Solar disinfection for the post-treatment of greywater by means of a continuous flow reactor

Natália Pansonato, Marcos V. G. Afonso, Carlos A. Salles, Marc Á. Boncz and Paula L. Paulo

ABSTRACT

SODIS (solar disinfection) is a low-cost alternative for water decontamination. The method is based on the exposure of water, contained in PET bottles, to direct sunlight, and mainly its UV-A and infrared components. The present research studied SODIS as a low cost alternative for the inactivation of *Escherichia coli* (*E. coli*) in treated greywater, aiming at its reuse for more noble applications. Experiments were performed in (i) batch mode (2 L PET-bottles), testing the effect of turbidity on system efficiency and, (ii) in a continuous pilot-scale reactor prototype (51 L, using interconnected 2 L-PET bottles), testing hydraulic retention times (HRT) of 18 and 24 h. Samples were exposed to an average solar radiation intensity of 518 W/m^2. The results obtained indicate that the SODIS system has potential for total coliforms and *E. coli* inactivation in the pre-treated greywater, reaching 2.1 log units *E. coli* inactivation in batch experiments for low turbidity samples (21 NTU), and >2 log units inactivation of total coliforms (and *E. coli*, when present) for the 24 h HRT-continuous prototype. The continuous flow prototype needs more testing and structural improvements to cope with the difficulties posed by algae growth, as they complicate maintaining conditions of constant flow and make frequent maintenance inevitable.

Key words | disinfection, *E. coli*, onsite treatment, photoreactor, reuse, SODIS

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INTRODUCTION

Due to both an increasing population and increasing agricultural demand, water is becoming a scarce resource. On the other hand, more and more freshwater resources suffer from pollution by discharges both from industry and agriculture, but also from domestic sewage. In agreement with ecological sanitation principles, the reuse of domestic effluents would reduce the amounts of effluent discharged in water courses and recycle human wastes, thus avoiding unnecessary contamination of water and soil, and reducing water consumption.

Greywater, representing about 70% of domestic sewage, has a great potential for reuse, due to its availability and its low content of pollutants, when compared to mixed sewage (Leal *et al.* 2007). Its composition depends, amongst other factors, on geographic region, number of householders, age group, lifestyle, socioeconomic class, habits, and water source used by the producing households. Greywater quality parameters can show variations of between 17 and 330 mg/L for suspended solids (SS) and between 15 and 240 NTU for turbidity (Friedler 2004). Although according to a number of authors the amount of pathogens in greywater can be considered low (Ridderstolpe 2004), others presented concentrations of thermotolerant coliforms in the ranges between 10^4 and 10^8 MPN/100 mL (Friedler 2004). One factor, contributing to the presence of more elevated levels of pathogens in greywater, is the presence of a relatively high concentration of easily biodegradable organic matter (Ridderstolpe 2004).

The relatively low concentration of pathogens normally found in greywater is reflected in the directives for safe reuse of water, which are less restrictive for greywater than for the reuse of effluents containing excreta. For restricted irrigation for instance, the recommendation is that the count of *Escherichia coli* (*E. coli*) remains below 10^5 (per 100 mL), while this count needs to remain below 10^3 for unrestricted irrigation (WHO 2006). The end use

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greywater will have in the household will depend on its quality. Greywater is usually directed towards less noble uses like watering (non edible) gardens and washing cars or sidewalks. Development of cheap and efficient methods for greywater disinfection, especially by means of continuous processes, would allow widening the field of possible applications of this resource and enable its reuse for more noble applications, like watering vegetable gardens and orchards and even flushing toilets.

