

1 **Title:** Meeting daily drinking water needs for communities in Sub-Saharan Africa using solar  
2 reactors for harvested rainwater

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**1 ABSTRACT**

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

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

## 1 1. INTRODUCTION

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

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

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

30 While chlorination, filtration and boiling are the most frequently used treatments, solar water  
31 disinfection (SODIS) can be used to treat small volumes of water in regions of high solar  
32 irradiation. Typical SODIS practice involves filling 1-2L PET (polyethylene terephthalate)  
33 containers with available water and placing them in full sunshine for a minimum of 6 hours.  
34 During solar exposure, UV radiation damages the microbial cells until they are completely non-  
35 viable. Damage is caused by i) UVB radiation which is absorbed by bacterial DNA preventing its

1 replication and/or generating mutations [8], and ii) UVA radiation reaching various endogenous  
2 or exogenous chromophores altering the electron transport chain which induces the creation of  
3 Reactive Oxygen Species (ROS) [9]. These ROS species cause oxidative stress that produces,  
4 inter alia, pyrimidine dimers, peroxidation of proteins and lipids or DNA rupture [10], which  
5 prevent normal cellular function.

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

19 Recent publications reported some reactor prototypes designed to improve SODIS efficacy.  
20 Factors including design and material costs were considered. The inclusion of Compound  
21 Parabolic Collectors (CPC) improved the inactivation of several pathogens including *E. coli*, *E.*  
22 *faecalis*, oocyst of *Cryptosporidium parvum*, etc. in clear and turbid waters below 30 NTU [15-  
23 18]. In the field, the efficacy of solar CPC reactors was also demonstrated in sub-Saharan Africa  
24 [19]. Nevertheless, the cost of these designs is still unaffordable for many communities in low-  
25 income countries. Simpler geometries, like V-trough mirrors, permit lowering the cost of the solar  
26 reactor manufacturing with quite good disinfection performance even at large scale of around 100  
27 litres per day [Martinez-Garcia, 2020].

28 Another way to improve the design of a SODIS reactor is to increment its capacity to transmit the  
29 solar radiation that inactivates the microorganisms in water, i.e. namely the UVA and UVB  
30 regions of the solar spectrum. According to previous modelling and research on this (Castro et  
31 al., validation 2018), the material of the photoreactor and its diameter are the most critical aspects  
32 on the good transmission of solar radiation to the water inside the reactor. Potential candidates  
33 for SODIS reactor materials must have mechanical and chemical stability, being light, resilient,  
34 have a high UV-transmittance and photostability, with additional reasonable cost and commercial  
35 availability. Among them, PET (polyethylene-ethylene-terephthalate), polycarbonates (PC),  
36 borosilicate, quartz, methacrylate are investigated. PET is the most widely used because proceeds

1 from reusable drinking plastic bottles and is accessible to the wide population at zero cost, but  
2 their resilience is poor, the transmittance is low in the UVA and UVB, and they are recommended  
3 to dispose after 6 months [Review Kevin, etc.]. PC containers have also low transmittance in the  
4 UVA, around 30% [Keogh et al., 2010] while other methacrylate materials transmit below 20%  
5 in the UVA. Borosilicate and quartz, while have good optical properties, are simply not viable for  
6 this application based on their weight, fragility and cost. The recent development of modified  
7 methacrylate materials for food industry and biotechnology (photo-bioreactors) have permitted to  
8 identify new polymeric materials that offer excellent properties from chemical and mechanical  
9 point of view while they have also great UV-transmission performance, this is the case of  
10 modified PMMA (poly(methyl-methacrylate)), selected as novel SODIS reactor material [21].

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

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

28

## 29 **2. MATERIALS AND METHODS**

### 30 *2.1. Solar photo-reactors*

31 Two solar photo-reactors designed and constructed by Ecosystem Environmental Services S.A.  
32 (Barcelona, Spain) have been tested. The 140L-V trough reactor consists of 3 transparent tubes  
33 (140 cm length, 5mm thickness, 200 mm diameter) and a total volume of 140L (illuminated  
34 volume 135 L, irradiated surface 1.8 m<sup>2</sup>). The 90L-V trough reactor consists of 8 tubes (140 cm  
35 length, 5mm thickness, 100 mm diameter) with a total volume of 90L (illuminated volume 87.5

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

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

### 17 *1.1. Solar disinfection tests under controlled conditions*

18 Preliminary SODIS tests were carried out simultaneously with both reactors from October 31<sup>st</sup> to  
19 November 22<sup>nd</sup> 2018 under real outdoor conditions for 5 hours (11:00 to 16:00 local time) each  
20 day at Plataforma Solar de Almeria (Almeria, South East of Spain, 37°84' N, 2°34' W) (Fig. 1b,c).

