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Solar photocatalysis as a tertiary treatment to remove emerging pollutants from wastewater treatment plant effluents

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ABSTRACT

Water taken from the outlet of a wastewater treatment plant from the South East of Spain has been treated by means of TiO_2-based solar photocatalysis. Preliminary analysis showed the presence of significant amounts of nine emerging pollutants (order of magnitude of ng/l): trimethoprim, ofloxacin, enrofloxacin, clarithromycin, acetaminophen, diclofenac, caffeine, thiabendazole and carbamazepine; and trace amounts of another two were detected, namely acetamiprid and erythromycin. Irradiation of the effluent in the presence of TiO_2 resulted in a significant removal of all the emerging pollutants, as most of them were detected only at trace amounts after the treatment. In addition to this, percentages of faecal bacteria elimination were close to 100%. Finally, experiments carried out using caffeine as model compound showed that a mild photo-Fenton process might be employed at neutral media in the presence of humic acids, although the performance was worse than photo-Fenton at acidic pH or TiO_2.

1. Introduction

Emerging pollutants (EPs) have deserved increasing attention from researchers as well as from public administrations. Although some inorganics can be considered among the EPs (e.g. nanomaterials), in most cases they are organic species such as perfluorinated compounds, pharmaceuticals, hormones, endocrine disruptors, drinking water and swimming pool disinfection byproducts, sunscreens, flame retardants, algal toxins, dioxane or pesticides and their degradation byproducts [1–3]. These pollutants are present at low concentrations at the outlet of wastewater treatment plants, and hence they can reach aquatic ecosystems such as rivers and lakes [4,5]. Although they should not be expected to exhibit an important acute toxicity at low concentrations (typically a few μg/l or even ng/l), they are persistent and phenomena such as bioaccumulation or synergetic toxicity should not be ruled out [5,6]. In addition, the presence of EPs could be considered a major inconvenience for the re-use of treated effluents as drinking water.

Conventional wastewater treatment plants are not so effective in the removal of emerging pollutants [7]. Hence, advanced methods should be applied to deal with this environmental concern, among them absorption by activated carbon, rejection by membranes, biodegradation or chemical advanced oxidation, as recently reviewed [7,8].

Among the chemical advanced oxidation processes, solar photocatalysis deserves major attention. They constitute a group of techniques that involve the "in situ" generation of highly oxidising species under solar irradiation, in the presence of a catalyst; titanium dioxide [9] and the photo-Fenton process (involving iron salts and hydrogen peroxide) [10] are the most widely employed among these methods. In fact, an important number of papers has been written in the last decade reporting on the use of these methods to treat a wide range of pollutants using sunlight as irradiation source [11–15]. Although their use as a pre-treatment to enhance the biocompatibility of toxic or non-biodegradable effluents has deserved much attention in recent years [16–20], using solar photocatalysis as a post-treatment might be an attractive alternative to remove emerging pollutants from the effluents of small wastewater treatment plants, since large surfaces needed for solar reactors might constitute a major limitation for bigger ones. In fact, some reviews have sumarized the available information on the applicability of solar photocatalysis to treat EPs [21–23]. In addition, some recent papers have reported on the application of photo-Fenton as a tertiary treatment to remove EPs at relatively low concentrations (ca. 5 μg/l) in simulated effluents from wastewater treatment plants [24,25]. Results were rather satisfactory as important removal of the studied EPs was achieved. However, as far as we know, just a few information is available on the treat-

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ment of real effluents, as they involve important problems such as their intrinsical low reprocibility, and the low EPs concentrations, which are commonly close to their limits of quantification. Nonetheless, the photo-Fenton is not free of disadvantages, in particular, the strong acidic pH required to avoid precipitation of iron; however, some recent papers have studied the possibility of applying (photo)-Fenton processes at circumneutral pH employing complexing agents (e.g. citric acid, humic acids) to increase iron solubility [26–29]. In addition, the small remnant dissolved iron concentration could be used to remove pollutants present in trace amounts. In fact, some elimination of EPs in simulated water by means of a neutral photo-Fenton has been reported [25,30].

With this background, the aim of this paper is to study the elimination of emerging pollutants at the outlet of a wastewater treatment plant from the East of Spain, which contains significant amounts of pharmaceuticals. Titanium dioxide has been tested as a tertiary treatment to remove the EPs previuosly detected in this effluent. The efficiency of this process has been compared with that of photo-Fenton at neutral conditions using caffeine as model compound.

