1.5. Microbial enumeration and quantification in SODIS tests in Uganda

The samples were analysed for *E. coli, E. faecalis*, Total coliforms (TC) and Total Plate Count (TPC). These are the Ugandan national indicators of drinking water quality [23]. Total Colifoms (TC), *E. coli* and *E. faecalis* were assayed using the standard membrane filtration method. Briefly, 100 mL of samples were filtered through sterile cellulose nitrate membrane filters (0.45 µm pore-size and 47-mm-diameter, (Gelman Sciences Inc. USA)) using a stainless steel membrane filtration manifold system (Sartorius Stedim 16842). For *E. coli* and TC, the filters were placed in an upright position onto chromogenic media (Conda Pronadisa 1340) and incubated at 37 ºC for 24 hours. All violet-dark blue colonies were presumed to be *E. coli* while the pink colonies were other coliforms. The pink colonies and *E. coli* colonies were summed up as TC. Further confirmatory tests were carried out by streaking *E. coli* colonies from the chromogenic media filters onto Les Endo agar base (Conda Pronadisa 1137) and the plates incubated at 35 ºC for 24 hours. All red/pink colonies with a metallic sheen were confirmed as *E. coli*. The ATCC 25922 *E. coli* strain obtained from the School of Veterinary Medicine, Makerere University was used as positive control.

For *E. faecalis*, filters were placed on Bartley medium (Conda, Pronadisa) and pre-incubated at 37 °C for 4 hours to aid bacterial resuscitation. They were then incubated at 36 ± 2 °C for a further 44 ± 4 hours. After incubation all red, maroon and pink colonies that were smooth and convex were counted and recorded as presumptive faecal streptococci. All membranes with positive presumptive results were transferred to a pre-warmed dish (44 °C) of Bile Esculin Azide Agar (Conda, Pronadisa). The plates were incubated at 44 ± 0.5 °C for 2 hours. After incubation, all colonies with a brown-black surrounding medium were counted and confirmed as *E. faecalis*. The strain NC08132 from the Uganda National Bureau of Standards Nakawa, Kampala was used as positive control.

Total Plate count (TPC) was evaluated using the plate count technique. A 0.1 mL of sample from selected serial dilutions was thinly spread onto yeast extract agar (Conda Pronadisa) and left at room temperature (22 ± 2ºC) for 24 hours before enumeration of colonies. All colonies were counted using an electronic colony counter (Stuart SC6, Germany). The limit of detection was 300 CFU/mL.

1.6. Ageing test of PMMA

Long-term degradation of the UV-transparent PMMA under accelerated and natural solar conditions was carried out at PSA (Almeria, Spain) following procedures described elsewhere [24]. Briefly, four pieces of 2x5 cm were obtained from a PMMA lid and exposed to both natural and accelerated ageing conditions. The transmittance degradation of this PMMA material was measured using a UV-spectrophotometer equipped with an integrating sphere (150 mm diameter and specular reflectance at incidence angles from 0 to 68º) (Perkin-Elmer Lambda 1050, Beaconsfield, UK) in the range 250-500 nm.

Testing of accelerated ageing was carried out in a chamber (Atlas UV Test, Atlas Materials Testing Technologies, Mt. Prospect, IL, USA), according to ISO-16474, specifically for testing ageing of materials under extreme climate conditions. In this study, PMMA pieces were exposed to uninterrupted direct solar UV radiation (45 W/m^2) with intervals of temperature consisting on 4 h at 60 °C followed by another 4 h at 50 °C. Transmittance of PMMA pieces was measured at regular intervals of 0, 300, 600 and 900 h.

Testing of natural ageing consisted of exposing PMMA pieces to direct strong sunlight under natural environmental conditions for 9 uninterrupted months (January-September 2017) at PSA. Transmittance was measured after 0, 3, 6 and 9 months of exposure time. Solar UV irradiance was measured during the test using the previously described solar pyranometer. Averaged solar UV irradiance values at noon ranged from 21.0 W/m^2 (January), 36.6 W/m^2 (March), 48.4 W/m^2 (May) and 39.6 W/m^2 (August), values typically detected on this location along the different seasons of the year.

3. RESULTS AND DISCUSSION

3.1. Accelerated and natural ageing of PMMA material

The transmittance profile of modified PMMA (wall-thickness 5 mm) in comparison with other transparent materials is shown in Fig. 2a. Quartz has the highest UV transmittance, however its high cost renders the manufacture of photo-reactors from this material too expensive for low-income countries. PMMA transmittance (from 45 to 88% in the UVB range, 280-320 nm, and an average of 90% in the UVA, 320-400 nm) is very high compared to other materials evaluated. From these results the modified PMMA is shown as the most UV-transparent compared with the other candidate materials for solar disinfection reactors. This modified PMMA is better even than borosilicate glass which is often considered to be one of the most promising materials with transmittance in the UVB (from 7 to 75%) and UVA (87%) for 1.8 mm thickness [17]. Therefore, PMMA appears to be a very good alternative to the more fragile borosilicate glass. Furthermore, this UV-transparent PMMA shows much higher UVA transmission compared to other candidate plastic materials, including PET (wall-thickness 0.4-0.5 mm, transmittance of 52%) [16; 25], polycarbonate (wall-thickness 1.4-1.6 mm, transmittance of 33%) [24-25] and other methacrylate (wall-thickness 10 mm, transmittance of 19%) [17], all of which have been previously investigated as candidate materials for large volume reactors/containers and pilot plants, for SODIS purposes.

Another key requirement for SODIS reactors is a long lifespan for the material under field conditions. Fig. 2b,c show the transmittance of PMMA material obtained under accelerated and natural ageing tests, respectively. The results show stable UV-transmittance after 900 h exposure to accelerated solar ageing (UV, temp. and humidity) and after 9 months under natural environmental conditions (Jan to Sept 2017 in the South of Spain). These results highlight the resistance and durability of this material to extreme environmental conditions, which is consistent with the performance reported by the manufacturer (GEHR PMMA®) [26] and other commercial sources for polymers [27]. This commercial PMMA also exhibits high mechanical strength and rigidity, high surface hardness, a polishable surface (see Table SI1), which makes it particularly well-suited for a material exposed to the extreme conditions that solar photoreactors typically experience.