21 Reactors were filled with synthetic harvested rainwater (SHRW) and suspensions of each  
22 microorganism were spiked to achieve ca. 10<sup>6</sup> CFU/mL for each bacterium and ca. 10<sup>5</sup> particles  
23 forming unit (PFU)/mL for MS2. After a dark homogenization by agitation, first sample (t = 0  
24 min) was taken out and the reactors were exposed to natural solar radiation. Along the treatment  
25 time (5 h), samples were taken regularly and the concentration of each microbial target analysed.  
26 Dark samples were also kept in the lab at room temperature (25 °C) and analysed at the end of  
27 each experiment for viability control purposes. Results of the dark controls showed that the  
28 microorganism concentrations remained stable (data not shown). Four replicates were carried out  
29 for testing solar inactivation of both bacteria and MS2. Results were highly reproducible (P value  
30 < 0.05). Statistical analysis was performed using ANOVA excel (Microsoft office 2016) and  
31 OriginPro 2015. The average values of microbial concentration at each time point were plotted in  
32 graphs with standard deviation as error bars. Samples were retested for regrowth of all bacteria at  
33 24 and 48 h after completion, although recovery of bacteria was not observed anytime the  
34 reduction reached the detection limit (DL).

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

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

4 where  $UV$  is the average value of UVA radiation received ( $W/m^2$ ), and  $\Delta t$  is the amount of time  
 5 the reactor is exposed to solar radiation

### 6 *1.2. Solar disinfection tests in Uganda*

7 For field testing, the reactors were installed at two primary schools: Arise & Shine (31.419648,  
 8 S0.496382°) and Kabuyoga (31.4392507, S0.499342°) both in Ndagwe subcounty, Makondo,  
 9 Lwengo district, in Southern Uganda (Fig. 1d,e). These schools had previously participated in a  
 10 SODIS project (Water is Life (WIL) 2010-2013. [22]) using the standard 2-L PET bottle  
 11 procedure and were selected for this study since they displayed excellent compliance with the  
 12 previous WIL guidelines. In addition, this area is characterized by the presence of HRW tanks as  
 13 source of collecting and storing fresh-water. Rainfall pattern is bimodal with two rainy seasons  
 14 (March-May and September-December) and an average annual rain fall of 1100-1200 mm with  
 15 100-110 rainy days [Lwengo District Local Government Statistical Abstract 2018-2019. Url;  
 16 <https://lwengo.go.ug>]

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

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

30

### 31 *1.3. Water Matrix*

32 In Spain, all the experiments were carried out with SHRW for which the reagents and



1 concentrations used were: NaCl (56.1 mg/L), K<sub>2</sub>SO<sub>4</sub> (17.4 mg/L), CaCl<sub>2</sub> (5.55 mg/L), MgCl<sub>2</sub>  
2 (5.71 mg/L), NH<sub>4</sub>NO<sub>3</sub> (12 mg/L), KH<sub>2</sub>PO<sub>4</sub> (0.14 mg/L) and CaSO<sub>4</sub>·2H<sub>2</sub>O (19.7 mg/L). This recipe  
3 is lab-made with sterile distilled water and it has been reported elsewhere [20]. The main physico-  
4 chemical parameters of SHRW are: pH value of 5.3, Conductivity of 261 µS/cm<sup>2</sup>, Turbidity < 0.5  
5 NTU and Total Organic Carbon < 0.1 mg/L.

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

#### 11 1.4. Microbial enumeration and quantification in SODIS tests in Spain

12 Three bacterial strains obtained from the Spanish Culture Collection (CECT) were used: *E. coli*  
13 K-12 (CECT 4624), *Enterococcus faecalis* (CECT 5143), and *Salmonella sub enteritidis* (CECT  
14 4155). These strains were grown in fresh liquid medium Luria-Bertani Broth (Merck KGaA<sup>®</sup>,  
15 Darmstadt, Germany) for *E. coli* and *E. faecalis*; and Tryptone Soya Broth (Merck KGaA<sup>®</sup>,  
16 Darmstadt, Germany) for *S. enteritidis*, incubated at 37 °C for 18-20 hours to reach stationary  
17 phase. Bacterial cultures were then centrifuged at 900xg for 10 minutes at 25 °C using a Rotine  
18 R380 (Hettich Zentrifugen, Germany). The pellets obtained were re-suspended in phosphate  
19 buffered saline (PBS) (Sigma-Aldrich<sup>®</sup>, Germany). Suspensions containing each bacterium were  
20 simultaneously diluted directly into the SHRW to reach an initial concentration of 10<sup>6</sup> CFU/mL.  
21 Samples were enumerated using the plate count method in different selective media: ENDO Agar  
22 (Merck KGaA, Darmstadt, Germany) for *E. coli*; Slanetz Bartley Agar (Scharlau<sup>®</sup>, Spain) for *E.*  
23 *faecalis* and Salmonella Shigella Agar (Scharlau<sup>®</sup>, Spain) for *S. enteritidis*. Volumes of 20 µL  
24 from water samples and ten-fold dilutions (in PBS) were spread onto each corresponding agar  
25 media to reach the detection limits (DL) of 17 CFU/mL. When lower microbial concentrations  
26 were expected, 500 µL of water sample were directly spread on each selective media to reduce  
27 the DL to 2 CFU/mL. Colonies were counted after incubation of 24-48h at 37 °C.