2. Experimental

2.1. Reagents

Acetaminophen, diclofenac, caffeine, thiabendazole, acetamiprid, trimethoprim, ofloxacin and carbamazepine (see Scheme 1 for structures) employed as standards and also as pollutants in spiked samples, were purchased from Aldrich. P-25 titanium dioxide, used as photocatalyst, was kindly supplied by Degussa. Hydrogen peroxide (30%, v/v) and ferrous sulphate, used in the photo-Fenton reactions, were purchased from Panreac. Standard solutions were prepared with Milli Q grade water.

Aqueous samples containing the EPs were taken from the effluent of the secondary settling tank of a wastewater treatment plant from the East of Spain. The plant consisted of a physical–chemical primary treatment followed by an aerobic activated sludge biological reactor. The main parameters of this effluent were systematically inside the following ranges: pH, 7.5; conductivity, 2.4–2.8 mS/cm; DOC, 15–50 mg/l; IC 70–90 mg/l; and COD 60–120 mg/l.

2.2. Reactions

Experiments using real wastewaters were carried out using two different pilot plants for wastewater detoxification (Solardetox Acadus-2006) based on compound parabolic collectors, CPCs, with a concentration factor (R_c) of 1 [15]. One of them, which has been described elsewhere [31] (3.0 m^2 irradiated surface, 24 l irradiated volume), was located at the wastewater treatment plant and it was employed to treat real wastewaters. It was loaded with 50 l of wastewater in each experiment; accumulated and instantaneous UVA radiation (accounting for ca. 7% of the total solar irradiation) was measured by means of a UV radiometer and expressed as $t_{30\,W}$, in order to normalise the changing irradiation conditions typical of solar experiments. Eq. (1) has been used in the $t_{30\,W}$ (in seconds) calculations, where UV_{ac} is the accumulated solar radiation (J/m^2), V_i the irradiated volume (l), V_t the total volume (l) and I the irradiance, for which an average value of 30 W/m^2 was considered.

$$t_{30\,W} = \frac{UV_{ac} \cdot V_i}{I \cdot V_t} \tag{1}$$

Experiments with spiked samples (5 extra mg/l of each pollutant, acetaminophen, diclofenac, caffeine, thiabendazole, acetamiprid, and trimethoprim) were carried out in a Solardetox Acadus-2001 (Ecosystem) plant, with a total surface of 0.26 m^2, and the irradiated volume was 1.83 l, which was located at the laboratories of Universidad Politécnica de Valencia. For every experiment, a reservoir was charged with 4 l of the solution.

When titanium dioxide was used as photocatalyst, its amount was in the range 0.2–0.5 g/l. In the photo-Fenton process, ferrous sulphate was employed as iron source; the initial concentration of iron was 5 mg/l and it was monitored throughout the experiment in order to add, when required, extra amounts in order to compensate for its precipitation at circumneutral pH. The amount of hydrogen peroxide was kept in the range 5–10 mg/l throughout the experiment in the pilot plant reactions. Blank controls were performed by irradiating the spiked sample in the absence of photocatalyst, and dark controls were also run to determine possible absorption of the pollutants onto the TiO_2 surface.

