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Effect of UV solar intensity and dose on the photocatalytic disinfection of bacteria and fungi

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Abstract

The purpose of this work was to study the dependence of solar photocatalytic and solar water disinfection on solar irradiation conditions under natural sunlight. This dependency was evaluated for solar photocatalysis with TiO_2 and solar-only disinfection of three microorganisms, a pure *E. coli* K-12 culture and two wild strains of the *Fusarium* genus, *F. solani* and *F. anthophilum*. Photocatalytic disinfection experiments were carried out with TiO_2 supported on a paper matrix around concentric tubes, in compound parabolic collectors (CPCs) or with TiO_2 as slurry in bottle reactors, under natural solar irradiation at the Plataforma Solar of Almería (Spain). The experiments were performed with different illuminated reactor surfaces, in different seasons of the year, and under changing weather conditions (i.e., cloudy and sunny days). All results show that once the minimum solar dose has been received, the photocatalytic disinfection efficacy is not particularly enhanced by any further increase. The solar-only disinfection turned out to be more susceptible to changes in solar irradiation, and therefore, only took place at higher irradiation intensities.

Keywords: *E. coli*; *F. solani*; *F. anthophilum*; Solar energy; Photocatalytic disinfection; TiO_2

1. Introduction

Water quality and its sustainable supply are major worldwide concerns. Standards and controls avoiding contamination by microorganisms, especially pathogenic specimens, underlie the safety of drinking water. Depending on the final use, water requirements, such as the WHO Guidelines for drinking water, may be very strict. Water used in agriculture must also comply with minimum safety standards, since irrigating water is a vehicle for plant pathogens and contagion, especially in intensive greenhouse agriculture, where the reuse of irrigation water is often limited due to contamination by phytopathogens. Water that does not meet these standards must be disinfected before its recirculation.

Because of its cheap, easy application, chlorination is often used for disinfection, however, among its negative effects are the appearance of trihalomethanes (THMs) as the by-products of its reaction with organic matter, phytotoxicity, and an unpleasant taste when used for drinking water [1,2]. Both the thermal energy of sunlight and its germicide properties have recently been used for disinfection [3,4]. In addition to large-scale applications in solar reactors [5–7], research for solar disinfection in recent years has often focused on small-volume (1.5 L) UV-light-transparent plastic bottles as batch reactors for domestic treatment of drinking water in areas with high solar irradiance [3,8]. Called the SODIS treatment, it has been proven successful for a wide range of microorganisms including bacteria, fungus spores, cysts, etc. [4,9,10].

Nevertheless, this type of solar disinfection is limited in applications with high volumes of water or more resistant microorganisms, and may therefore be enhanced by the addition of a photocatalyst semiconductor. This advanced oxidation technology can be deployed for air and water treatment using TiO_2, an already well-analyzed, low-cost photocatalyst. The wide range of TiO_2 applications was recently reviewed by Fujishima [11]. Among its other applications, TiO_2 for the treatment of different types of water contamination has been studied in depth [12].

When TiO_2 is excited by the energy of near UV-radiation (<400 nm) a photocatalytic reaction that generates electron–hole pairs on the semiconductor surface takes place [13]. In the presence of water and oxygen, hydroxyl radicals ($^{\bullet}OH$) are

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formed [14]. Hydroxyl radicals are known to be strong, not very selective oxidizing agents. Furthermore, water treatment with TiO_2 photocatalysis does not require the addition of consumable chemicals. Killing microbial cells with a photoexcited semiconductor powder was first reported by Matsunaga *et al.* [15]. Since then, an increasing amount of research has contributed to the development of new materials, supported photocatalysts, photoreactors and procedures for water disinfection. Results suggest that oxidative damage first takes place on the cell wall, where the TiO_2 photocatalytic surface makes contact with the cell [16,17]. Maness presented evidence of peroxidation of the polyunsaturated phospholipid component of the lipid cell membrane, which produces major life-threatening damage leading to a loss of essential functions, such as respiratory activity, and consequently to cell death [16]. Although it is uncertain which reactive oxygen species are directly involved in the photokilling process, the main reactive oxygen species (ROS) are OH radicals [18], $O_2^{\bullet -}$ and H_2O_2 [19]. Many publications have focused on the application of TiO_2 photocatalytic disinfection at laboratory scale [20], however those concentrating on the use of solar energy [21,22], or on pilot-plant scale applications under natural sunlight are scarce [5,6,23–25]. Some work has also been published on the successful disinfection of water from real sources such as rivers, lakes and wells [26,27].

Disinfection yield with chemicals depends on the concentration of the bactericidal agent and contact time with the microorganisms [28]. In UV-disinfection systems, the yield depends on UV-lamp irradiation time (254 nm), characterized by their performance [29]. The most common way of comparing the resistance of different types of microorganisms to a UV-disinfection system is by determining the ''UV dose'' in kJ m^{-2}, defined as the product of the UV intensity, expressed as UV irradiance (W/m^2) [30], and irradiation time needed for a given disinfection level, as measured by the decrease in colony forming units (CFU) [31,32,9,10]. The efficacy of solar systems, in which the sun is the source of photons at a wavelength of 300 nm to approximately 1400 nm [33], can also be characterized by the disinfecting ''solar UV dose'' (kJ m^{-2}). In solar reactor systems, the unit considered is often the accumulated solar UV energy (kJ L^{-1}) received during photocatalytic disinfection [25,13,6]. Some authors consider the global solar spectrum when comparing natural and simulated sunlight disinfection performance [4]. Nevertheless, the most suitable way of comparing solar disinfection system efficiency (with or without catalyst) still remains undecided. This is probably due to the changeable irradiation conditions of sunlight and the limited knowledge of the mechanisms governing the solar-only and solar photocatalytic (TiO_2) disinfection processes. Even if only the definition of specific criteria is considered essential, very few contributions have focused on the issue of comparing solar photocatalytic disinfection experiments by the solar dose or solar energy received, as do Rincón and Pulgarin [26].