Recently, Gomes de Castro Monsores et al. (2020) reported opposing results for a different commercial PMMA subjected to similar accelerated aging tests. They observed chemical alterations in the materials affecting UV-vis transmittance, increasing the yellow appearance and fragility [28]. This highlights the importance of carefully characterizing the optical properties and longevity of any new transparent material for SODIS photo-reactor manufacturing. Additionally, the selection of PMMA for this research was based on its 'food grade' characteristic, but the potential migration of chemicals from the PMMA into the solar treated water over extended periods of time may have toxicological effects which are object of research in a parallel investigation.

3.2. Disinfection performance under controlled conditions (synthetic rainwater)

Fig. 3a shows the inactivation profiles of bacteria (*E. coli, S. enteritidis* and *E. faecalis*) and MS2 coliphage in SHRW using the 140 L solar V-trough reactor. The DL from initial concentrations of ca. 10^6 CFU/mL was attained for all bacteria; meanwhile, for MS2 coliphage a removal of > 5-LRV was observed. Bacterial inactivation followed a log-linear decay, and the kinetic constants (*k*) were determined according to Chick-Watson's law. *E. coli* ($k=0.112\pm0.011$ min^{-1}, R^2=0.96) and *S. enteritidis* ($k=0.107\pm0.003$ min^{-1}, R^2=0.99) showed similar inactivation rates, which required a solar UVA dose of 173 kJ/m^2 or 80 minutes of solar exposure to reach DL. *E. faecalis* inactivation rate was slower ($k=0.083\pm0.005$ min^{-1}, R^2=0.97), and required a higher dose (256 kJ/m^2 and 120 min) to reduce 6-LRV. MS2 (*k=0.006±0.001 min^{-1}*, R^2=0.70) was effectively reduced for more than 5-LRV with 620 kJ/m^2 (dose) or 5 h of solar exposure.

Fig. 3b shows the inactivation of the same microbial consortium in the 90 L solar V-trough reactor. Bacterial inactivation profiles were very similar and slightly quicker than those from the 140 L V-trough reactor, with lower solar UVA dose required to attain the DL or similar LRV e.g., 5-LRV was reached after 119 kJ/m^2 (60 min) for *E. coli* (*k=0.159±0.016 min^{-1}*, R^2=0.96) and *S. enteritidis* (*k=0.143±0.005 min^{-1}*, R^2=0.99) and 212 kJ/m^2 (100 min) for *E. faecalis* (*k=0.105±0.008 min^{-1}*, R^2=0.96). In the case of MS2 (*k=0.013±0.001 min^{-1}*, R^2=0.99), 479 kJ/m^2 and 300 min were required to reach the DL (more than 5-LRV).

All experiments were conducted under full-sunshine conditions. Solar UVA irradiance measured during SODIS tests under controlled conditions ranged from 13 to 40 W/m^2. Water temperature increased from 10 to 27 ºC, allowing to neglect any possible thermal effect as a key factor of bacterial or of MS2 inactivation which literature proved to be over 45º C and 40º C respectively [12, 29].

Several studies in the literature have reported different efficiency levels for disinfection of water using SODIS. Results vary strongly depending on the volume of water, the materials used for the photoreactor and the nature of the pathogen (Table 1). The most frequently used material and volume, 0.5–2L with PET, requires between 3 to >6 h to attain 6-LRV in bacteria [15, 30] and >16h for MS2 [31] depending on the radiation conditions and water characteristics.

Other publications explore larger volumes (20-50L) using polypropylene, polycarbonate and methacrylate with and without solar reflectors. In these cases, the volume increase is accompanied by an increase in diameter, which compromises the light penetration depending on the optical properties of the water (turbidity and UV-transmittance). We can observe 6-LRV for *E. coli* in polycarbonate 19L bottle in less than 3 h [25], in a 20L polypropylene bucket within 3 h [24] and up to 6 h in methacrylate. This can be explained due to their UV-transmission properties (Fig. 2) and the pattern of light scattering within the reactors [32].

When looking at similar UV-transmittance materials, such as borosilicate glass and PMMA, we observe that the results presented here attain a 6-LRV of *E. coli* within 80 minutes (90 L of treated water), which is a similar performance to a glass V-trough reactor which was able to treat 54L of water in 90 min [20].

Even for highly UV-transparent materials, the optical path length inside the usually cylindrical photo-reactors, plays an important role, as they can be constructed so that the UV-radiation penetrates the inner layers of water while the treatment volume is maximised. This also depends on the availability of materials at such diameters. This would allow larger, and more efficiently treated, volumes of water. In our case, two different diameters were investigated, 100 and 200 mm. Both solar reactors reduce bacteria by > 5 LRV as observed for *E. coli, E. faecalis* and *S. enteritidis* (Fig. 3, Table 1), requiring a solar UVA dose up to 220 and 270 kJ/m^2 for 90L and 140L V-trough reactor, respectively. This corresponds to 100 – 120 min of solar exposure for each reactor respectively. Such treatment times are comparable or lower than previously reported SODIS reactors (Table 1), and deliver volumes of purified water that are 3-10 times larger. Comparing both reactor performances, the 90 L solar V-trough reactor required from 20 to 30% less of solar UVA dose to obtain the same result, which may be attributed to the smaller tube diameter.

In a previous study, the effectiveness of the V-trough mirrors against CPC mirrors for SODIS purposes was investigated using photo-reactors made of borosilicate glass with a tube diameter of 75 mm. In this case, under similarly controlled conditions, > 5-LRV for the same bacterial species was reached using V-trough mirrors with a solar UVA dose of 254 kJ/m^2 [20]. This solar UVA dose value agrees with the values obtained in the present study but using PMMA material, reinforcing therefore the suggestion that this transparent material is a favourable choice for use in SODIS-based technologies.