Solar disinfection, also known by its acronym SODIS, is a low-cost alternative for water disinfection. The method is based on the exposure of water, contained in PET bottles, to direct sunlight. This method is now recommended by the World Health Organization (WHO) as a viable method for water treatment at household level (Meierhofer & Wegelin 2002), and is being used in several developing countries as a way to guarantee safe water use, mainly in areas where treated water is not readily available to the population. It is a simple and efficient technology, using two components of sunlight: UV-A light, capable of accelerating oxidative processes by increasing the concentration of Reactive Oxygen Species (ROS), damaging membrane structures and DNA of microorganisms, and infrared light, used for increasing the water temperature, keeping in mind that microorganisms in general are sensitive to heat (SODIS 2003a). While application of SODIS permits batchwise treatment of water, the amounts that can be treated in this way are limited, when compared to the amounts of water needed daily, and the technology is thus not viable for the production of larger volumes of disinfected water, necessary when trying to reuse most of the greywater produced in a household.

Solar disinfection has been studied for many years in Europe (Wegelin *et al.* 1994; Sommer *et al.* 1997; SODIS 2003a; Ubomba-Jaswa *et al.* 2009), Asia and the USA, but also in Brazil. According to the literature, it is recommended to use SODIS only when the turbidity of the water to be treated is less than 30 NTU, because suspended solids reduce the penetration of sunlight and thus protect the microorganisms from the effects of irradiation, reducing its effectiveness. Several studies (Acra *et al.* 1984; Wegelin *et al.* 1994; Reed 1997; Sommer *et al.* 1997) show the efficiency of the method, demonstrating possible inactivation of 99.9% of thermotolerant coliforms during a period of, on average, 5 h of exposure to sunlight. This efficiency however, still according to literature, depends on local sunlight conditions, weather (overcast or not), water quality, type of recipient to be used and water depth and exposed surface area.

Kehoe *et al.* (2001) used synthetic samples of water inoculated with *E. coli* at a concentration of around 10^6 MPN/100 mL, with a turbidity of 300 NTU, in 500 mL PET bottles, obtaining total *E. coli* inactivation in a period of 8.5 h, during sunny days in Malaysia (average sunlight irradiation of 956 W/m^2). Fisher *et al.* (2008) used addition of 30% H_2O_2 to filtered river water samples, to accelerate the solar disinfection rate, both at ambient and at elevated temperatures. His results show that in the presence of a concentration of around 500 μmol/L the rate of inactivation of *E. coli* doubles, even during the experiments carried out on overcast days. Techniques like batchwise solar disinfection, and solar disinfection assisted by (i) TiO_2 (Duffy *et al.* 2004), (ii) photocatalytical oxidation with a UV lamp, assisted by TiO_2 (Li *et al.* 2003), (iii) solar disinfection in a reflective bag (Walker *et al.* 2004) and (v) solar radiation disinfection in an optimised reactor with a reflective base, high UV transmission cover, TiO_2 coated ceramic rings, and vigorous aeration (Davies *et al.* 2009) were successfully tested, but such systems are not adequate for installation in individual houses, as their operation and maintenance require attention. When studying literature on the subject, not one publication was found in which a SODIS system was used for the treatment of raw or pre-treated greywater without using additives.

The aim of this research was to assess the efficiency of a SODIS system for the disinfection of greywater, first by means of batch experiments, for testing the effect of turbidity and of the addition of hydrogen peroxide as a co-disinfectant, and in a second phase-based on the results of the batch experiments by means of experiments with a prototype continuous flow reactor, testing the performance of such a system for the post-treatment of greywater.

MATERIALS AND METHODS

Climate data

Climate data referring to the research location as used in this study were obtained from INMETs on-line database (INMET 2009), data used were ambient temperature and intensity of solar radiation. Median solar radiation intensity during both experiments (July 2008 for batch and May 2009 for continuous experiments, Figure 1) was from 518 ± 162 to 600 ± 116 W/m^2, between 9:00 h and 15:00 h. The radiation levels were statistically similar amongst all days ($p = 0.01$, t_{student}). Ambient temperatures

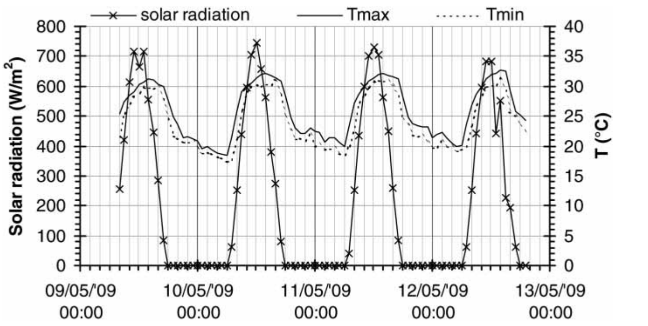

Figure 1 | Temperature and solar irradiation data for the research location (INMET 2009).

in the experimental periods varied between 19 and 33 °C (winter).