The goal of this work was to determine disinfection performance by the solar dose and energy per unit of volume received under very different experimental conditions and microorganisms. This was assessed in two reactor systems: (a) a CPC solar reactor pilot plant with *E. coli* and (b) bottle reactors with the fungi, *Fusarium solani* and *Fusarium anthophilum*. Three different types of solar radiation experiments were studied: (i) at different times on sunny days close together in the same season and (ii) in different seasons; and (iii) solar tests done on days close together, but under different weather conditions (cloudy and sunny).

2. Experimental methods

2.1. Bacteria strain and quantification

Escherichia coli K-12 was inoculated in a Luria broth nutrient medium (Miller's LB Broth, Sigma–Aldrich, USA) and incubated at 37 °C by constant agitation under aerobic conditions. Growth was monitored by optical density measurement at 600 nm. Bacteria were collected after 24 h of stationary-phase incubation, yielding a concentration of 10^9 CFU/mL. *E. coli* suspensions were centrifuged at 3000 rpm for 10 min and washed three times with saline solution (0.9% NaCl). Finally, the bacteria pellet was resuspended in distilled water and diluted in the 14-L photoreactor tank to the cell density required for the initial concentration. The reactor was kept running in darkness for 15 min to allow bacteria to adjust to the environment and come to a homogeneous suspension before exposure. Then a 0-min sample was taken and kept in the dark as a ''control sample''. After 90 min this ''control sample'' and the 90-min reactor sample were simultaneously replated. The samples taken during the experiment were serially diluted in distilled water and plated 16 times (16 × 10 μL) on Luria agar (Sigma–Aldrich, USA). Colonies were counted after incubation for 24 h at 37 °C. Where fewer than 10 colonies per plate were observed, 250 μL of the sample were plated for a detection limit of 4 CFU/mL.

2.2. Fungal strain and quantification

The fungi used were *Fusarium solani* and *Fusarium anthophilum*. Both fungi were chosen for their importance as pathogenic fungi in agriculture and their medium (*F. solani*) and low (*F. anthophilum*) resistance to photocatalytic disinfection as found in previous work [34]. The strains were original wild fungi obtained from soil cultures in Almería (southern Spain). The fungal colonies were transferred to an agar sporulation medium containing sodium and potassium chloride in Petri dishes exposed to UV-C radiation from a mercury lamp (40 W) for 15 days at 25 °C to produce the required number of spores (10^5–10^7 CFU/plate) [34]. Our disinfection work was based on spore inactivation as spores are the most resistant fungal life form. The spores were detached from the mycelia and agar by washing the plates with distilled water. The suspension obtained was homogenized by mechanical agitation, and the concentration was determined by direct count using a phase contrast microscope. The initial adjusted experimental concentration was approx. 10^3 CFU/mL. 50–250-μL samples of the water were plated out using the spread-plate technique on acidified (pH4) malt agar (Sigma–Aldrich, USA).

Where fewer than 10 colonies per plate were observed, 500 μL of the sample was plated to a detection limit of 2 CFU/mL. Each measurement was made in triplicate, with three sample inoculations on three plates. After 2 days of incubation at 28 °C in the dark, the colonies were counted. The same protocol had already been used in previous work [34].

2.3. Solar CPC reactor (pilot plant) and supported catalyst

The solar reactors used for bacteria disinfection were compound parabolic solar collectors (CPCs) developed and manufactured by AoSol Ltd. (Portugal) [35]. Two borosilicate glass tubes with cylindrical polypropylene supports inside (32-mm diameter) were placed in the focus of the CPC reactor. The CPC modules (tubes, supports, and CPC) were mounted on a fixed platform tilted 37° (local latitude) and connected in series so that water flowed directly from one to another and finally into a tank. A centrifugal pump returned the water to the collectors. The illuminated solar collector surface was 0.4 m^2. The outer diameter of the glass tubes was 50 mm and the illuminated volume of the whole system was 2.27 L out of a total reactor volume of 14 L. The CPC photoreactor system with the concentric support has been described in detail elsewhere [7]. The water temperature in the reactor was monitored during all the experiments and was always below 30 °C. All experiments were performed in duplicate under natural sunlight using twin solar CPC reactors installed at the Plataforma Solar of Almería. All experiments started between 9:00 and 10:30 a.m. local time.

Bacteria disinfection experiments in the CPC solar reactors were made with immobilized TiO_2 manufactured by Ahlstrom Research & Services, France [36]. The 20 g-TiO_2 m^{-2} catalyst load was immobilised on synthetic fibres called ''Type KN Ahlstrom paper'' © (activated carbon, uniformly woven, 460-μm thick, and grammage 80 g m^{-2}). The matrix was coated with Degussa P25 TiO_2 using an aqueous dispersion of colloidal SiO_2 binder transparent to UV radiation [36,37]. The concentric supports were wrapped with sheets of Ahlstrom paper and then inserted in the glass tubes. After this, the solar reactor was filled with distilled water and covered to avoid light entering during bacteria inoculation in the reactor. Once the bacteria suspension had been circulated for 15 min (adaptation and homogenization time), the cover was removed and the experiment began.