3.3. Disinfection capacity in the field (rural Uganda)

E. coli, E. faecalis, total coliforms (TC) and total plate counts (TPC) concentrations obtained, before and after 6 h-solar treatment, during the assessment of the V-trough reactors in the Arise & Shine and Kabuyoga primary schools in Uganda are summarized in Tables 2 and 3, respectively. For comparison purposes, the same rainwater was treated in 2L-PET bottles simultaneously.

According to the Ugandan standards for potable water [23], the maximum permissible concentration of each microbial indicator analysed in this study is as follows: 0 cells per 100 mL for *E. coli* and TC, 50 colonies per mL for TPC measured at 37 ºC. No reference for *E. faecalis* is included in the standard, but 0 cells per 100 mL is assumed to be the desirable condition.

Regarding the microbial quality of the raw rainwater, similar trends were found in both locations, i.e., the potable standards were not met and large fluctuations in the microbial concentrations were detected throughout the year. The concentrations of TPC and TC observed were 10^2 to 10^6 CFU/mL and from <DL to 10^3 CFU/100mL, respectively, while complete absence or very low concentration (<200 CFU/100 mL) were detected for *E. coli* and *E. faecalis*.

The results obtained after 6 h of solar treatment in the V-trough reactors showed complete absence of *E. coli* and *E. faecalis* in 100 mL regardless of the season, with the only exception of a sample where 2±2 CFU/100 mL of *E. coli* was detected in Kabuyoga primary (Table 3), reaching an almost complete absence of bacteria from a very high initial concentration (Raw water: 283±8

CFU/100 mL). In those samples with initially detected concentrations, the reactors were effective in reducing 2 LRV to undetectable concentrations. The effectiveness of the solar reactors to reduce TC was by 2-3 LRV, meeting the Ugandan drinking water standards for most treated water samples, with the exception of samples from January, March and September in both schools and also for the June sample at Arise and Shine primary school. With the exception of the months of August and September, all the solar treated water samples did not meet the Uganda drinking water standards (<50 CFU/ml) for TPC. However, it is noteworthy that even without complete disinfection, a 4 LRV was observed, which indicates a great improvement in the microbial quality of the water.

Comparing the results with those obtained with PET bottles, we observe a much higher efficiency for the solar reactors from the point of view of effectiveness and the amount of treated water.

E. coli and Enterococcus spp., were completely inactivated in 95% and 100% of the batches of treated water respectively. These two bacterial species are of public health concern given their roles in infections that can be fatal in children. As expected from the results obtained under controlled conditions, no significant differences in the performance of both reactors were observed in the field, concluding therefore that the best option for implementation is the 140L V-trough reactor due to its higher batch volume of treated water. Similar results have been previously observed by Reyneke et al. (2020) who examined the performance of these two reactors for treating rainwater in rural communities of South Africa (although their azimuthal inclinations were altered to compensate for their more Southerly latitude). They observe a reduction of *E. coli*, total, faecal coliforms and enterococci after 8 h of solar treatment in southern hemisphere winter, achieving the values required by South African and international drinking water standards. It was also observed that in 43% of the tested samples, heterotrophic bacteria exceeded the standard drinking water limit, while reductions of ~ 75% were obtained for several opportunistic pathogens including *Klebsiella* spp., *Legionella* spp., *Pseudomonas* spp., *Salmonella* spp. and *Cryptosporidium* spp. oocysts [32]. These results agree with those recorded from the field in Uganda and validate the improved water disinfection capability of solar V-trough reactor designs under real field conditions for community applications.

In spite that the microbial quality requirements of the Ugandan Standard for potable water are not met only for TPC in the 50% of the samples, the improvement of the microbial quality of roof-harvested rainwater is a great step, as the water could be used for other domestic purposes reducing many household risks as discussed by Reyneke et al. (2020). Furthermore, additional barriers could reduce the remaining risks.

SODIS can be considered ‘better-than-nothing’ when deployed as PET bottles in households, while the SODIS rainwater reactors proposed enhances the performance of PET bottles in terms of amount of water produced, quality and treatment time. The use of additional drinking treatment barriers, i.e. filtration, chlorination etc. may add safety to the finality of the water. The same limitation is found in other drinking water treatments, where additional treatment steps are also required.

3.4. Can solar V-trough reactors deliver daily drinking water needs affordably?

3.4.1. Solar resource

The capability of delivering solar treated water using these reactors depends on the local solar resources and the dose required to reach the desired disinfection level. Fig. 4a shows the average monthly solar irradiance dose in kJ/m^2 for Uganda and Spain [38]. It clearly shows different distribution patterns. For Uganda a stable UVA dose of ca. 1000 kJ/m^2 [39] is observed due to its Equatorial location, while a seasonally fluctuating UVA dose from ca. 500 to 1500 kJ/m^2 is recorded in Spain (37^o N), and an averaged sunshine duration of 8-10 hours per day. Therefore, both locations have sufficient solar UVA resource to inactivate the most solar resilient indicator organism, MS2, which requires an average dose of at least 500 kJ/m^2 to attain 4-5 LRV.

Looking at one day in any month of the year in Uganda (Fig. 4b), the daily average solar UVA dose clearly shows that two batches of water could be treated using these reactors. This means that there will be at least 6 hours of solar exposure with 500 kJ/m^2 of solar UVA dose from January to December, on average. Although, there may be a few exceptions for rainy periods, it could be stated that the solar treatment duration is 4±2 depending on weather conditions.

Consequently, the 140L-V trough reactor could produce 280 L of treated water per day (two batches of 140 L per day). If we consider an annual total of 2,300 – 2,500 h of sun (equal to 300 sunny days per year) in the area [40], then 84 000L of drinking water could be delivered every year with this reactor in Uganda.

3.4.2. Cost analysis and materials selection

Several types of material are used in the construction of the photo-reactors, including anodized-aluminum mirrors and aluminum frames, which are highly resistant to stressful environmental conditions. Both materials have already demonstrated high durability and robustness in the field as well as the PMMA material used in the photoreactor, with at least 10 years of functional life-time [41]. Nevertheless, the entire solar reactor under field conditions requires more analysis after its use for longer times to ensure the functionality life-time. The absence of automated features in the photo-reactor designs avoids over-reliance on electrical energy, requiring only the installation in an unshaded, full-sunshine location near the community point of use. The simplicity of the systems makes them also almost user-independent; since the only routine maintenance they require is periodic cleaning.