Batch experiments

The batch experiments were performed on the rooftop of the CCET building at the Federal University of Mato Grosso do Sul, Campo Grande, MS, Brazil (20°30′ S, 54°36′ W, 544 m. elevation). The greywater samples were collected in a greywater treatment system installed in a 9-person household in the same city. The system comprises of (1) a commercial grease trap (for the kitchen fraction of the greywater), (2) an inspection box (where the kitchen, laundry and shower fractions join), (3) a sedimentation tank, (4) a horizontal flow constructed wetland (HF-CW), and (5) a vertical flow constructed wetland (VF-CW). Both wetlands were cultivated with ornamental plants (Paulo *et al.* 2009). Samples of different turbidity were obtained from different sampling points: high turbidity greywater was collected from the sedimentation tank effluent (213 NTU, E_1) and HF-CW effluent (196 NTU, E_2), while low turbidity greywater was collected from VF-CW effluent (21 NTU, E_3). Further characteristics of the samples used are presented in Table 1.

The experimental setup consisted of 20 transparent PET bottles of 2 L capacity each. For all experiments, the bottles were exposed to sunlight on horizontal fibre-cement roof-tiles, for a period of 24 h starting at 9:00 h. Samples were collected from the bottles after periods of 0, 1, 3, 6 and 24 h, values chosen based on SODIS (2003b). The intervals of 1 and 3 h were chosen to obtain more representative *E. coli* deactivation curves, as the deactivation was expected to occur more rapidly in the initial period of the experiment. The interval of 24 h was chosen to verify the occurrence of any significant bacterial re-growth in the night (dark) period. The high-turbidity sample (E_1) was exposed to sunlight both without and with addition of a small amount of H_2O_2 (500 μmol/L), to study the efficiency of an additive on the disinfection of high-turbidity samples. All experiments were carried out using 4 bottles per test, sampling one bottle for each interval, thus avoiding that any experiment would be based on one bottle only. Parameters analysed during the experiment were turbidity, total coliforms, *E. coli*, pH, total suspended solids and temperature.

In a second batch experiment, one 2 L PET bottle was equipped with a temperature probe and a redox meter (Provitec Dosatronic MV1000 top, Provitec Ltda, São Paulo – SP, BR), coupled to a PC equipped with a data aquisition board (MCC, Norton-MA, USA) and datalogging software ('Guardian', developed in-house), and filled with sample E_2, to study the effect of ambient temperature, sunlight and H_2O_2 addition (500 μmol/L) on water

Table 1 | Initial characteristics of the three different greywater types used in the experiments

Parameter	Sample characteristics E_1	E_2	E_3	E_3[c]
Turbidity (NTU)	213	196	21	1.8
TSS[a] (mg/L)	121.3	100.7	14.5	Not detected
COD (mg_{O2}/L)	652	160	25.0[b]	9[b]
PO_4^{3-} (mg/L)	5.4	5.7	3.2	0.58
pH	5.69	6.96	7.02	7.1
T (°C)	24.0	22.5	22.0	
E. coli (MPN/100 mL)	6.6×10^5	8.1×10^4	2.0×10^4	
Total coliforms (MPN/100 mL)	8.7×10^8	6.5×10^7	8.2×10^6	1.7×10^3

[a]Total Suspended Solids.
[b]Residual COD, poorly biodegradable.
[c]Characterisation at time of continuous experiments.

temperature and redox potential inside the bottle, and to test the effect of H_2O_2 as an algal growth inhibitor.