2.4. Solar bottle reactor and slurry catalyst

The experiments with fungi were performed in 250 mL DURAN-Glass (Schott, Germany) reactor bottles. Glass covers (Schott) were used instead of plastic lids, to allow the solar radiation to enter the bottle reactor from all directions. The bottles were stirred with magnetic stirrers at 100 rpm during the experiment. All experiments were performed in triplicate under natural sunlight at the Plataforma Solar de Almeria (latitude 37.09°N, longitude 2.36°W). Solar photocatalytic and solar-only disinfection tests were carried out simultaneously and the control bottles (one with and another without TiO_2) were stored under the same conditions, but in the dark for each *Fusarium* species. The temperature, measured during all experiments, was always below 30 °C, allowing thermal inactivation of fungi to be discarded, as *Fusarium* spores have been shown to still be germinating at this temperature [38,39]. Nevertheless, the dark control samples were kept at the same temperature as solar experiments to avoid thermal differences between irradiated and non-irradiated samples.

For the bottle reactor experiments, Degussa P25 TiO_2 was used as slurry at a concentration of 35 mg L^{-1}, which is the optimal catalyst load for the optical path in this reactor [40]. The fungus suspension was added to the total 200-mL volume of water and left for 15 min in the dark (adaptation and homogenization time). Thereafter, the TiO_2 slurry catalyst was added and the bottle reactors were exposed to solar irradiation on a horizontal platform.

2.5. Solar radiation evaluation

UV radiation was measured with two similar global UV-A radiometers (Model CUV3, KIPP&ZONEN, the Netherlands, with a typical sensitivity of 264 μV W^{-1} m^{-2}), one of them mounted on a platform tilted 37°, and the other with no inclination. In this way, it was possible to evaluate the solar UV irradiance received in the two above mentioned solar systems, the tilted CPC reactor and the bottle reactor. For comparison of solar test results, the solar radiation was evaluated in terms of solar UV irradiance, which is defined as the rate at which solar radiant energy is incident on a surface per unit area of surface (W m^{-2}) [41], solar UV dose received on the illuminated reactor surface, I_{UV} (J m^{-2}), and the accumulated UV energy per unit of treated water volume, Q_{UV} (J L^{-1}), which is frequently used for applications in solar reactors (Eq. (1)) [6,26].

$$Q_{UV} = \sum_n \overline{UV}_{n-1} \frac{A_r}{V_t} (t_n - t_{n-1}) \quad (1)$$

where t_n is the experimental time for n-sample, $\overline{UV}_{n-1}$ is the average solar ultraviolet radiation measured during the period $(t_n - t_{n-1})$, A_r is the illuminated collector surface and V_t, the total reactor volume.

3. Results and discussion

3.1. Effect of irradiated CPC solar reactor collector surface on E. coli disinfection

The effect of changing the illuminated reactor surface on solar photocatalytic disinfection was found in simultaneous experiments with different illuminated collector surfaces. The experiments were repeated on another day with similar light irradiance (intensity) under the same conditions. Fig. 1a shows the progress of *E. coli* concentration in the CPC reactor during two experimental series with 0.4-m^2 and 0.2-m^2 irradiated collector surfaces. In both cases, a 4.5-log decrease in cultivable bacteria was observed after 90 min of photocatalytic treatment. In both experiments, the average solar UV irradiance was