For this analysis we are choosing the 140L-V trough reactor as it was more efficient in terms of delivered treated water per sunny day. The production costs of the reactor estimated at 1000 € (930 € for the materials, and the rest is for labour and overheads, Table S~~-~~I2). Operational costs are negligible (manpower for cleaning). Considering 10 years of operation (840 000L drinking water delivered), this equates to a cost of €0.0012 per litre of solar treated water. This cost is 25 times cheaper than the current cost of chlorine treatment which was estimated at €0.030 in 2007 [42]. According to the UN [43], the minimum amount of drinking water for domestic/human use is around 25L per person per day, then the cost of water with this solar reactor will be of about €10.95 per person per year, assuming the reactor is operative for 10 years. The cost of drinking water varies from country to country enormously, while OCDE areas pay very little, €0.08 per 50 L of supplied drinking water, the Sub-Saharan countries prices are around €0.58 per 50L from a tanker truck [44].

The reactors, discussed herein, are prototypes fabricated under an EU project, where the most ideal materials were selected for each purpose. Nevertheless, material selection for some generic components (i.e. pipes, valves, framing) can be adapted to the local context, so that they can be easily found locally. The frame and structure costs were not included in the production cost, as it can be locally built at very low cost with available robust materials, permitting community co-creation of their own water systems. Key selections are the solar mirrors and transparent tubes. Anodized aluminum (13% of the materials cost) may not be available everywhere, but alternative reflective materials – more accessible and cheaper – could be used, i.e. aluminum foil, however the associated losses in reflectivity negatively impact the disinfection efficiency. The most expensive part of the reactor is the UV-transparent PMMA tubes (55% of the materials cost), as they are not produced at industrial scale. This element is critical for the good disinfection performance of the solar treatment; its transparency and diameter are quite a challenge when thinking about traditional materials like borosilicate glass. Similar thickness, diameter and length tube made of borosilicate glass becomes twice more expensive than PMMA and pose an extra risk due to the heaviness of the empty glass tubes. For example, the borosilicate glass tube with 5 mm thickness, 200 mm diameter and 1.5 m length weighs 10,2 kg and costs 124 € (www.schott.com).

3.4.3. Social impact

Technological solutions such as the designed V-trough solar reactors may enhance the population health and well-being of communities in Sub-Saharan Africa. In the real scenario of field studies in Uganda, it should be noted that, although the country has enjoyed tremendous economic growth in recent years, it still grapples with the challenge of providing safe water to all its citizens. Over 22 million people (>50% of the population) especially in the rural areas have no access to drinking water and this leads to more than 9500 deaths annually [45]. Also, most Ugandans access their water from surface sources such as lakes, rivers, open wells and dams [13] and only recently, the implementation of tanks to collect rainwater, has occurred in the country as another act of mitigation of water scarcity. Therefore, the implementation of decentralized solar reactors providing safer drinking water is a future and promising solution.

The amount of treated water daily per each photo-reactor, 280L and 180L, contributes greatly towards daily drinking water requirements for community uses, such as for those pupils attending the schools in which the reactors were field tested (ca. 300 pupils and assuming the capability of the system to treat two batches per day under full sunshine). Nevertheless, other scenarios could also be possible such as the installation of reactors in health facilities and at household level for a full family of seven people which would meet the water needs per person established in the range of 20-50 L per day according to the recently reported data by the UN [43].

4. CONCLUSIONS

Two solar reactors, based on V-trough mirrors and UV-transparent PMMA tubes, have been built and tested under controlled conditions in Spain, and in rural community conditions in Uganda. Both reactor designs have demonstrated a capacity to disinfect 280 and 180 L of rainwater per day with the only requirement having enough solar UV resource as detailed below.

Both solar reactors achieved reductions of more than 5-LRV against all the pathogenic bacteria (*E. coli, E. faecalis, S. enteritidis*) tested, when exposed to up to 270 kJ/m^2 of UVA, and 620 kJ/m^2 were needed to attain 5-LRV for MS2 coliphage. *E. coli* and *S. enteritidis* were found to be more sensitive to solar UVA than *E. faecalis*. The differences between both reactor performances were around 20% in terms of the required dose, with the fastest inactivation rates observed in the 90L-V trough reactor.

One year testing in the field, at two rural schools of Uganda, confirmed the promising results obtained in controlled conditions (Spain). From 2 to 3-LRV of *E. coli*, Total Coliforms and *E. faecalis* were attained in natural harvested rainwater, requiring 4±2 hours of solar exposure, depending on the weather season.

Analysis of the PMMA reactor tubes demonstrated high UVB-A transmittance (60-90%) and excellent photostability, confirmed via solar aging tests (accelerated and natural) over 9 months, confirming its suitability for this solar application.

The cost analysis of this solar technology showed that it is an affordable decentralized drinking water intervention that could be used in micro-communities, schools, clinics, etc. The 140L-V trough solar reactor can provide 84,000 liters of water per year in Uganda, at a cost of €0.0012 liter considering 10 years of lifespan system, 25 times cheaper than onsite chlorination. This is equivalent to about €10.95 per person per year to meet the minimum drinking and domestic water needs established by the UN through the SDG6 (25 L per person per day).

Due to the scarcity of published SODIS research from the field, the implementation of a solar technology such as these reactors may still be difficult. In this sense, there is a clear need to validate these technologies under a wide range of environmental and social conditions to confirm SODIS as a safe household water treatment (HWT) technology.

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Figure captions

Table 1. Data of microbial inactivation by SODIS in different containers under natural sunlight from cases reported in literature.

Table 2. Data of microbial counting detected during testing of the solar photo-reactor installed in Arise and Shine primary school (Makondo, Uganda).

Table 3. Data of microbial counting detected during testing of the solar photo-reactor installed in Kabuyoga primary school (Makondo, Uganda).