28 MS2 Coliphage (ATCC 15597B1) and the bacterial host *E. coli* C300 171 (ATCC 15597) were  
29 obtained from the American Type Culture Collection (ATCC). Aliquots of virus stock solution  
30 were added directly into the SHRW to reach an initial concentration of 10<sup>5</sup>-10<sup>6</sup> PFU/mL. Stocks  
31 of MS2 infective particles and enumeration procedure were prepared using Tryptone Yeast  
32 Glucose (TYG) medium containing the following reagents from Sigma-Aldrich: Tryptone (10.0  
33 g/L) Yeast Extract (1.0 g/L), NaCl (8.0 g/L), Glucose (10.0 g/L), CaCl<sub>2</sub> (2.94 g/L) and Thiamine  
34 (0.1 g/L); additionally, 5 and 15 mg/L of Bacteriological Agar was added to prepare semi-solid  
35 and solid agar medium, respectively. The *E. coli* host was cultivated for 6 h in fresh liquid medium



(TYG) at 37 °C 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 °C 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 Coliforms (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 °C 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 °C 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  $36 \pm 2$  °C for a further  $44 \pm 4$  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  $44 \pm 0.5$  °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 ( $22 \pm 2$ °C) 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 *1.6. Ageing test of PMMA*

2 Long-term degradation of the UV-transparent PMMA under accelerated and natural solar  
3 conditions was carried out at PSA (Almeria, Spain) following procedures described elsewhere  
4 [24]. Briefly, four pieces of 2x5 cm were obtained from a PMMA lid and exposed to both natural  
5 and accelerated ageing conditions. The transmittance degradation of this PMMA material was  
6 measured using a UV-spectrophotometer equipped with an integrating sphere (150 mm diameter  
7 and specular reflectance at incidence angles from 0 to 68°) (Perkin-Elmer Lambda 1050,  
8 Beaconsfield, UK) in the range 250-500 nm.

9 Testing of accelerated ageing was carried out in a chamber (Atlas UV Test, Atlas Materials  
10 Testing Technologies, Mt. Prospect, IL, USA), according to ISO-16474, specifically for testing  
11 ageing of materials under extreme climate conditions. In this study, PMMA pieces were exposed  
12 to uninterrupted direct solar UV radiation ( $45 \text{ W/m}^2$ ) with intervals of temperature consisting on  
13 4 h at 60 °C followed by another 4 h at 50 °C. Transmittance of PMMA pieces was measured at  
14 regular intervals of 0, 300, 600 and 900 h.

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

22

## 23 **3. RESULTS AND DISCUSSION**

### 24 *3.1. Accelerated and natural ageing of PMMA material*

25 The transmittance profile of modified PMMA (wall-thickness 5 mm) in comparison with other  
26 transparent materials is shown in Fig. 2a. Quartz has the highest UV transmittance, however its  
27 high cost renders the manufacture of photo-reactors from this material too expensive for low-  
28 income countries. PMMA transmittance (from 45 to 88% in the UVB range, 280-320 nm, and an  
29 average of 90% in the UVA, 320-400 nm) is very high compared to other materials evaluated.  
30 From these results the modified PMMA is shown as the most UV-transparent compared with the  
31 other candidate materials for solar disinfection reactors. This modified PMMA is better even than  
32 borosilicate glass which is often considered to be one of the most promising materials with  
33 transmittance in the UVB (from 7 to 75%) and UVA (87%) for 1.8 mm thickness [17]. Therefore,  
34 PMMA appears to be a very good alternative to the more fragile borosilicate glass. Furthermore,  
35 this UV-transparent PMMA shows much higher UVA transmission compared to other candidate

1 plastic materials, including PET (wall-thickness 0.4-0.5 mm, transmittance of 52%) [16; 25],  
2 polycarbonate (wall-thickness 1.4-1.6 mm, transmittance of 33%) [24-25] and other methacrylate  
3 (wall-thickness 10 mm, transmittance of 19%) [17], all of which have been previously  
4 investigated as candidate materials for large volume reactors/containers and pilot plants, for  
5 SODIS purposes.

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

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

### 26 27 3.2. Disinfection performance under controlled conditions (synthetic rainwater)

28 Fig. 3a shows the inactivation profiles of bacteria (*E. coli*, *S. enteritidis* and *E. faecalis*) and MS2  
29 coliphage in SHRW using the 140 L solar V-trough reactor. The DL from initial concentrations  
30 of ca. 10<sup>6</sup> CFU/mL was attained for all bacteria; meanwhile, for MS2 coliphage a removal of >  
31 5-LRV was observed. Bacterial inactivation followed a log-linear decay, and the kinetic constants  
32 (*k*) were determined according to Chick-Watson’s law. *E. coli* ( $k=0.112\pm0.011\text{ min}^{-1}$ ,  $R^2=0.96$ )  
33 and *S. enteritidis* ( $k=0.107\pm0.003\text{ min}^{-1}$ ,  $R^2=0.99$ ) showed similar inactivation rates, which  
34 required a solar UVA dose of 173 kJ/m<sup>2</sup> or 80 minutes of solar exposure to reach DL. *E. faecalis*  
35 inactivation rate was slower ( $k=0.083\pm0.005\text{ min}^{-1}$ ,  $R^2=0.97$ ), and required a higher dose (256

1 kJ/m<sup>2</sup> and 120 min) to reduce 6-LRV. MS2 ( $k=0.006\pm 0.001 \text{ min}^{-1}$ ,  $R^2=0.70$ ) was effectively  
2 reduced for more than 5-LRV with 620 kJ/m<sup>2</sup> (dose) or 5 h of solar exposure.