Continuous experiment

A pilot-scale prototype of the continuous reactor was designed to treat only part of the effluent of the vertical-flow constructed wetland, E_3 (at the time of the continuous experiments the quality of effluent E_3 had improved considerably, see characterisation in Table 1, right hand column). The experimental set up consisted of 24 interconnected 2 L transparent PET soft-drink bottles, aiming at obtaining a low cost system. The total volume of the reactor was 51 L.

The system was constructed by connecting the neck of one bottle to the bottom of the next bottle, forming tubes of three bottles each in series. These series were then interconnected using flexible PVC tubing of 3/8″ internal diameter, thus resulting in a Plug Flow Reactor with a zig-zag configuration. After bottles 3, 6, 9 and 15, sampling taps ($P_{1–4}$) were incorporated in the connecting PVC tubes (see Figure 2). The prototype was installed on a piece of corrugated fibre-cement roof tiling, oriented to the north and inclined 20°, corresponding to the latitude of Campo Grande – MS.

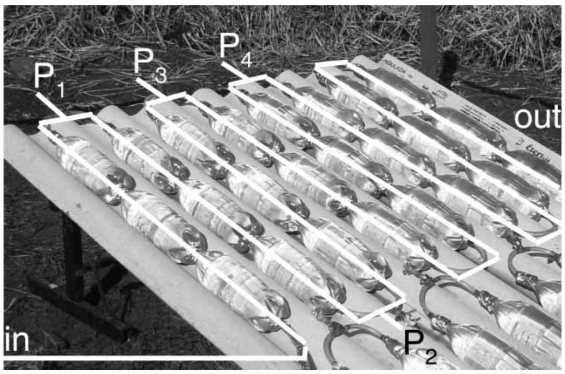

Figure 2 | Continuous SODIS setup installed on location (May 2, 2009). $P_{1–4}$: sampling points.

The reactor was gravity-fed from a constant-level reservoir collecting the VF-CW effluent by means of a restricting valve; excess VF-CW effluent not fed to the SODIS system was drained from this reservoir by means of a fixed-level overflow. Experiments were carried out using two different hydraulic retention times (HRT): 24 and 18 h, by applying flow rates of 2.13 and 2.83 L/h respectively. The first with the objective to guarantee that all water treated was exposed to strong sunlight for a period of at least 6 h, and the second to attempt to treat a higher flow of greywater, while still maintaining a 6 h light period (although not always of sufficient intensity). Taking into account that a continuous system will always operate part of the time without sunlight exposure, it was also assessed whether the order of exposure (sunlight or dark first) would affect the efficiency of the system or permit bacterial re-growth. The sampling scheme is presented in Table 2. Measurements were taken at the indicated time of day at the sample ports, providing a sample with the indicated treatment time. Varying sequences of exposure to radiation (light, insolation > 500 W/m^2) and non-radiation (dark, insolation < 500 W/m^2) were thus obtained. Insolation with an intensity below 500 W/m^2 was considered as 'dark', as such radiation intensity is considered insufficient for solar disinfection even with prolonged exposure (Meierhofer & Wegelin 2002).

Table 2 | Samples analysed, identified by time of insolation (T_0 is influent) and dark/light pattern applied to these samples for both continuous experiments (24 h and 18 h HRT)

HRT: 24 h (*Q*: 2.13 L/h)					**HRT: 18 h (*Q*: 2.83 L/h)**				
		Dark/light pattern[a]					**Dark/light pattern**[a]		
Time (h)	**Sample**[b]	**Light (h)**	**Dark (h)**	**Light (h)**	**Time (h)**	**Sample**[b]	**Dark (h)**	**Light (h)**	**Dark (h)**
09:00	T_0	–	–	–	08:00	T_0	–	–	–
12:00	T_0, T_3	3	–	–	10:15	$T_{2.25}$	1	1.25	–
15:00	T_0, T_6	6	–	–	12:30	$T_{4,5}$	1	3.5	–
09:00[c]	T_{24}	6	18	–	14:00	T_0	–	–	–
12:00[c]	T_{24}	3	18	3	14:45	$T_{6.75}$	1	5.75	–
15:00[c]	T_{24}	–	18	6	23:00[d]	T_0	–	–	–
					08:00[c]	T_{18}		1	17
					17:00[c]	T_{18}	10	6	2

[a]Dark/light pattern as experienced by sample (except T_0) withdrawn at the indicated time.
[b]Number in subscript indicates treatment time in hours to which sample was subjected.
[c]Next day.
[d]Collected at 17:00 h, assuming that coliforms MPN in the influent would not change significantly between 17:00 h and 23:00 h.