Fig. 1. (a) Diagram of tube and mirror shape: (b) photograph of 140L and (c) 90L solar photoreactors at PSA facilities (Almeria, Spain): (d) Field photographs of 140L solar reactor at Kabuyoga Primary school and (e) 90L solar reactor at Arise and Shine primary school in Southern Uganda.

Fig. 2. Transmittance of PMMA used in the reactors: a) comparison with other materials, b) accelerated ageing, and c) natural ageing tests. The inset figures show the UVA/B regions of interest.

Fig. 3. Bacterial and MS2 coliphage inactivation by SODIS in SHRW under controlled conditions using a) 140L and b) 90L solar V-trough reactor.

Fig. 4. a) Averaged global horizontal irradiance (GHI) and solar UVA horizontal irradiance dose (UVA-HI) in Uganda and Spain from 2006 to 2016. b) Daily solar UVA dose along a year in Uganda. Data from [38].

Table 1.

SODIS-Reactor Type	Water Matrix	LRV Pathogen	UVA Dose (kJ/m^2) /Exposure Time (h)	Ref
Studies under natural sunlight & controlled conditions				
2L-PET Bottles 2.5L-BSi tube 2.5L-BSi CPC reactor	Well water	> 5 *E. coli* K12	340 / 3 h 210 / 2 h 150 / 1.5 h	[15]
1.5 & 2L-PET bottles on corrugated iron	Ground water	> 4 Bacterial consortium	Global irradiance data: 1,040-1,059 W/m^2 (30.6 MJ/m^2 in 8 h) *C. jejuni*: 20 min *Y. enterocolitica*: 150 min *S. epidermidis:* 45 min *E. coli* O157*:* 90 min *B. subtilis:* 16 h	[30]
22.5L-Methacrylate CPC Reactor	Well water	> 6 *E. coli* K12	> 655 / < 6 h	[17]
2.5L-BSi CPC reactor (CF:1&1.89)	Well water	> 6 *E. coli* K12	229-245 / 2 h-1 h	[33]
19L-PC Containers. 2L-PET bottles.	Well water	> 4 Lab and wild *E. coli* and *E. faecalis*	PC - PET *E. coli* K12: 250 / 2.5 h - 200 / 2 h *E. faecalis:* 435/ 4 h (both) Wild *E. coli:* 730 / 2.5 h -665/3.5 h Wild *E. faecalis:* 680 / 4.5 h (both)	[25]
0.5L-PET Bottles	Tap water	> 6 MS2	Global irradiance data: 1.34 kJ/cm^2 / ≈ 16 h	[31]
4L-Bags of PE, PE-EVA & 2L-PET Bottles	Well water	*Enterococcus* Bags: 4 PET Bottles: 2	≈ 645 /4 h	[34][1]
20L-PP Buckets. 1.5L-PET Bottles.	Well water	> 5 *E. coli* ≈ 2.5 MS2	Buckets – PET bottle *E. coli* K12*:* 250–300/3 h -500/4 h MS2: 500 / 5h -600 / > 5 h	[24]
34L-BSi CPC reactor. 54L-BSi V-trough reactor.	Synthetic rainwater	> 5 Bacterial consortium	CPC - V-trough *E. coli* K12:230/≈ 1.5h - 240/≈1.5h *E. faecalis*: 254 /1.5 h - 254 / 1.5 h *S. enteritidis*: 151 / 1 h - 160 / 1 h *P.aeruginosa*:95/40min-122/50min	[20]
Studies in the field				
1.5L-PET bottles.	Surface Water	2	Total coliform ≈ 309 / 3 h *Salmonella* sp ≈ 412 / 4 h	[35][1]
1L Glass and PET bottles over corrugated iron	Well water + 5 and 150 NTU	Wild *E. coli* 5 NTU > 6 150 NTU > 5	ND/ 5 NTU = 3 h 150 NTU = 6 h	[22]
25L-BSi CPC Reactor.	Natural water	> 3 Wild *E. coli*	ND / 7 h	[19][2]
Bags of PE, PE-EVA & 2L-PET Bottles.	Well water	3 Wild *E. coli* and *Enterococcus*	PE - PE-EVA - PET *E. coli:* 245- 219 - 227 *Enterococcus:* 370 - 1140 - 520	[36]
2L-PET bottles.	Rainwater	≈ 2 Wild *E. coli* and Faecal Enterococci	ND / > 6 h	[6]
80L & 140L-PMMA V-trough reactor	Rainwater	> 3 Enterococci, Total coliforms, *E. coli*	≈ 712 / 8 h	[32][1]

BSi: Borosilicate glass; PMMA: Polymethylmethacrylate; ND: No data provided; CF: concentration factor; PE: Polyethylene; EVA: Ethyl Vinyl Acetate.
[1]Calculated kJ/m^2 using data provided by authors; [2]LRV ranged from 3 to 6 depending of the season;

Table 2.

Rainwater Sample	Total Plate Count (CFU/mL)	Total Coliform (CFU/100mL)	*E. coli* (CFU/100mL)	*E. feacalis* (CFU/100mL)	Date (weather)
Raw	35150 ± 45042	318 ± 11	77 ± 10	< DL	29.01.19 (sunny)
Reactor	365 ± 191	4 ± 1	< DL	< DL	
Raw	45000 ± 7071	3 ± 1	< DL	11 ± 1	12.02.19 (overcast)
Reactor	1400 ± 424	1 ± 1	< DL	< DL	
Raw	1300000±282843	327 ± 8	77 ± 16	2 ± 0	12.03.19 (sunny)
Reactor	4250 ± 353	17 ± 23	< DL	< DL	
Raw	12900 ± 1131	490 ± 67	< DL	< DL	18.06.19 (sunny)
Reactor	6400 ± 1273	132 ± 5	< DL	< DL	
Raw	12900 ± 1131	490 ± 67	< DL	< DL	18.07.19 (sunny)
Reactor	62 ± 11	< DL	< DL	< DL	
Raw	2100 ± 424	< DL	< DL	< DL	29.08.19 (cloudy)
Reactor	3 ± 1	< DL	< DL	< DL	
PET	31 ± 4	< DL	< DL	< DL	
Raw	121500 ± 14849	1116 ± 17	< DL	17 ± 6	10.09.19 (sunny)
Reactor	30500 ± 4950	125 ± 9	< DL	< DL	
PET	89000 ± 117379	1108 ± 62	< DL	< DL	
Raw	3050 ± 495	< DL	< DL	13 ± 3	22.10.19 (Heavy rain)
Reactor	26 ± 6	< DL	< DL	< DL	
PET	380 ± 368	1171 ± 1454	7 ± 7	< DL	
Raw	380 ± 85	< DL	< DL	< DL	12.11.19 (cloudy)
Reactor	20 ± 14	< DL	< DL	< DL	
PET	39 ± 11	30 ± 4	1 ± 0	< DL	