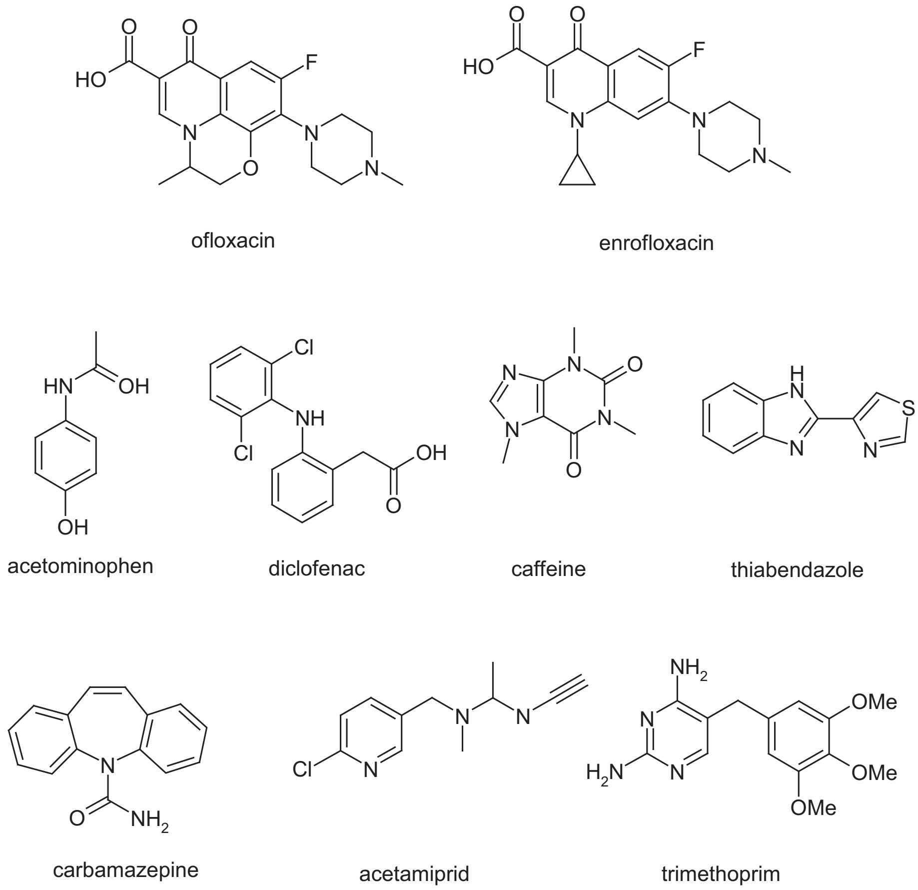
Finally, laboratory scale reactions were carried out with a model compound, caffeine; this compound was chosen because it reached the highest initial concentrations in the studied samples. In order to minimize experimental errors and to obtain reliable and comparable time resolved data, reactions were irradiated with a solar simulator (Oriel Instruments, Model 81160 equipped with a 300 W xenon lamp) and high initial concentrations of caffeine were used (50 mg/l). Experiments were performed with TiO_2 (0.2 g/l), photo-Fenton at the optimal pH of 2.8, at pH = 7 and at pH = 7 in the presence of humic acids (2 mg/l); all reactions were run with distilled water and tap water, in order to determine the possible role of carbonates. Irradiations were performed in cylindrical open glass vessels. Magnetic stirring was kept all along the reaction time and water was periodically added in order to compensate for the evaporation loss. 250 mg/l of H_2O_2 were added in a single addition at the beginning of the reaction in the laboratory scale experiments; this was the stoichiometric amount of H_2O_2 needed to mineralise completely the caffeine added.

2.3. Analysis

Samples were periodically taken from the reactors for identification and quantification of pollutants and immediately filtered (0.45 μm polypropylene, Teknokroma) and concentrated in order to prevent further reaction when H_2O_2 was present. Solid phase extraction was employed for samples concentration: 200 ml of the aqueous solution at neutral pH were flown though a LiChrolut EN 200 mg (Merck) cartridge; then the organics were recovered with 3 ml of methanol. They were then injected in a GCMS-QP2010S (Shimadzu) gas chromatograph equipped with a quadrupole mass analyser. During the analysis, temperature was increased from 160 °C to 200 °C with a 0.5 °C/min rate and kept at 200 °C for 30 min. A Meta X5 Teknokroma column was used.

Alternatively, HPLC–MS was employed for detection of trace amounts of emerging pollutants. The method is based on the EPA 1694 standardized procedures. Briefly, the sample was divided in two aliquots, the pH adjusted to 2 and 10 respectively and concentrated by solid phase extraction (HLB cartridges). Samples were recovered with methanol and formic acid and injected, at least twice, in a HPLC provided with a triple quadrupole mass detector working in MRM mode.

Dissolved organic carbon (DOC) was determined with a Shimadzu model TOC-V CSH apparatus. It was also provided with a chemoluminescence detector, able to analyse total dissolved nitrogen (TN); samples were at least twice injected. The concentration of iron was determined according to the o-phenantroline standardized procedure [32]; briefly, all the iron was reduced to iron (II) by addition of hydroquinone and the pH was adjusted to 3.5; then o-phenantroline was added and the red complex formed was



Scheme 1. Chemical structures of emerging pollutants treated in this work.

determined spectrophotometrically at 508 nm. Remaining hydrogen peroxide was measured by a colorimetric method with test stripes (Merckoquant), obtained from Merck.