Analysis

The analysed parameters were: pH, temperature, turbidity, total coliforms, and *E. coli*. Sample temperature was always determined at the moment of collection. All other analyses were performed in the Laboratory of Water Quality of UFMS, according to the Standard Methods for the Examination of Water and Wastewater (APHA 2005). For determination of total coliforms and *E. coli*, Colilert assays (IDEXX, Westbrook-ME, USA) were used to obtain the MPN (most probable number).

RESULTS AND DISCUSSION

Batch experiments

In Table 3 the results of the batch experiments, performed with the three different pretreated greywater samples (E_1, E_2 and E_3), are presented.

In both E_1 and E_2, the samples with relatively high initial turbidity (213 and 196 NTU respectively), some sedimentation could be observed (turbidity removal of around 17% in both cases). Further batch experiments, with samples taken from both agitated and non-agitated bottles (data not shown) indicated that sedimentation could be responsible for the removal of at least one log unit of *E. coli*. The results obtained after 24 h show that no re-growth occurred. The results also show reduction of SODIS efficiency when applied to solutions with a turbidity of over 30 NTU: the highest *E. coli* inactivation was obtained in sample E_3, whilst the lowest inactivation was obtained in sample E_1, thus confirming results from the literature (SODIS 2003b). On the other hand, in absolute numbers, most *E. coli* was inactivated in E_1 (high turbidity), but this is most likely the result of the higher initial *E. coli* count in E_1 and also a result of sedimentation. In parallel, an experiment was performed in which 500 μmol/L of H_2O_2 was added to E_1. The intention of this specific test was to assess its efficiency as a co-disinfectant for high turbidity samples. The experiment showed a great (more than threefold) increase in the rate of *E. coli* inactivation (results not shown), most likely because peroxide addition under UV illumination greatly increases the concentration of reactive oxygen species (ROS), in the absence of H_2O_2 formed in much lower concentration from the dissolved oxygen present in the water being treated (Khaengraeng & Reed 2005). The concentration of reactive oxygen species formed by interaction between UV-light, water and oxygen must be the main factor in *E. coli* inactivation, as the temperature of the water in the bottle, varying with ambient temperature and sunlight intensity, never exceeded 43 °C (Figure 3).

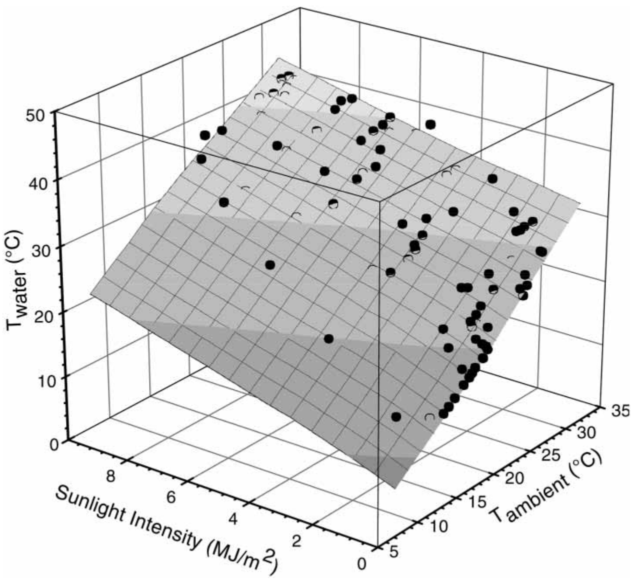

Figure 3 | Water temperature measured inside SODIS bottle as a result of sunlight intensity and ambient temperature.

