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Validation of a solar-thermal water disinfection model for *Escherichia coli* inactivation in pilot scale solar reactors and real conditions

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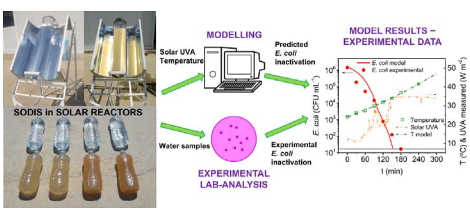
GRAPHICAL ABSTRACT



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ABSTRACT

In the present work, the *synergistic SODIS-thermal model*, describing the *E. coli* inactivation by solar exposure (SODIS) considering the synergistic effect of solar UV photons and solar heating of water under controlled conditions of irradiance and temperature, is validated under real field conditions. The main objective of this work is to demonstrate its capability to predict the solar bacterial inactivation in several solar reactor designs, different scales, and under real field conditions, i.e. variable solar irradiation, water turbidity and temperature. The model was proven to be able to predict satisfactorily the *E. coli* inactivation under different climate conditions in plastic 2-L PET (polyethylene terephthalate) bottles, the most widely used for SODIS application, in isotonic and natural well water. This model predicts also, with a high acceptance level (NRMSLE < 20%), the *E. coli* inactivation in turbid water, experimentally studied with an artificial turbidity agent (kaolin) and natural red soils to simulate the turbidity between 5 and 300 NTU. The simulation results for turbid water were performed using the Radiative Transfer Equation for the incident irradiance. In addition, the model was applied for different reactor designs (volumes ranged 2.5–22.5 L) and materials (polycarbonate, borosilicate and methacrylate) concluding that transmittance affects significantly to the incident radiation and hence to the bacterial inactivation. The predicted water disinfection of the *synergistic SODIS-thermal model* has important implications in photo-reactor design as a potential tool for comparing the efficiency of new prototypes and for automatized control systems for SODIS reactors. A 'safe time' and 'safe UV-A dose' were defined as the minimal time or UV-A dose necessary to achieve a certain bacterial reduction.

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1. Introduction

The lack of unsafe drinking water and inadequate hygiene and sanitation contributes to more than one million deaths each year [1]. The World Health Organization (WHO) has been working in the last decades to enhance the situation for those whose water supplies are unsafe. One approach is household water treatment and safe storage (HWTS) to prevent contamination during water collection, transport, and use in the home. In 2002, Sobsey et al. reviewed a number of the HWTS approved by the WHO, including boiling, chlorination, filtration and solar disinfection (SODIS) [2]. The last mentioned technique, is a water treatment that exploits the sunlight source to reduce the microbial load of water. It simply involves filling a container with the water and exposing it to direct sunlight. SODIS has been deeply assessed under both, laboratory and field conditions [3].

Although the microbiological efficacy of the method against a variety of pathogens has been demonstrated, there are still some obstacles in the application of SODIS at larger scale in developing countries. Some research in the field was focused on overcoming the limitations for SODIS compliance for example, the high treatment time (at least 6 h) required to reach certain bacterial reduction, the low effectiveness in cloudy days or with turbid waters, the low volume of treated water limited to maximum capacity of the used PET bottles (1–2 L), the risk of potential bacterial regrowth after the treatment, weather dependency, and high resistance of some waterborne pathogens as spores, parasites and virus to be inactivated by solar exposure [3]. Keane et al. reviewed the state-of-the-art of design and materials used for improved solar water disinfection [4] including, acrylic bottles to obtain better inactivation results, (ii) photo-catalyst coated cylinders (typically TiO_2 or doped TiO_2) on bottles to reduce the treatment time and to assure no bacterial regrowth [5] and (iii) substitution of small bottles by 19-L polycarbonate ones that permits treating larger volume of water at a time [6]. On the other hand, photo-reactors with low-cost solar collectors that have been designed for solar disinfection purposes have demonstrated to be a promising choice. The main advantage of this type of reactors is the increase of the inlet photon flux in the water sample resulting in a reduction of the treatment time of larger volumes of water [7]. Nonetheless, it is necessary to remember that SODIS is, for the moment, considered as an intervention technique to provide safe drinking water to little communities in low-income areas, with lack of access to safe drinking water resources, thus materials and operational costs of the reactors should be maintained as cheap as possible. This requirement is accomplished by Compound Parabolic Collectors (CPC) reactors, which become a good candidate for SODIS implementation, and have successfully proven for solar disinfection [7,8,9], photo-catalytic water disinfection [10], and water decontamination [11,12]. Although these photo-reactors have several advantages against bottles such as higher solar photon flux in water or exploitation of both direct and diffuse radiation leading to a higher efficiency in cloudy days, the photo-reactors consider also some aspects that affect the disinfection performance. Re-circulatory flow systems have dark areas delivering the solar dose in an interrupted manner to the water. The ratio of illuminated volume/total volume and the way of delivering the solar dose affects to the disinfection efficiency [13].