3 Fig. 3b shows the inactivation of the same microbial consortium in the 90 L solar V-trough  
4 reactor. Bacterial inactivation profiles were very similar and slightly quicker than those from the  
5 140 L V-trough reactor, with lower solar UVA dose required to attain the DL or similar LRV e.g.,  
6 5-LRV was reached after 119 kJ/m<sup>2</sup> (60 min) for *E. coli* ( $k=0.159\pm 0.016 \text{ min}^{-1}$ ,  $R^2=0.96$ ) and *S.*  
7 *enteritidis* ( $k=0.143\pm 0.005 \text{ min}^{-1}$ ,  $R^2=0.99$ ) and 212 kJ/m<sup>2</sup> (100 min) for *E. faecalis*  
8 ( $k=0.105\pm 0.008 \text{ min}^{-1}$ ,  $R^2=0.96$ ). In the case of MS2 ( $k=0.013\pm 0.001 \text{ min}^{-1}$ ,  $R^2=0.99$ ), 479 kJ/m<sup>2</sup>  
9 and 300 min were required to reach the DL (more than 5-LRV).

10 All experiments were conducted under full-sunshine conditions. Solar UVA irradiance measured  
11 during SODIS tests under controlled conditions ranged from 13 to 40 W/m<sup>2</sup>. Water temperature  
12 increased from 10 to 27 °C, allowing to neglect any possible thermal effect as a key factor of  
13 bacterial or of MS2 inactivation which literature proved to be over 45° C and 40° C respectively  
14 [12, 29].

15 Several studies in the literature have reported different efficiency levels for disinfection of water  
16 using SODIS. Results vary strongly depending on the volume of water, the materials used for the  
17 photoreactor and the nature of the pathogen (Table 1). The most frequently used material and  
18 volume, 0.5–2L with PET, requires between 3 to >6 h to attain 6-LRV in bacteria [15, 30] and  
19 >16h for MS2 [31] depending on the radiation conditions and water characteristics.

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

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

31 Even for highly UV-transparent materials, the optical path length inside the usually cylindrical  
32 photo-reactors, plays an important role, as they can be constructed so that the UV-radiation  
33 penetrates the inner layers of water while the treatment volume is maximised. This also depends  
34 on the availability of materials at such diameters. This would allow larger, and more efficiently  
35 treated, volumes of water. In our case, two different diameters were investigated, 100 and 200

1 mm. Both solar reactors reduce bacteria by > 5 LRV as observed for *E. coli*, *E. faecalis* and *S.*  
2 *enteritidis* (Fig. 3, Table 1), requiring a solar UVA dose up to 220 and 270 kJ/m<sup>2</sup> for 90L and  
3 140L V-trough reactor, respectively. This corresponds to 100 – 120 min of solar exposure for  
4 each reactor respectively. Such treatment times are comparable or lower than previously reported  
5 SODIS reactors (Table 1), and deliver volumes of purified water that are 3-10 times larger.  
6 Comparing both reactor performances, the 90 L solar V-trough reactor required from 20 to 30%  
7 less of solar UVA dose to obtain the same result, which may be attributed to the smaller tube  
8 diameter.

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

### 17 3.3. Disinfection capacity in the field (rural Uganda)

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

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

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

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

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

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

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

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

34 SODIS can be considered 'better-than-nothing' when deployed as PET bottles in households,  
35 while the SODIS rainwater reactors proposed enhances the performance of PET bottles in terms



1 of amount of water produced, quality and treatment time. The use of additional drinking treatment  
2 barriers, i.e. filtration, chlorination etc. may add safety to the finality of the water. The same  
3 limitation is found in other drinking water treatments, where additional treatment steps are also  
4 required.

### 6 *3.4. Can solar V-trough reactors deliver daily drinking water needs affordably?*

#### 7 *3.4.1. Solar resource*

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

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

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

#### 26 *3.4.2. Cost analysis and materials selection*

27 Several types of material are used in the construction of the photo-reactors, including anodized-  
28 aluminum mirrors and aluminum frames, which are highly resistant to stressful environmental  
29 conditions. Both materials have already demonstrated high durability and robustness in the field  
30 as well as the PMMA material used in the photoreactor, with at least 10 years of functional life-  
31 time [41]. Nevertheless, the entire solar reactor under field conditions requires more analysis after  
32 its use for longer times to ensure the functionality life-time. The absence of automated features in  
33 the photo-reactor designs avoids over-reliance on electrical energy, requiring only the installation  
34 in an unshaded, full-sunshine location near the community point of use. The simplicity of the



1 systems makes them also almost user-independent; since the only routine maintenance they  
2 require is periodic cleaning.