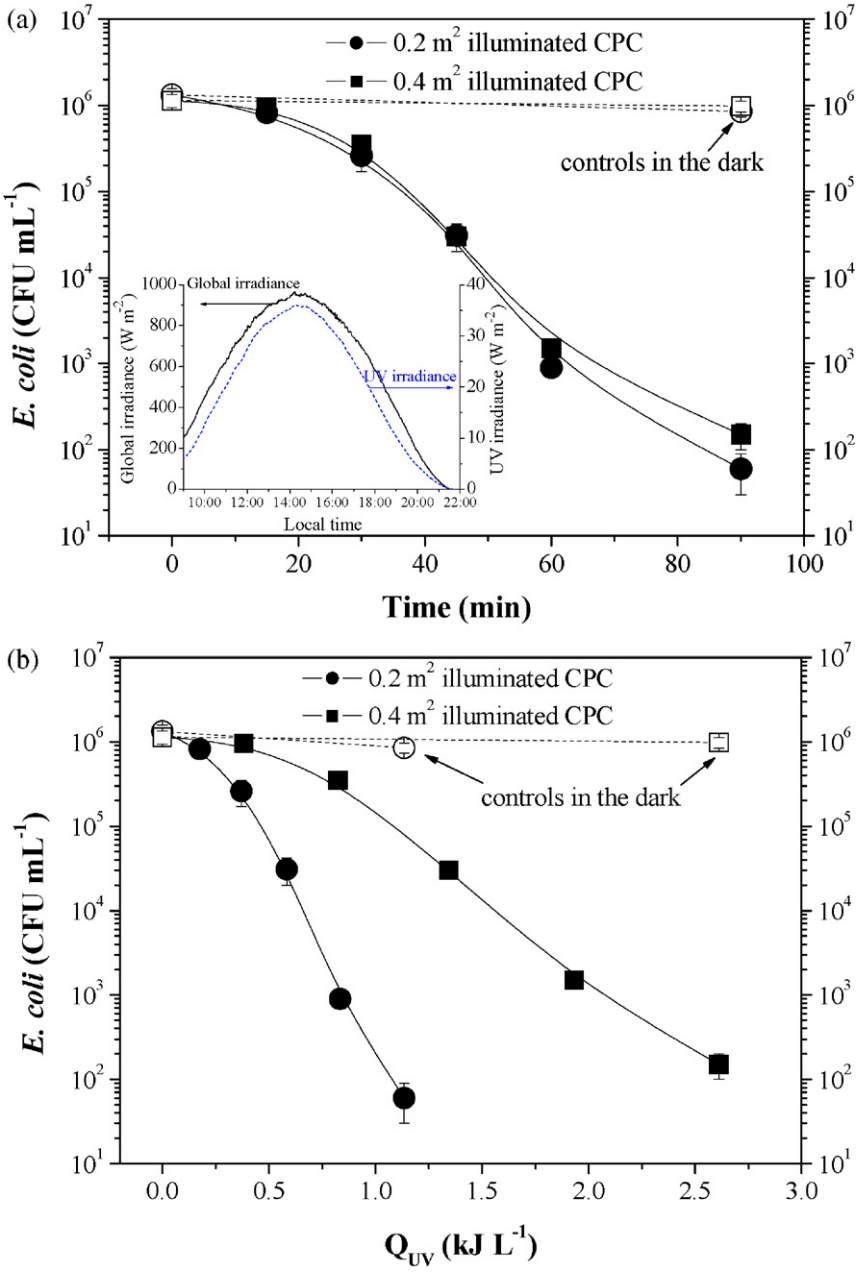

Fig. 1. Solar inactivation of *E. coli* with the immobilized Ahlstrom catalyst in the CPC reactors with 0.2 m^2 (●) and 0.4 m^2 (■) of irradiated collector surface over time (a) and Q_{UV} (b). The inset contains the solar UV (- - -) and global (—) irradiance measured during the experiments (8 May, 2005, in Almería, Spain). Each point represents the average of replicates, and vertical lines show the statistical error at 95% confidence level.

16.5 W m^{-2}, therefore the solar UV dose received during the solar tests was 89 kJ m^{-2}. The parameter varied was the accumulated UV energy per unit of volume entering the water in the reactor, which was 1.3 kJ L^{-1} and 2.6 kJ L^{-1}, respectively.

Fig. 1a shows that *E. coli* was inactivated following the same kinetics in both experimental systems even though one of them received twice the solar UV energy as the other. Fig. 1b shows the results plotted against Q_{UV}, where it can be observed that the experiment in which the surface was irradiated less leads to faster bacteria inactivation for the UV energy per unit of volume received. This can be interpreted as the system with less illuminated area receiving fewer solar UV photons, achieves the same disinfection result, a 4.5-log decrease in *E. coli* after 90 min. This means that in the system with twice the irradiated surface, that is, twice the amount of incoming photons, photon efficiency is lower, probably because not all the photons are necessary for disinfection. It can therefore be concluded that when a solar photocatalytic system has received the UV energy necessary for disinfection, an increased reactor surface does not necessarily lead to better disinfection performance. Similar behaviour has been recently reported assuming that a minimum amount of energy is sufficient to inactivate all the bacteria cells [9,26].

Results from our previous work with solar-only disinfection confirm that *E. coli* inactivation in CPC reactors is not significantly improved by larger illuminated collector surfaces

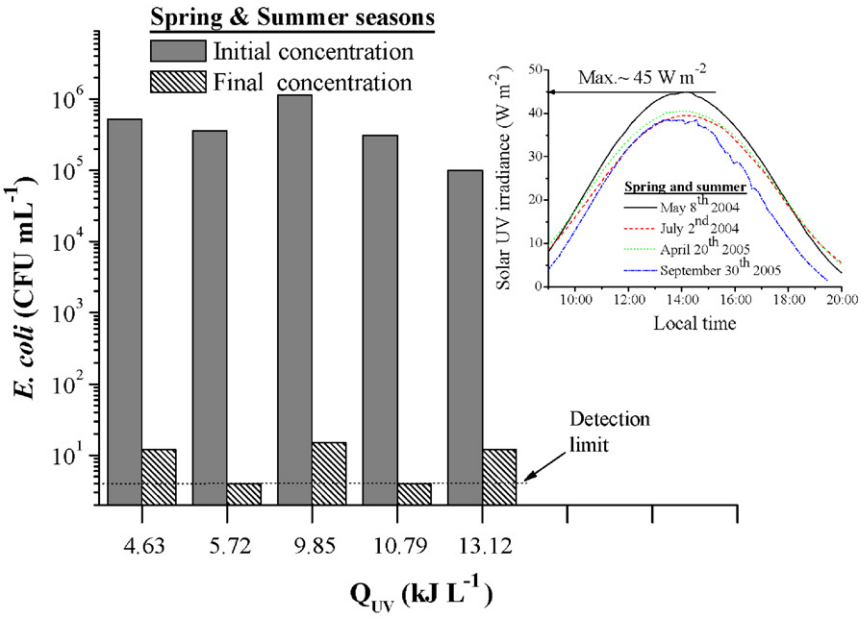

Fig. 2. Inactivation of *E. coli* by sunlight over Q_{UV} in the 0.4-m^2 CPC reactor with the immobilized Ahlstrom catalyst during different experiments in spring and summer. Inset: solar UV irradiance over time on 4 days in spring and summer, 2004–2005 at the PSA. Each bar represents the average of the replicates.