For microbiological assays, samples (100 ml) were filtered though cellulose membranes (0.45 μm). The membrane was deposited onto Petri plates (Chromocult TBX Agar) and incubated at 30 °C for 4 h; then temperature was increased to 45 °C and kept for 20 h. After incubation, samples were examined with a microscope. *Escherichia coli* colonies show a characteristic green-blue colour.

3. Results and discussion

Table 1 shows the presence of eleven EPs at the inlet of the aeration tank of the biological reactor and at the effluent of the secondary settlement tank, with concentration ranging from 0.03 to 15 μg/l: five antibiotics (trimethoprim, ofloxacin, enrofloxacin, clarithromycin and erythromycin), one analgesic (acetaminophen), one anti-inflammatory drug (diclofenac), one psychiatric drug (carbamazepine), one stimulating drug (caffeine), a fungicide (thiabendazole) and a pesticide (acetamiprid). Although some elimination was observed at the wastewater treatment plant in some cases, especially remarkable in the case of caffeine, acetaminophen and diclofenac, which were the ones showing higher concentration in the influent (above 1 μg/l), most of them remained unaffected by the biological treatment. However, significant concentrations of all the EPs were still detected in the effluent and hence, a chemical post-treatment appears necessary.

Titanium dioxide was investigated as photocatalyst. Experiments were carried out with the effluent of the studied wastewater treatment plant. Samples were taken after 3 and 6 h of irradiation (which represented a t_{30W} of ca. 200 and 420 min respectively) in order to determine the remaining concentration of emerging pollutants (see Fig. 1). Only in eight cases, the concentration was high enough to allow a reliable quantification and it was found that the percentages of removal after 3 h ranged from 26% achieved for clarithromycin to 98% that was reached in the case of caffeine; after 6 h of treatment, these values either remained constant or were slightly increased (only for clarithromycin and enrofloxacin, showing rather low initial concentration, a significant enhancement in the percentages of removal was observed, 57%). It is remarkable

Table 1
Concentration of eleven emerging pollutants at the influent of the aeration tank of the biological reactor and at the effluent of the secondary settlement tank of the wastewater treatment plant. Percentages of removal are also given; when initial concentration were too low to give reliable percentages of removal, data are given between brackets.

Use	Compound	Concentration (μg/l)		Removal (%)
		Influent	Effluent	
Antibiotics	Erythromycin	0.03	0.03	(–)
	Trimethoprim	0.14	0.11	(19)
	Ofloxacin	0.16	0.25	(–)
	Enrofloxacin	0.22	0.26	(–)
	Clarithromycin	0.10	0.07	(28)
Analgesic	Acetaminophen	1.57	0.03	98
Anti-inflamatory	Diclofenac	2.84	0.87	70
Psychiatric drug	Carbamazepine	0.04	0.07	(–)
Stimulating	Caffeine	15.79	0.20	99
Fungicide	Thiabendazole	0.09	0.11	(–)
Insecticide	Acetamiprid	0.05	0.05	(–)

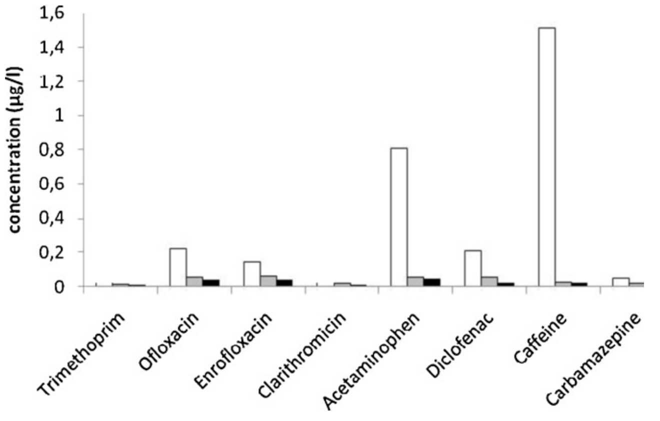


Fig. 1. Concentration of eight emerging pollutants at the outlet of a wastewater treatment plant (white bars), after 3 h (grey bars) and 6 h (black bars) of solar irradiation in the presence of 0.2 g/l of TiO_2.

that again in this case, higher percentages of removal were obtained for those pollutants showing a higher initial concentration, namely caffeine (1.51 µg/l) and acetaminophen (0.81 µg/l); final concentrations were below their limits of quantitation in four cases.