< DL: Data below detection limit of 1 CFU/100 mL; Raw: Harvested Rainwater collected from the tank; Reactor: treated rainwater after 6 h of solar exposure in the solar reactor; PET: harvested rainwater after 6 h of solar exposure using the 2L-PET bottle.

Table 3.

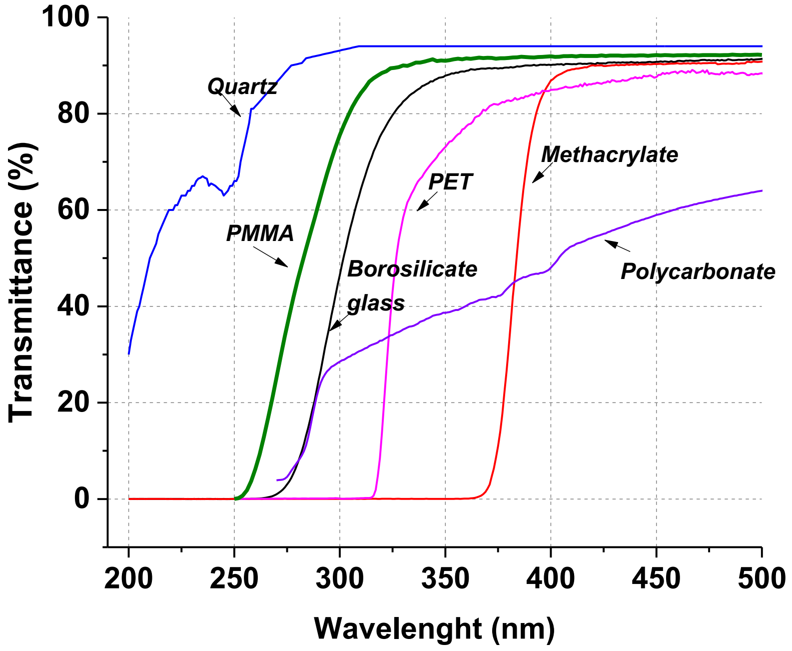
Rainwater Sample	Total Plate Count (CFU/mL)	Total Coliform (CFU/100mL)	*E. coli* (CFU/100mL)	*E. feacalis* (CFU/100mL)	Date (weather)
Raw	51000 ± 22627	270 ± 68	< DL	18 ± 10	29.01.19 (sunny)
Reactor	150 ± 42	7 ± 1	< DL	< DL	
Raw	230000±70710	135 ± 13	3 ± 0	151 ± 6	12.02.19 (overcast)
Reactor	750 ± 212	< DL	< DL	< DL	
Raw	27000 ± 4243	238 ± 23	< DL	1 ± 0	12.03.19 (sunny)
Reactor	4100 ± 566	8 ± 1	< DL	< DL	
Raw	8400 ± 1131	2 ± 1	< DL	< DL	18.06.19 (sunny)
Reactor	3000 ± 425	< DL	< DL	< DL	
Raw	21500 ± 9192	2 ± 3	< DL	< DL	18.07.19 (sunny)
Reactor	13 ± 4	< DL	< DL	< DL	
Raw	370 ± 85	< DL	1 ± 1	21 ± 2	29.08.19 (cloudy)
Reactor	11 ± 2	< DL	< DL	< DL	
PET	185 ± 49	< DL	< DL	< DL	
Raw	38500 ± 6364	1100 ± 28	283 ± 8	< DL	10.09.19 (sunny)
Reactor	5500 ± 2121	285 ± 74	2 ± 2	< DL	
PET	12000 ± 8485	1060 ± 39	1 ± 1	1 ± 1	
Raw	2700 ± 989	1086 ± 20	8 ± 4	< DL	22.10.19 (Heavy rain)
Reactor	30 ±14	< DL	< DL	< DL	
PET	11000 ± 14142	1255 ± 247	21 ± 21	7 ± 4	
Raw	1768 ±752	38 ± 10	< DL	< DL	12.11.19 (cloudy)
Reactor	17 ± 4	< DL	< DL	< DL	
PET	44500 ± 7778	206 ± 24	< DL	5 ± 1	

< DL: Data below detection limit of 1 CFU/100 mL; Raw: Harvested Rainwater collected from the tank; Reactor: treated rainwater after 6 h of solar exposure in the solar reactor; PET: harvested rainwater after 6 h of solar exposure using the 2L-PET bottle.

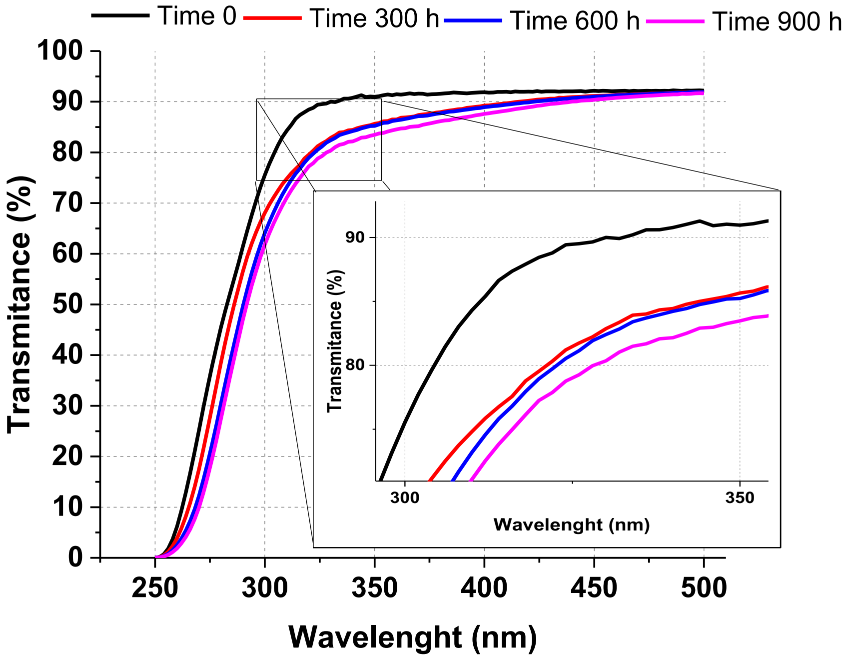
Fig. 1.