[6]. The results presented here confirm this tendency, even though the solar-only effect is combined with photocatalysis. Therefore, to the extent that the work in the CPC photoreactors represents an approximation to real water disinfection field applications, the possibility of saving in materials for CPC modules with a smaller reflector surface is of great interest.

3.2. *E. coli* inactivation in summer and winter

Figs. 2 and 3 show the seasonal influence on photocatalytic inactivation of *E. coli* in the CPC reactor. The experimental series is plotted as the initial (solid grey bars) and final bacteria concentrations (striped bars) over Q_{UV}, as found in several experiments in the CPC reactor with 0.4 m^2 of irradiated surface for 90 min on completely sunny mornings. Fig. 2 shows spring and summer disinfection performance, from the 1st of March until the 1st of October, 2004 and 2005, under strong solar irradiation. Q_{UV} was from 4 to 13 kJ L^{-1} and yielded an average 5-log reduction in cultivable bacteria. Fig. 3 shows bacteria disinfection in the seasons with the least solar irradiation, from 1st October to 1st March, 2004 and 2005, with Q_{UV} only between 3 and 4 kJ L^{-1}. Bacteria inactivation is from 3 to 5 logs. Therefore, the average autumn–winter disinfection yield was slightly lower than in the spring and

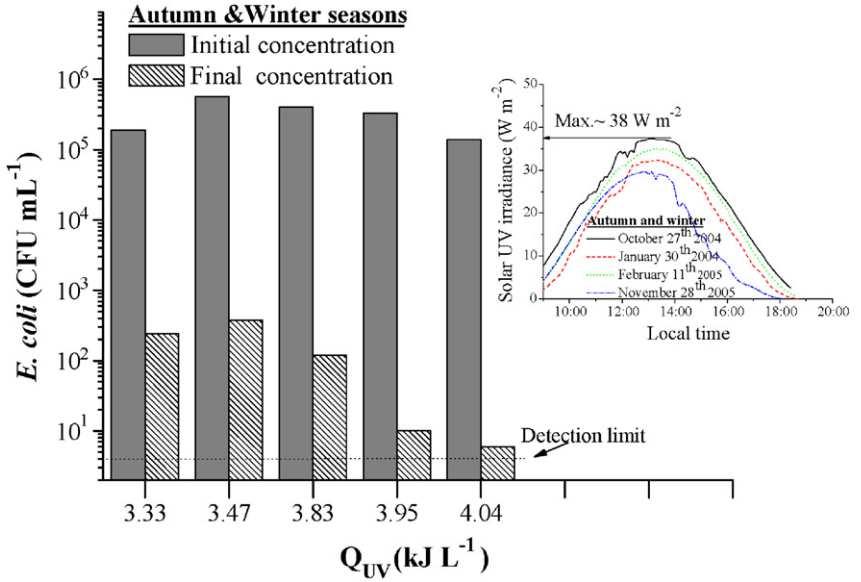

Fig. 3. Inactivation of *E. coli* by sunlight over Q_{UV} in different experiments in the 0.4-m^2 CPC reactor with immobilized Ahlstrom catalyst in autumn and winter. Inset: solar UV irradiance over time on 4 days in autumn and winter of 2004–2005 at PSA. Each bar represents the average of replicates.

summer. Fig. 3 shows that higher disinfection yields are achieved with more accumulated energy in autumn and winter; while in spring and summer, disinfection results are equally good regardless of the total amount of energy received.

The temperature in the reactor was higher (25–30 °C) in spring and summer than in autumn and winter (15–21 °C), but disinfection performance cannot be attributed mainly to a thermal effect, since there is only synergy between solar radiation and temperature above 45 °C [3]. Nevertheless, the photocatalytic disinfection rate for *E. coli* has been shown to increase when the temperature varies from 23 to 45 °C [42].

This experimental evidence points out once more that photocatalytic disinfection can produce a certain disinfection with a minimum of UV photons. Below this there is a correlation between disinfection yield and UV energy received, and above, disinfection remains similar regardless of the energy received. Therefore, disinfection by photocatalysis is not exactly proportional to Q_{UV}. Figs. 2 and 3 show that 4 kJ L^{-1} seems to be the minimum Q_{UV} for 5-log inactivation of *E. coli* under these experimental conditions.

Other authors who have previously studied the dependency of photocatalytic disinfection on light irradiance at laboratory scale have generally found that up to a certain radiant flux, faster inactivation of *E. coli* occurs at higher light intensities (irradiance W m^{-2}) with square-root dependence of the disinfection rate on light intensity [43,44,18]. In our winter experiments, in addition to the lower accumulated energy over the experimental time (J L^{-1}), lower average solar irradiance (W m^{-2}) also has to be taken into account. In this regard, the disinfection experiments shown in Fig. 3 still show proportional dependence of disinfection performance on overall irradiance, whereas in Fig. 2 irradiance can no longer be seen as the driving factor in the process. Similar slightly better disinfection in summer than in autumn was also reported by Rincon and Pulgarín, who also compared *E. coli* disinfection experiments in solar CPC reactors in different seasons and, like ours, found no linear correlation between disinfection yield and energy received at any other time of the year [25].

