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The antagonistic and synergistic effects of temperature during solar disinfection of synthetic secondary effluent

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ABSTRACT

A 4-factor, multilevel, full factorial design of 240 experiments was performed in order to investigate the effect of temperature on the inactivation efficiency of spiked *Escherichia coli* in simulated solar disinfection of a synthetic secondary effluent. The initial population of the microorganisms was 10^3, 10^4, 10^5 and 10^6 CFU/mL, the exposure time 1, 2, 3 and 4 h, the treatment temperature 20, 30, 40, 50 and 60 °C and the sunlight intensity 0, 800 and 1200 W/m^2. Radical changes in bacterial behavior, process efficiency and remaining populations were observed, while treating effluents in discreet temperatures. Elevating treatment temperature from 20 to 40 °C drastically impaired disinfection. Thermal inactivation with no regrowth predominated at 50 °C and total inactivation of microorganisms was observed at 60 °C in non-irradiated samples. Irradiation at 800 and 1200 W/m^2 much increased inactivation efficiency, especially at 50 and 60 °C, proving sensitive light-temperature synergy at those temperatures. Total inactivation was achieved within 4 h under a range of treatment conditions, including all samples at 1200 W/m^2, or 60 °C samples at 800 W/m^2. Also, 99.9–100% efficiencies and final population below 1000 CFU/100 mL were obtained at 800 W/m^2 and temperatures of 50 °C and above. Treatment time, temperature and intensity are the critical parameters for the disinfection process, while initial population is insignificant for removal efficiency. An explanation of the mechanism of the process as well as a general linear model predicting the outcome of the experiments is also suggested.

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1. Introduction

The scientific basis of solar disinfection was established in the 80s by Acra et al. [1], marking an era of important advances in solar water purification. Gradually, the laboratory work was implemented in the field, with studies performed by Wegelin et al. [2] or McGuigan et al. [3], which set the milestones for solar disinfection (SODIS) of water. More specific studies have followed throughout the years, which highlighted the important parameters of the process, as the UV-A dose, boosting efficacy and rendering SODIS a safe practice [4–6], by explaining the acute inactivation of microorganisms after a few hours of exposure to sunlight.

In parallel, many studies have initiated a cycle of investigations over the efficacy of solar disinfection for wastewater. This field was relatively unexplored and several aspects needed to be studied; this knowledge area welcomed works conducted by Kositzi et al. [7] and Polo-Lopez et al. [8] and Rizzo et al. [9], that have investigated several aspects of solar photolytic and photocatalytic treatment in different microorganisms (*E. coli*, *Fusarium*). Interest was also given in the enhancement of the process by technical means, such as compound parabolic collector (CPC) solar photo-reactors [10,11], with special focus given to the application and reuse of wastewater.

Although an interesting practice, there has not been enough focus on the possibility of treating wastewater exclusively with sunlight. Works that have demonstrated potential application margins, such as Davies-Colley et al. [12] and Craggs et al. [13] in waste stabilization ponds, have indicated the efficiency of sunlight in disinfecting wastewater as well. However, the high retention times make them less attractive than catalytic processes as far as

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Nomenclature

CFU	Colony Forming Units
W	Watts
DOE	Design of Experiments
SS	Sum of Squares
Seq SS	Sequential Sum of Squares
Adj SS	Adjusted Sum of Squares
DF	Degrees of Freedom
Ci	Concentration (at time = *i*)
$\log_{10}$ U	logarithmic Units
F	*F*-test
P	*P*-value
t	treatment time
T	temperature
C	initial bacterial population
I	light intensity
S	Standard Error of the Regression
PRESS	Prediction Sum of Squares
R-Sq	Sum of Squared Residuals
R-Sq(adj)	Adjusted Sum of Squared Residuals
R-Sq(pred)	Predicted Sum of Squared Residuals

the application point of view is concerned. However, developing countries benefited a lot from SODIS and can possibly benefit from solar disinfection of wastewater. Sanitation conditions in many African countries are marginally non-existent and untreated or poorly treated sewage end up polluting the drinking water supplies [14]. It also occurs that the pre-mentioned regions are areas with a vast number of sunny days per year, so an application of the disinfecting action of light without other technological means could be attractive.