Aluminium mirror
Tube
Metal Frame
a)
b)
c)
RAINWATER TANK
d)
RAINWATER TANK
e)

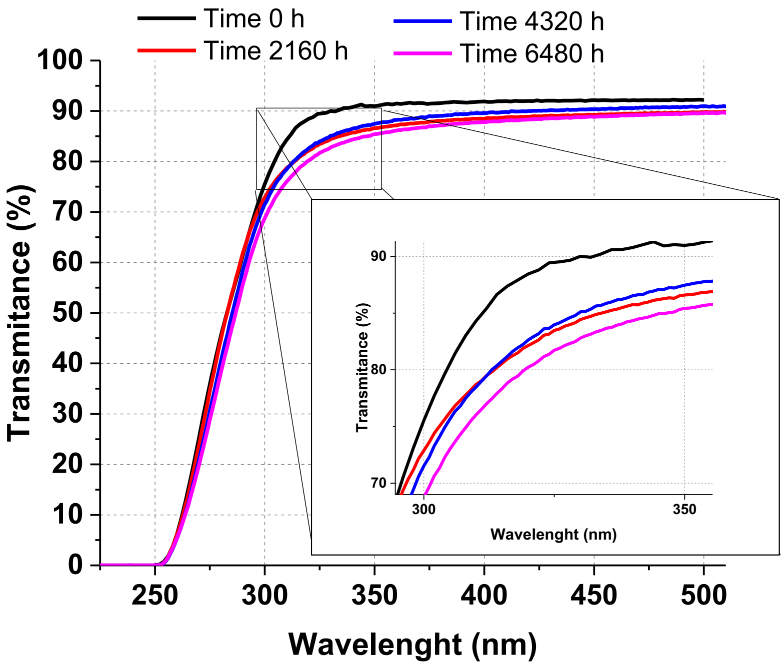
Fig. 2.


Transmittance (%)
Wavelenght (nm)
0
20
40
60
80
100
200
250
300
350
400
450
500
Quartz
PMMA
Borosilicate glass
PET
Methacrylate
Polycarbonate

a)

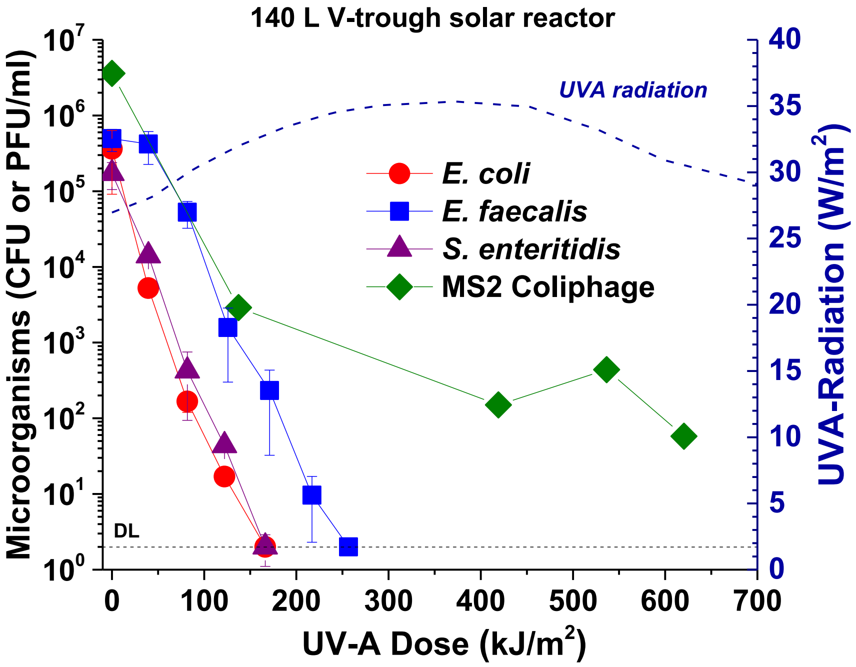

Time 0
Time 300 h
Time 600 h
Time 900 h
Transmittance (%)
Wavelenght (nm)
0
10
20
30
40
50
60
70
80
90
100
250
300
350
400
450
500
Transmittance (%)
80
90
300
350
Wavelenght (nm)

b)