Table 3 | Concentrations, and relative and log inactivation of *E. coli* for samples E_1, E_2 and E_3 during batch experiments

Time (h)	E_1 *E. coli*[a]	% Inact.[b]	Inact[c]	E_2 *E. coli*[a]	% Inact.[b]	Inact[c]	E_3 *E. coli*[a]	% Inact.[b]	Inact[c]
0	6.58×10^5	0	0.00	8.10×10^4	0	0.00	2.03×10^4	0	0.00
1	3.86×10^5	44.0	0.25	6.87×10^4	15.2	0.07	8.07×10^3	60.2	0.40
3	2.89×10^5	56.0	0.36	6.26×10^4	22.7	0.11	5.90×10^2	97.0	1.54
6	2.28×10^5	65.3	0.46	3.11×10^3	96.2	1.42	1.61×10^2	99.2	2.10
24	5.29×10^4	92.0	1.09	2.69×10^3	96.6	1.47	1.48×10^2	99.3	2.14

[a] *E. coli* is given in MPN/100 mL.
[b] %Inact. – percentage inactivation (relative).
[c] Log reduction *E. coli* count.

Although the addition of H_2O_2 has not been considered for the continuous solar disinfection process yet, it might be effective for algal growth inhibition in the continuous reactor. Diluted H_2O_2 could be added periodically (spike doses injected in the system inlet) for this purpose.

Continuous experiments

For the continuous experiments, the discussion about bacterial inactivation was based on concentrations of total coliforms. The reason is that *E. coli* concentration in E_3, the SODIS reactor inlet (T_0), was very low, probably due to a better efficiency of the greywater treatment system (wetlands) or because of changes in the householders' habits at the time of the continuous SODIS experiment.

The experiments showed that the log reduction of total coliforms obtained is almost linear with received solar radiation energy (insolation, solar radiation intensity integrated over exposure time; Figure 4), independent of initial pathogen concentration or time interval used, and that >99% reductions of total coliform counts could be obtained with the amount of insolation to which the system was subjected. Coliform reduction seemed slightly more effective at 18 h HRT than at 24 h HRT, but the difference may be statistically insignificant, given the error margins involved. Operating the reactor continuously at 18 h HRT is not practical though, as in such a situation, unlike when applying a 24 h HRT, part of the treated water will never see enough sunlight to be adequately treated.

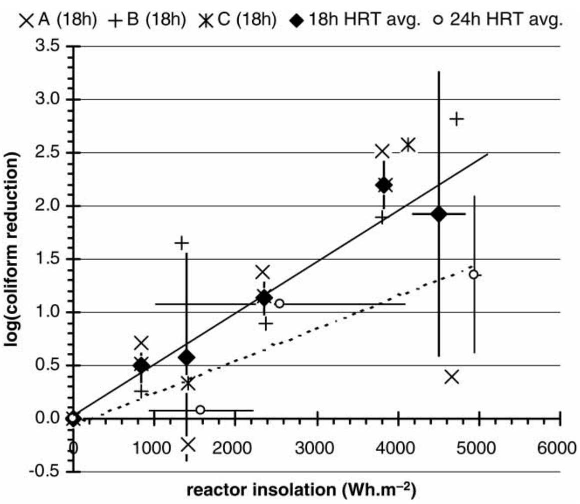

Figure 4 | Effect of received insolation on total coliform reduction; averages of reactor operating at 18 h (solid line) and 24 h HRT (dotted line).

Table 4 shows total coliforms and *E. coli* concentrations during different periods of 24 h ($T_0 \ldots T_{24}$, starting at different hours of the day), as well as the inactivation percentage of total coliforms. The results obtained when starting at 09:00 h suggest that a slight re-growth took place, because in this experiment the 24 h sample (T_{24}) is taken right after the dark period. On the other hand, the highest removal is observed in the 15:00 h run, probably because here the dark period is followed by the maximum of 6 h of effective radiation. For the run starting at noon (12:00 h) no conclusions on re-growth could be drawn, since no intermediate samples were analysed along the experiment.