3 For this analysis we are choosing the 140L-V trough reactor as it was more efficient in terms of  
4 delivered treated water per sunny day. The production costs of the reactor estimated at 1000 €  
5 (930 € for the materials, and the rest is for labour and overheads, Table S-I2). Operational costs  
6 are negligible (manpower for cleaning). Considering 10 years of operation (840 000L drinking  
7 water delivered), this equates to a cost of €0.0012 per litre of solar treated water. This cost is 25  
8 times cheaper than the current cost of chlorine treatment which was estimated at €0.030 in 2007  
9 [42]. According to the UN [43], the minimum amount of drinking water for domestic/human use  
10 is around 25L per person per day, then the cost of water with this solar reactor will be of about  
11 €10.95 per person per year, assuming the reactor is operative for 10 years. The cost of drinking  
12 water varies from country to country enormously, while OCDE areas pay very little, €0.08 per  
13 50 L of supplied drinking water, the Sub-Saharan countries prices are around €0.58 per 50L from  
14 a tanker truck [44].

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

### 32 33 3.4.3. Social impact

34 Technological solutions such as the designed V-trough solar reactors may enhance the population  
35 health and well-being of communities in Sub-Saharan Africa. In the real scenario of field studies

1 in Uganda, it should be noted that, although the country has enjoyed tremendous economic growth  
2 in recent years, it still grapples with the challenge of providing safe water to all its citizens. Over  
3 22 million people (>50% of the population) especially in the rural areas have no access to drinking  
4 water and this leads to more than 9500 deaths annually [45]. Also, most Ugandans access their  
5 water from surface sources such as lakes, rivers, open wells and dams [13] and only recently, the  
6 implementation of tanks to collect rainwater, has occurred in the country as another act of  
7 mitigation of water scarcity. Therefore, the implementation of decentralized solar reactors  
8 providing safer drinking water is a future and promising solution.

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

#### 17 4. CONCLUSIONS

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

22 Both solar reactors achieved reductions of more than 5-LRV against all the pathogenic bacteria  
23 (*E. coli*, *E. faecalis*, *S. enteritidis*) tested, when exposed to up to 270 kJ/m<sup>2</sup> of UVA, and 620  
24 kJ/m<sup>2</sup> were needed to attain 5-LRV for MS2 coliphage. *E. coli* and *S. enteritidis* were found to be  
25 more sensitive to solar UVA than *E. faecalis*. The differences between both reactor performances  
26 were around 20% in terms of the required dose, with the fastest inactivation rates observed in the  
27 90L-V trough reactor.

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

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

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

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

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- 8

1 **Figure captions**

2

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

5

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

8

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

11

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

16

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

20

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

23

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

Table 1.

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

BSi: Borosilicate glass; PMMA: Polymethylmethacrylate; ND: No data provided; CF: concentration factor; PE: Polyethylene; EVA: Ethyl Vinyl Acetate.

<sup>1</sup>Calculated kJ/m<sup>2</sup> using data provided by authors; <sup>2</sup>LRV ranged from 3 to 6 depending of the season;

**Table 2.**

Rainwater Sample	Total Plate Count (CFU/mL)	Total Coliform (CFU/100mL)	<i>E. coli</i> (CFU/100mL)	<i>E. feacalis</i> (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)	<i>E. coli</i> (CFU/100mL)	<i>E. feacalis</i> (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.