In spite of the efforts done up to date to design new SODIS reactors based on previous knowledge on photo-catalytic applications, there are still not any tailor-made and inexpensive design for SODIS efficient photo-reactors for solar water disinfection at large scale for further implementation in developing countries or isolated communities. In this sense, a mechanistic model of the process could help to understand how the main factors influencing SODIS are involved in the disinfection and how to manage them to obtain the best inactivation results. In a previous study, we proposed an intracellular mechanistic model that explained the *E. coli* inactivation mediated solar UVA photons [14]. In this work, the biological complex process that results in bacteria inactivation was summarized by the main intracellular bacterial reactions that occur in parallel during *E. coli* inactivation, and the kinetic parameters of those reactions were obtained therein. Following this, a new version of this model including the effect of the water temperature was developed, the *synergistic SODIS-thermal model* [15]. With this contribution the mild-heat effect and the UVA factor were proven to lead to a synergistic action that improves the disinfection efficiency. The *synergistic SODIS-thermal model* was validated in an open vessel reactor in a solar simulator under controlled conditions of irradiance and water temperature.

The objective of the present work is validate the *synergistic SODIS-thermal* model for *E. coli* inactivation [15] in different solar reactors, including the most common SODIS container, i.e. a 2-L PET bottle, under real field conditions of water turbidity, variable solar radiation and ambient temperature in variable weather conditions. Although this model was developed using experimental data of the SODIS process conducted in isotonic water, it is also tested with clear natural water obtained from a well. The turbidity generated by an artificial agent (kaolin) and natural red soil was also evaluated in this work taking into account the light depletion in the water. The incident radiation in the photo-reactor containing turbid waters was estimated considering the scattering effect of the particles solving the Radiative Transfer Equation (RTE) for a 2-dimensional 2-directional system. The *synergistic SODIS-thermal model* was proven to satisfactorily predict the bacterial inactivation profile in water with turbidity ranged between 5 and 300 NTU at different climate conditions. In addition, the influence of using several batch reactor designs including different volumes, ranging from 2.5 to 22.5 L and materials (polycarbonate, borosilicate and methacrylate) was studied by the comparison of the modelled simulation results and the experimental inactivation results. Finally we observed that the evaluated *synergistic SODIS-thermal model* is capable to predict the *E. coli* inactivation times-profiles under different natural conditions of solar irradiance, water temperature and turbidity in different reactor configurations in isotonic and well water.

2. Material and methods

2.1. *E. coli* strains enumeration and quantification

E. coli strain K12 was obtained from the Spanish Culture Collection (CECT 4624) and used for experiments in isotonic and well water spiked with seeded bacteria. Fresh liquid cultures were prepared in Luria-Bertani nutrient medium (LB Broth, Panreac) and incubated at 37 °C with rotary shaking for 20 h, to reach the stationary phase (10^9 CFU mL^{-1}). Bacterial suspensions were harvested by centrifugation at 900*g* for 10 min and then the bacterial pellet was re-suspended in phosphate-buffered saline (PBS) and diluted directly in the reactor to an initial concentration of 10^6 CFU mL^{-1}. The samples taken during the experiments were enumerated using the standard plate counting method through serial 10-fold dilutions in PBS, placing onto Luria Bertani agar three 20 μL drops of each dilution, reaching a detection limit (DL) of 17 CFU mL^{-1}. Colonies were counted after incubation for 24 h at 37 °C.

2.2. Solar water disinfection reactors

All the photo-reactors used in this work were batch reactors that are described below:

(i) PET bottles: plastic bottles widely used for SODIS application in the field and also under research in a number of SODIS articles [6,7]. The total volume of the container was 2 L. The transmittance of PET in the UVA range is in average equal to 52 %. All experiments were performed with the bottles resting on their side on the ground exposed to direct sunlight in an open area without shadows.

(ii) 19-L PC: bottle made of polycarbonate (PC), described elsewhere