In general, the re-growth phenomena experienced in treated wastewater – regardless of the disinfection technique adopted – indicate the presence of nutrients and essential oligo-elements. Lingering in treated wastewater after disinfection, these compounds provide a fertile substrate for some resistant microorganisms (Alonso *et al.* 2004). As inactivation was not complete, it could be expected that the remaining microorganisms could grow in the presence of BOD and these nutrients under non-radiation conditions.

Table 4 | Concentration and % inactivation for total coliforms, and concentration of *E. coli* in the continuous experiment with 24 h HRT

Period	Sample	Temp (°C)	Tot. colif. (MPN/100 mL)	*E. coli* (MPN/100 mL)	% inactivation Tot. colif.
09:00–09:00 h	T_0	21	1.2×10^2	5.5	0.0
	T_3 (3 h)	21	1.0×10^2	<1	16.7
	T_6 (6 h)	24	1.0×10^1	<1	91.7
	T_{24} (24 h)	34	3.7×10^1	<1	69.2
12:00–12:00 h	T_0		5.4×10^1	<1	0.0
	T_{24} (24 h)	38	1.0×10^0	<1	98.1
15:00–15:00 h	T_0		6.6×10^1	2	0.0
	T_{24} (24 h)	38	<1	<1	100.0

In spite of the good results obtained, the continuous SODIS-prototype presented some technical flaws. Some leakages were detected, so better glue and connecting devices should be tried for a second version of the reactor. Worse, a fast growth of algae was observed inside bottles and tubing within only one month of operation, even though the effluent of the vertical wetland (which was continuously fed to the SODIS system) was almost free of nutrients (0.58 mg/L of PO_4^{3-}), suspended solids (not detected); and organic matter (9 mg_{O2}/L of COD, the COD/BOD ratio being around 4). The growth of the algae also caused clogging of the valves where the flow was controlled, requiring intensive maintenance to ensure maintenance of the proper HRT. After finishing the preliminary continuous experiments, one bottle containing algae was removed from the plug flow system and transferred to the roof of the lab, where a test was performed with the addition of the same concentration of H_2O_2 as in the earlier batch experiments, whilst monitoring water temperature and redox potential. The algae were eliminated from the bottle within a few days, while the redox potential returned to the value of 200–250 mV measured in experiments without H_2O_2 addition.

CONCLUSIONS AND RECOMMENDATIONS

The present research studied the solar disinfection as a low cost alternative for *E. coli* inactivation for treated greywater, aiming at its reuse for more noble applications. The results obtained so far indicate that the continuous prototype has a large potential for *E. coli* inactivation in greywater, reaching a 2.1 log inactivation of *E. coli* in batch experiments for low turbidity samples, and a >2 log inactivation of total coliforms (and *E. coli*, when present) during continuous SODIS treatment with a 24 h HRT. Thus, with respect to the parameter *E. coli*, the treated greywater could be used for unrestricted irrigation, according to WHO (2006), which recommends that *E. coli* count should be below 10^3/100 mL.

The 24 h HRT proposed is based on literature data and on the results of our batch and continuous experiments, as the objective should be that all greywater, no matter the time it enters the reactor, is exposed to solar radiation for at least 6 h.

More research is needed for solving the problems associated with algae growth in continuous SODIS systems. The periodic use of low spike doses of H_2O_2 could be useful to inhibit algal growth, common in tertiary treatments, because it was shown effective in a batch test and because H_2O_2 addition does not generate potentially problematic by-products the way chlorination does. Investigating methods to remove residual phosphorus concentrations from the reactor influent could be useful as well.

Because, during the continuous experiments, influent concentrations of *E. coli* and total coliforms were very low (0 … 10^2 NMP/100 mL), we recommend studying the effect of initial coliform concentrations on bacterial inhibition and regrowth and on system effectiveness in more detail, and with higher coliform counts in the influent.

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