3.3. Effect of time of day on Fusarium inactivation

Fig. 4 shows solar-only and solar photocatalytic inactivation of *F. solani* under two different solar irradiance conditions. Both organisms have been demonstrated to be susceptible to solar-only and solar photocatlytic disinfection under natural and simulated sunlight [10,34]. The experiments described in this article started at different times on the same sunny day and, therefore, with different solar irradiance. One test series (solar-only and photocatalysis) started at 08:30 local time, and the other series began at 10:15 local time. While previous results (Figs. 1–3) had shown a 5-log reduction in bacteria after 1.5 h of treatment using immobilized catalysts, Fig. 4 shows that the photocatalytic disinfection of *F. solani* using a TiO_2 slurry requires at least 3 h of solar exposure to reduce approximately 1300 CFU/mL down to the detection limit. Similar disinfection kinetics and total disinfection times for experiments performed under high solar irradiance have previously been reported for both *Fusarium* species, as well as *F. equiseti*, *F. verticillioides*, and *F. oxysporum* [34].

A look at Fig. 4 shows much better performance by TiO_2 photocatalytic disinfection than solar-only. Inactivation of this fungus by photocatalysis is similar in both runs, but displaced in time, while the solar-only disinfection experiment has a 2-h lag in the first experiment. Fig. 5a and b show the hourly average UV irradiance (solid bars) and the solar UV dose (bars with diagonal fill) during the series shown in Fig. 4. The experiment that started at 10:15 needed 485 kJ m^{-2} for photocatalytic inactivation of 1300 CFU/mL down to the detection limit

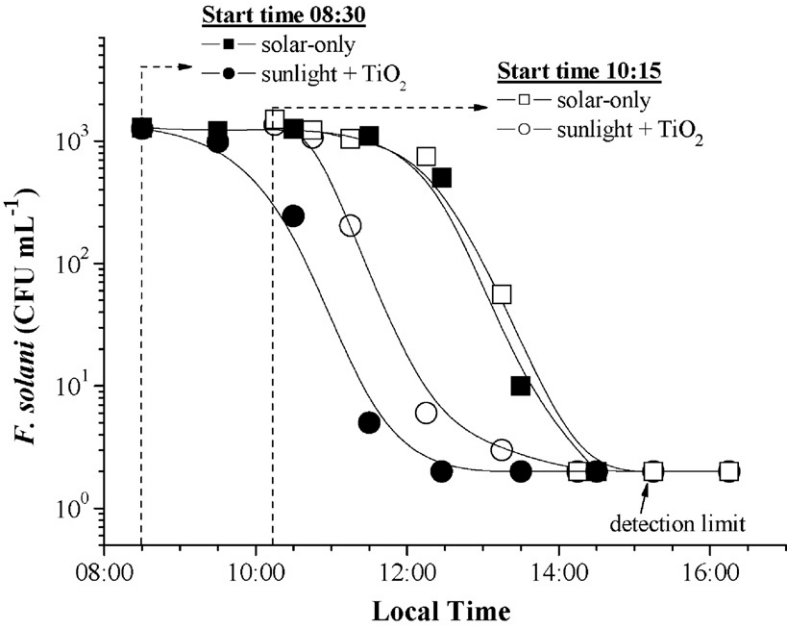

Fig. 4. Photocatalytic inactivation of *F. solani* under natural solar radiation during experiments starting at 08:30 with (●) and without TiO_2 (■) and at 10:15 with (○) and without TiO_2 (□). Initial concentration 1.3×10^3 CFU/mL. Each point represents the average of triplicates.