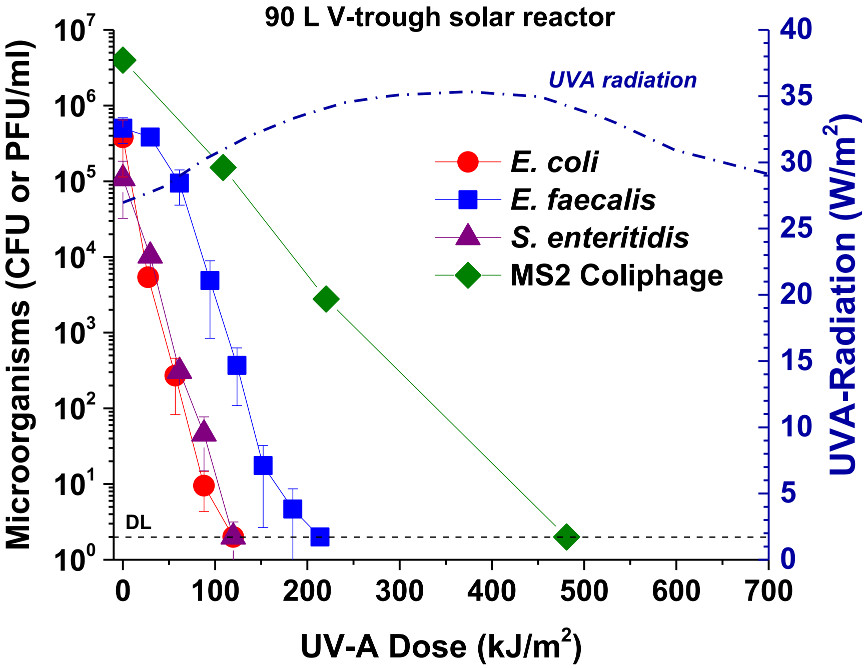

Time 0 h
Time 2160 h
Time 4320 h
Time 6480 h
Transmitance (%)
100
90
80
70
60
50
40
30
20
10
0
250
300
350
400
450
500
Wavelenght (nm)
Transmitance (%)
90
80
70
300
350
Wavelenght (nm)

c)

Fig. 3.

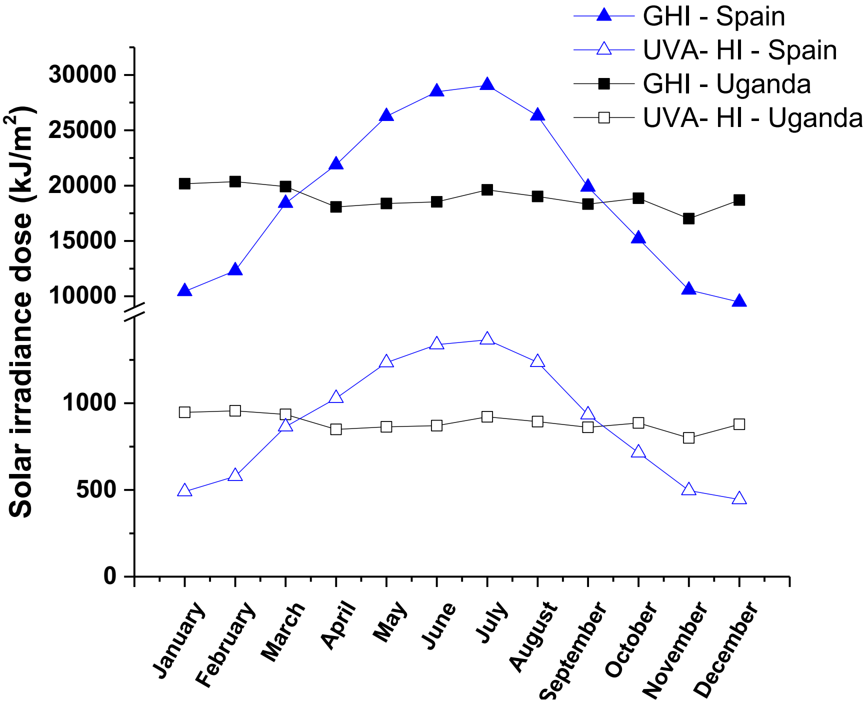

140 L V-trough solar reactor
Microorganisms (CFU or PFU/ml)
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
DL
UVA radiation
E. coli
E. faecalis
S. enteritidis
MS2 Coliphage
UVA-Radiation (W/m^2)
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
UV-A Dose (kJ/m^2)

a)

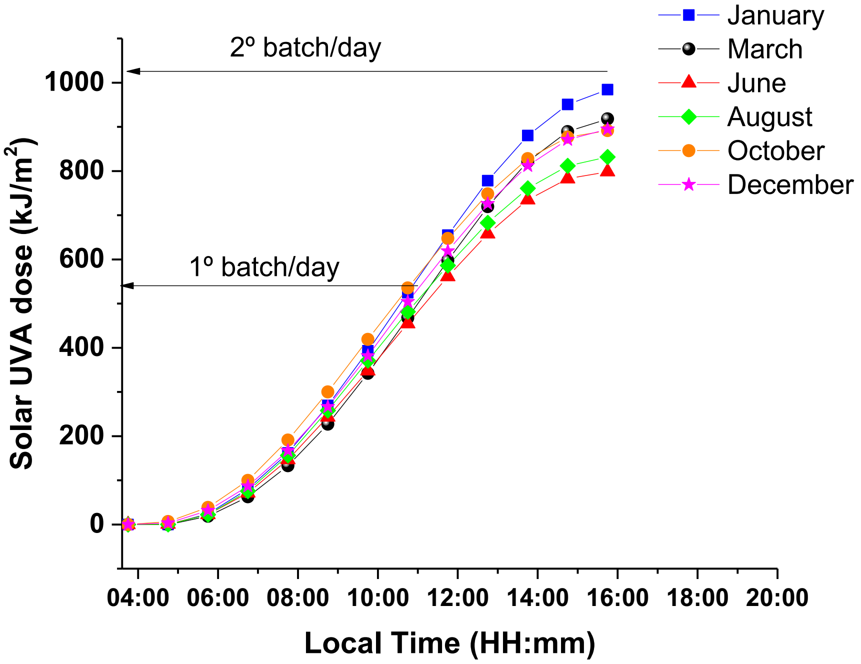

90 L V-trough solar reactor
Microorganisms (CFU or PFU/ml)
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
DL
UVA radiation
E. coli
E. faecalis
S. enteritidis
MS2 Coliphage
UVA-Radiation (W/m^2)
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
UV-A Dose (kJ/m^2)

b)

Fig. 4.


GHI - Spain
UVA- HI - Spain
GHI - Uganda
UVA- HI - Uganda
Solar irradiance dose (kJ/m^2)
30000
25000
20000
15000
10000
1000
500
0
January
February
March
April
May
June
July
August
September
October
November
December

a)


January
March
June
August
October
December
2º batch/day
1º batch/day
Solar UVA dose (kJ/m^2)
1000
800
600
400
200
0
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
Local Time (HH:mm)

b)