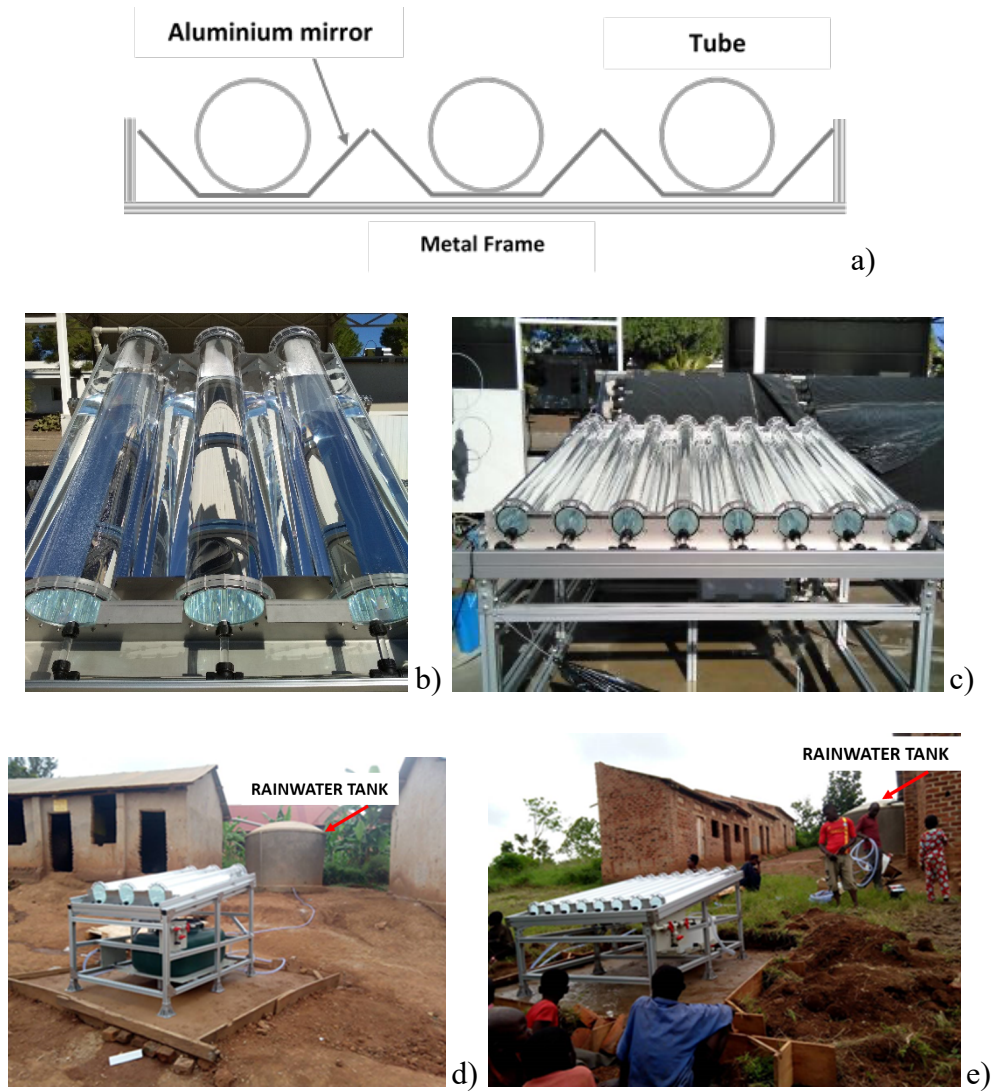
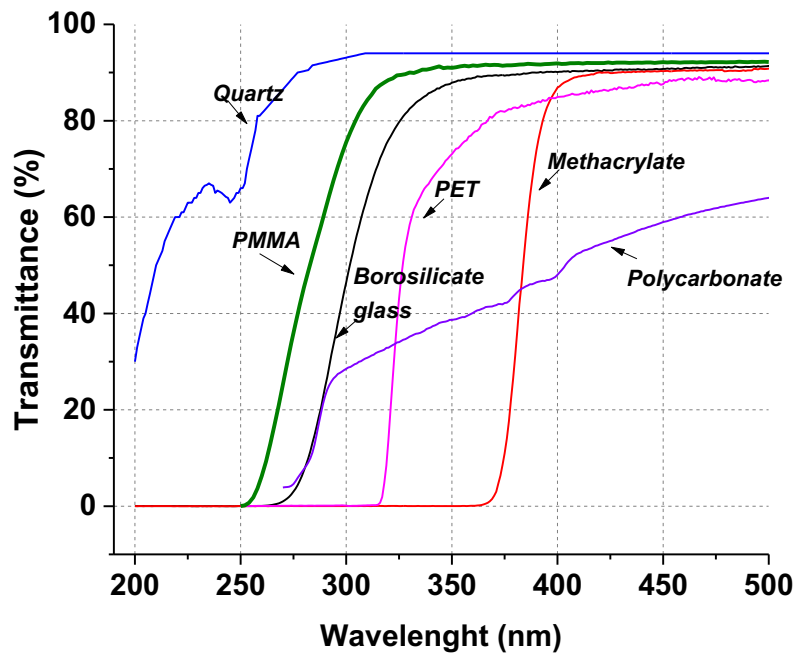
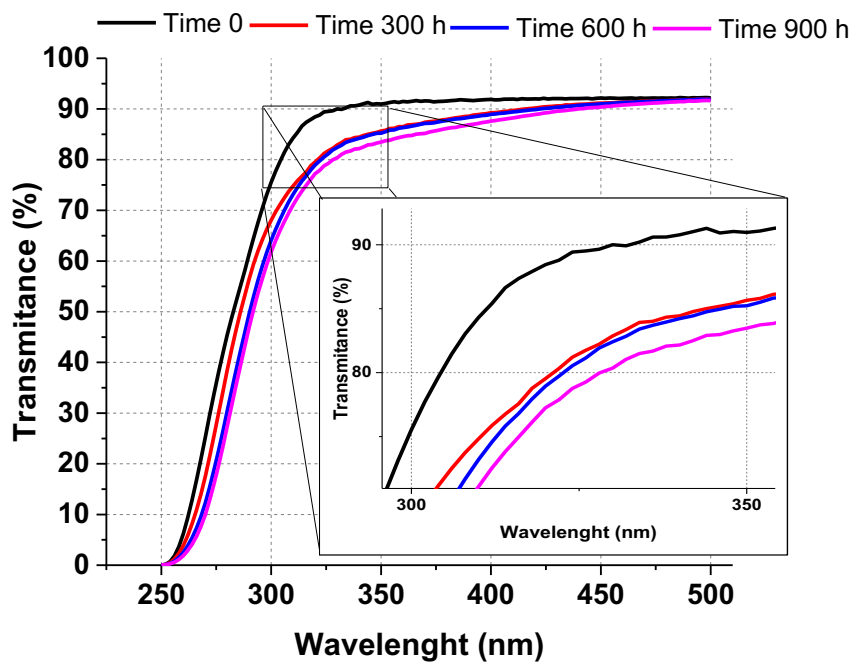


Fig. 2.