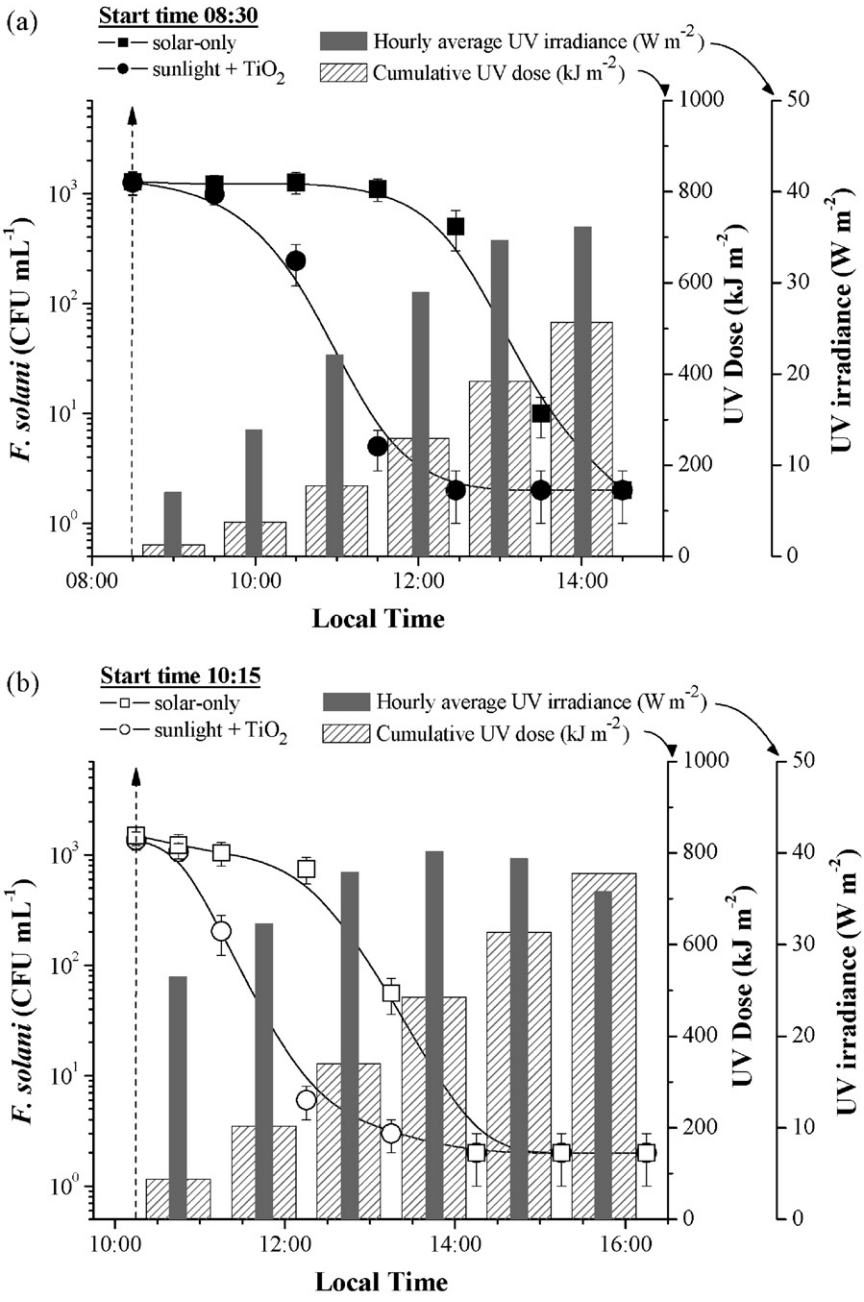

Fig. 5. Effect of the cumulative solar UV dose (bars with diagonal fill) and hourly average solar UV irradiance (solid bars) on the photocatalytic inactivation of *F. solani* under natural solar radiation with (●, ○) and without TiO_2 (■, □). Experiments started at 08:30 (a) and at 10:15 (b). Initial concentration of *F. solani* 1.3×10^3 CFU/mL. Each point represents the average of triplicates, and vertical lines show the statistical error at 95% confidence level.

(2 CFU/mL), while the experiment that started at 08:30, which received a lower solar UV dose (259 kJ m^{-2}) because the average UV irradiance was lower, arrived at the same result after 4 h of solar photocatalytic treatment. The first point of the photocatalytic kinetics in Fig. 5a and b shows that the disinfection rate was slightly more accelerated with high UV irradiance (Fig. 5b) than low UV irradiance (Fig. 5a). Nevertheless, once the system had received a certain UV dose, disinfection was similar in both cases, regardless of the total UV-dose received. Thus, a minimum UV dose or, with respect to future applications for solar reactor disinfection, a similar minimum Q_{UV} for disinfection can also be assumed for the photocatalytic disinfection of *F. solani*.

Solar-only disinfection is affected very differently by UV irradiance and dose. Fig. 5a shows that for 3 h, when the average UV irradiance was below 25 W m^{-2} and the UV dose was 154 kJ m^{-2} the *F. solani* concentration remained constant. When the UV irradiance rose to 32 W m^{-2} and UV dose to 204 kJ m^{-2} (Fig. 5b), the concentration started to diminish after 2 h of solar exposure. At least 6 h of solar exposure were necessary to reach total abatement of the initial fungus concentration with a low irradiance yielding a solar UV dose of