Solar wastewater disinfection follows the same principles as water disinfection; the effect of light against pathogens is the same, but practically, one of the major differences lies in the support microorganisms find in this water matrix. The presence of ions and nutrients, organic matter, etc. provides solid ground for their survival and growth [15]. The process depends on several parameters, which complicate the study more than the drinking water one. Another important aspect is the temperature conditions that are present during the treatment. SODIS applications have reported elevated temperatures and synergistic actions of light and UV [2,3], in otherwise simpler water matrices. Reed [16] highlighted, among others, the presence of organic substances in SODIS water; the case of wastewater is an even enhanced one.

Hence, since the number of examined parameters is high, it is useful to employ experimental design techniques, which permit the extraction of information otherwise not visible [17]. This tool has been proven efficient in works that study wastewater disinfection [18,19], by creating a pre-designed set of experiments, which explains the process and the interactions between the studied parameters.

Under this prism, the current work focuses on the disinfection of wastewater by solar light alone and a statistical approach has been done, to investigate the behavior of microorganisms in synthetic secondary wastewater, when exposed to sunlight. In summary, a full factorial design has been employed to further investigate the effects of (i) exposure time, (ii) treatment temperature, (iii) initial bacterial population and (iv) sunlight intensity on *E. coli*, in batch tests, simulating solar disinfection of secondary treated wastewater. The efficiency of the process was measured, as well as a construction of a general linear model, working as an indicator of the process efficiency.

2. Materials and methods

2.1. Preparation of the synthetic secondary effluent

The pre-experimental processes involved with the preparation of the synthetic wastewater included two significant parts: the preparation of the *E. coli* suspension and the actual wastewater, performed as follows.

2.1.1. Preparation of the bacterial cultures

The selected microorganism was an *E. coli* K12 strain (MG 1655) and was provided from "Deutsche Sammlung von Mikroorganismen und Zellkulturen". Pre-cultures supplied a colony intended for loop-inoculation in sterile Luria-Bertani broth (10 g Bacto™ Tryptone, 5 g Yeast extract, and 10 g NaCl, per liter of distilled water). After incubation overnight and collection in the stationary phase, bacteria were washed three times, by centrifugation at 5000 rpm, with a neutral pH pre-sterilized saline solution, containing 8 g/L NaCl and 0.8 g/L KCl. The result was a bacterial suspension of 10^9 CFU/mL, approximately.

2.1.2. Composition of the synthetic wastewater

The wastewater employed was described analytically elsewhere [20]. The preparation of the synthetic wastewater took place as follows: 160 mg/L peptone, 110 mg/L meat extract, 30 mg/L urea, 28 mg/L K_2HPO_4, 7 mg/L NaCl, 4 mg/L $CaCl_2{\cdot}2H_2O$ and 2 mg/L $Mg_2SO_4{\cdot}7H_2O$. The initial COD was 250 mg/L COD. In order to better approximate the values of secondary effluent, a 10% dilution was used [21]. 1 mL of concentrated (10^9) bacterial solution per liter was dispersed in the solution, to reach an initial population of 10^6 CFU/mL. Consecutive dilutions were done to achieve the lower initial populations.

2.2. Simulated solar light specifications

The light source was a bench-scale Suntest solar simulator from Hanau, employing a 1500 W air-cooled Xenon lamp, with effective illumination surface of 560 cm^2. A portion of 0.5% of the emitted photons fall within a range shorter than 300 nm (UVB) and 7% in the UVA area (320–400 nm). After 400 nm, the emission spectrum follows the solar spectrum. The solar simulator also contains an uncoated quartz glass light tube and cut-off filters for UVC and IR wavelengths. The three intensity levels employed in this study (0, 800 and 1200 W) were monitored by a Global and UV radiometer (Kipp & Zonen Mod. CM3 and CUV3). Concerning the applied intensities, 800 W/m^2 is a feasible value of solar irradiance, in the areas candidate for solar disinfection, in general. On the other hand, 1200 W/m^2 is a relatively high value chosen in purpose, defining (i) a neighboring value to the highest intensity able to reach earth's crust and (ii) a value with profound results, in order to stress the modifications in bacterial kinetics; our investigations (data not shown) indicated that values around 1000 W/m^2 had the desired effect, but not as obvious as the presented ones.

2.3. Reactor configuration

The batch tests that withheld the bacterial samples were cylindrical double-wall Pyrex glass bottle reactors (outer diameter 7.5 cm, inner diameter 6.5 cm, height 9 cm, irradiation surface 20.41 cm^2), which allow control of the temperature and UVB transmission, as well as mild stirring with magnetic stirrer. Water was taken from the body of the irradiated sample, still under stirring.

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