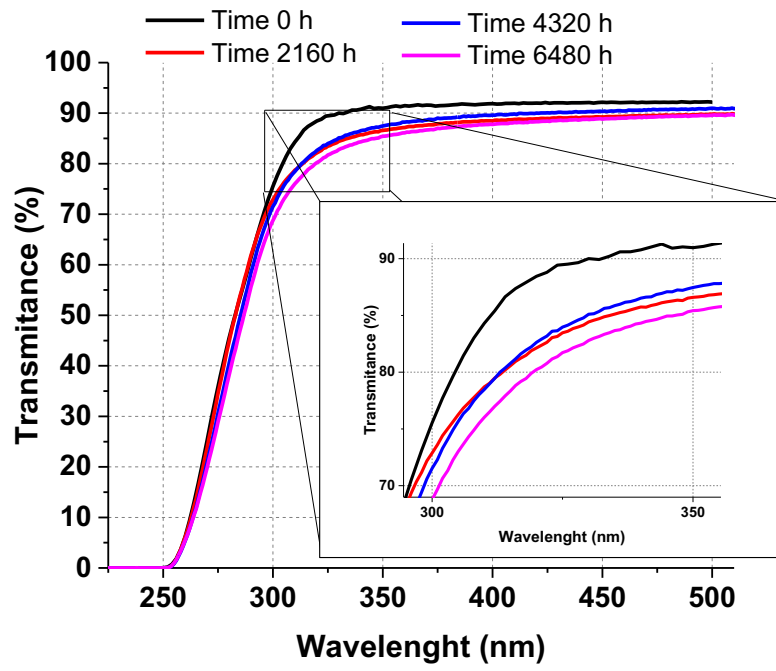


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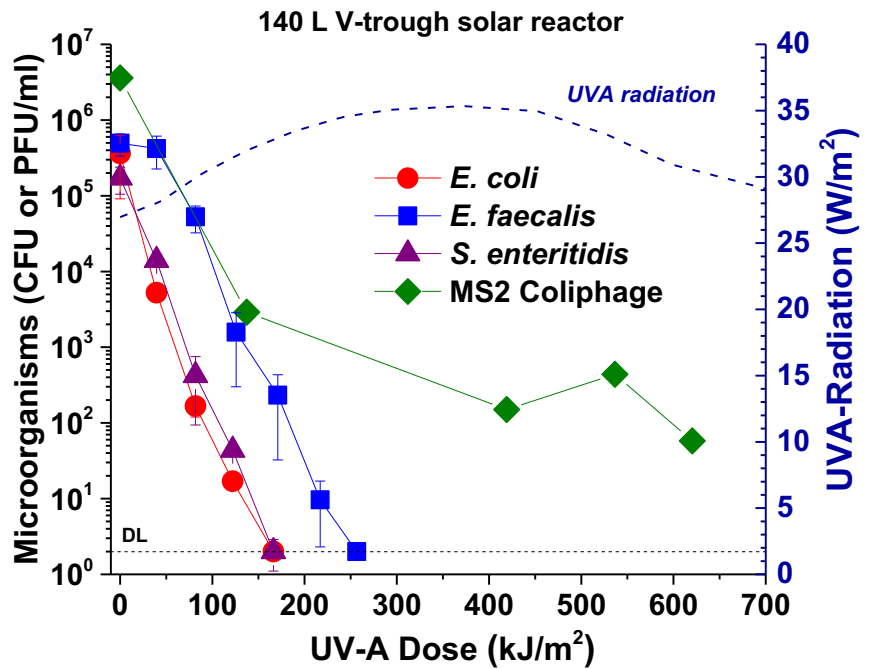
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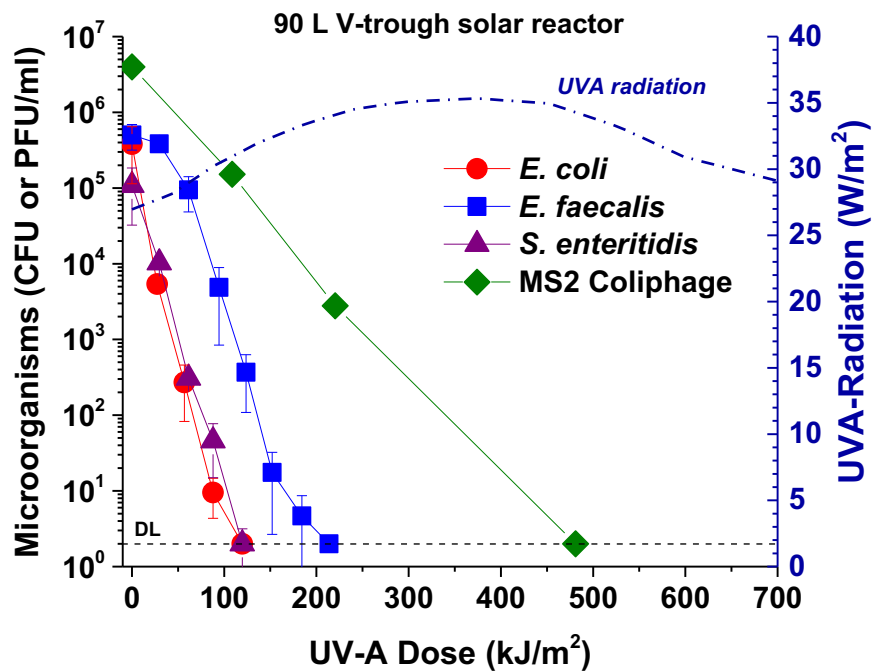