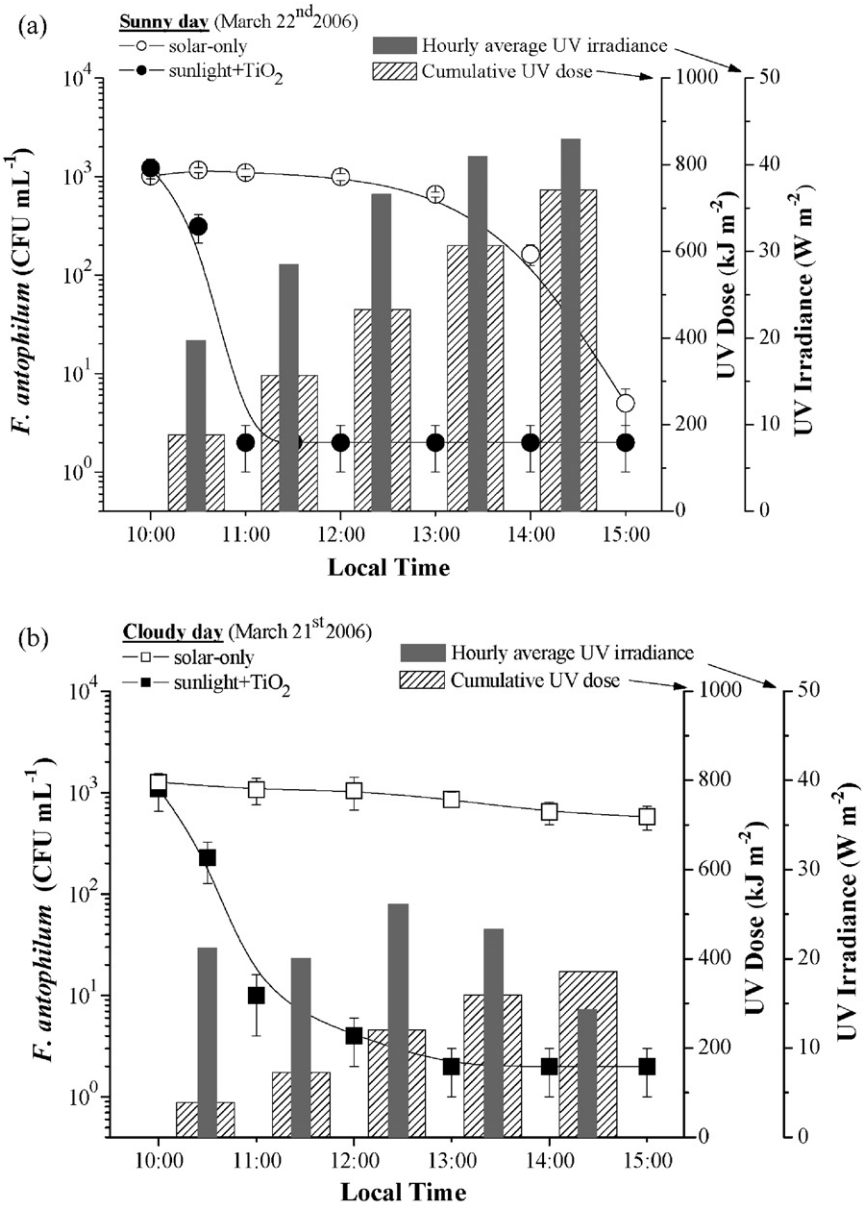

Fig. 6. Effect of the cumulative solar UV dose (bars with diagonal fill) and hourly average solar UV irradiance (solid bars) on the photocatalytic inactivation of *F. anthophilum* under natural solar radiation with (■, ●) and without TiO_2 (○, □). Experiments under sunny (a) and cloudy conditions (b). Initial concentration of *F. anthophilum* 1.0–1.3 × 10^3 CFU/mL. Each point represents the average of triplicates, and vertical lines show the statistical error at 95% confidence level.

514 kJ m^{-2} (Fig. 5a). Whereas the inactivation with high UV irradiance took only 4 h of exposure, reaching a similar solar UV dose of 485 kJ m^{-2} (Fig. 5b). Therefore, this result can be interpreted in two ways, a minimum UV irradiance (solar UV intensity) is required for solar-only disinfection, which, in the case under study, is around 30 W m^{-2}, or, that a certain solar UV dose is required, which is approximately 500 kJ m^{-2}, the corresponding Q_{UV} for solar reactors would be around of 8.25 kJ L^{-1}.

3.4. Fusarium inactivation under different weather conditions (sunny and cloudy)

Another type of *Fusarium*, *F. antophilum*, was employed in this study. This fungus was less resistant to photocatalytic treatment than *F. solani*. Fig. 6 shows two experiments, one performed on a completely sunny day (a) and the second on a cloudy day (b), with lower solar irradiance. The solar irradiance on the sunny day went from 20 to 43 W m^{-2}, while during the cloudy day it went only from 14 to 26 W m^{-2}. Photocatalytic disinfection on the sunny day took only 1 h to reduce the fungus from 10^3 CFU/mL to the detection limit, but 2 h under cloudy conditions. A solar UV dose of 145 kJ m^{-2} was enough to inactivate all fungus colonies on the cloudy day. Under sunny conditions, the UV-dose received after 1 h was higher, 176 kJ m^{-1}.

The results of photocatalysis in Fig. 6 show similar disinfection kinetics under both sunny and cloudy conditions. On the other hand, the solar-only disinfection under both conditions (low and high solar irradiance) is clearly different.

After 5 h of solar exposure, the concentration of *F. anthophilum* is reduced from 1300 CFU/mL down to 600 CFU/mL under cloudy conditions, and from 1000 CFU/mL down to 5 CFU/mL on the sunny day. The UV dose was 372 kJ m^{-2} on the cloudy day, and 741 kJ m^{-2}, on the sunny day. It can therefore be said that the UV dose necessary to disinfect this fungus is very low when TiO_2 is used regardless of the solar irradiation conditions, while solar-only disinfection requires a higher UV dose and therefore the difference in results under sunny and cloudy conditions is also greater. Furthermore, it may be observed that the necessary UV dose or intensity (irradiance) needed for disinfection of this fungus was only received on the sunny day. This result also underlines the importance of using TiO_2 to ensure the solar disinfection treatment of fungal spores under suboptimal conditions.

4. Conclusions

- Increasing the reactor surface does not necessarily lead to better disinfection performance. Once a solar photocatalytic system has received the necessary amount of UV energy, disinfection is reached regardless of the irradiated surface.
- Comparison of experiments in different seasons, early and later in the day, and under cloudy and sunny conditions, leads us to conclude that solar photocatalytic disinfection of *E. coli*, *F. solani*, and *F. anthophilum* does not depend proportionally on solar UV irradiance (solar UV intensity) as long as enough photons have been received for disinfection. The minimum UV energy necessary to reach a certain disinfection depends on the microorganism and the reactor configuration.
- Solar-only disinfection was found to be more dependent on irradiation conditions than photocatalytic disinfection. It requires higher minimum solar UV irradiance (solar UV intensity) and higher minimum UV dose for disinfection than solar photocatalytic disinfection.

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