c)

Fig. 3.

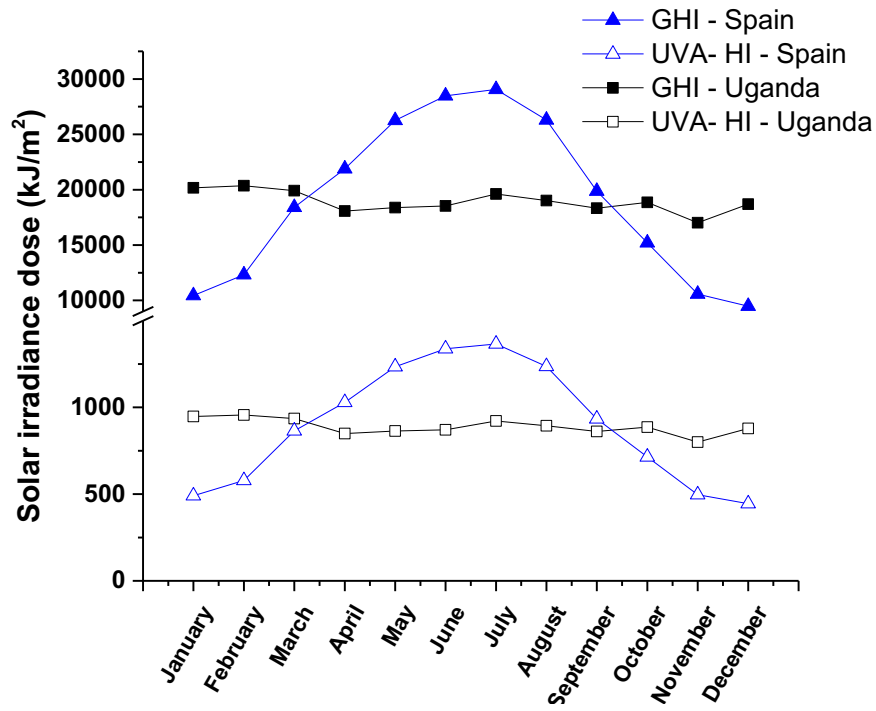


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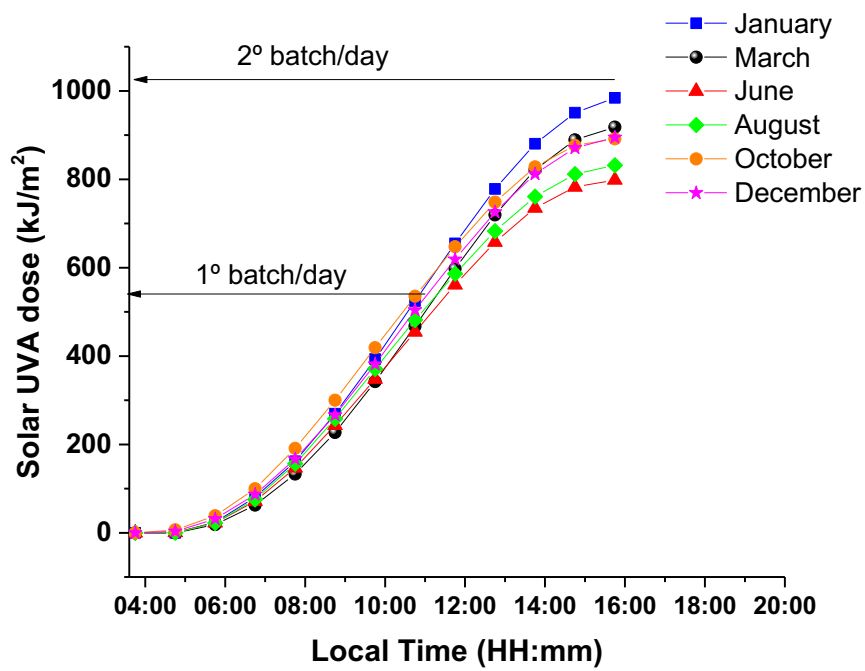


b)

Fig. 4.



a)



b)