Dissolved organic carbon (DOC) was also measured during the reaction. Although the amount of organic matter is not the main problem related with this kind of effluent because of the low initial level, it is interesting to study the mineralization achieved in the process. Fig. 2 shows a plot of DOC and total nitrogen vs. $t_{30\,W}$ all along the reaction; these data indicate that there was some mineralization at the beginning of the process; then, stabilisation of this parameter was observed after $t_{30\,W}$ = 100 min in the range of 10–15 mg/l; this behaviour is consistent with the formation of low amounts of organic by-products which are refractory to TiO_2 photocatalysis, such as aliphatic intermediates [15]. Total nitrogen did not suffer a significant variation during the experiment. Although destruction of nitrogenated EPs was detected, N atoms were still present in the solution, probably as nitrogenated organic by-products or as inorganic species such as ammonia or nitrates, explaining the constant values of TN; formation of volatile nitrogenated compounds should be ruled out.

As indicated in Section 1, the effluent of a wastewater treatment plant is intrinsically variable; hence, in order to determine the real applicability of this technique, repetition of the process in different days is a necessary step. Tables 2 and 3 show the initial concentration of the EPs in the different assays as well as the remaining concentration after 3 and 6 h of treatment, with 0.2 g/l and 0.5 g/l of TiO_2. Comparison among initial values shows the high variability in the concentration of some EPs, in particular caffeine. Final results were comparable in all cases, reaching concentrations which were in most cases below 0.01 µg/l; only ofloxacin seemed to be more refractory to photo-oxidation (final concentrations were systematically around 0.04 µg/l). A comparison between Tables 2 and 3 indicates that using 0.5 g/l of TiO_2 did not enhance significantly the removal of the pollutants. This is a well known effect in photocatalysis which can be attributed to a screen effect of the outer TiO_2 particles which prevents irradiation of the inner ones [15].

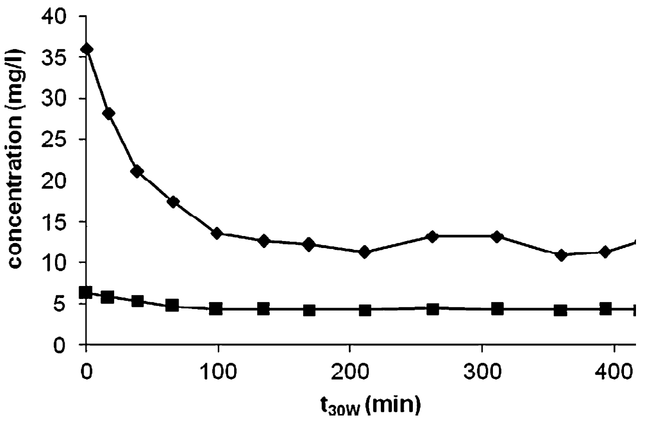


Fig. 2. Solar photocatalytic treatment (TiO_2) of the effluent of a wastewater treatment plant: Plot of dissolved organic carbon (◆) and total nitrogen (■) vs. irradiation intensity ($t_{30\,W}$).

Table 2
Concentration of eleven emerging pollutants at the outlet of a wastewater treatment plant and after 3 h and 6 h of solar irradiation in the presence of 0.2 g/l of TiO_2.

	Sample 1			Sample 2		
	0 h	3 h	6 h	0 h	3 h	6 h
Erythromycin	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Trimethoprim	0.024	0.012	<0.01	0.034	<0.01	<0.01
Ofloxacin	0.203	0.043	0.045	0.154	0.046	0.045
Enrofloxacin	0.188	0.062	0.018	0.143	0.015	0.013
Clarithromycin	0.033	0.023	0.010	0.022	<0.01	<0.01
Acetaminophen	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Diclofenac	0.327	0.040	0.032	0.225	0.044	0.034
Carbamazepine	0.061	0.021	0.012	0.051	0.010	0.010
Caffeine	1.98	<0.05	<0.05	0.25	<0.05	<0.05
Thiabendazole	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Acetamiprid	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

The effluent was spiked with an extra amount of some of the studied pollutants (5 mg/l of acetaminophen, diclofenac, caffeine, thiabendazole, acetamiprid and trimethoprim) in order to determine the real order of reactivity of these compounds towards photocatalysis, as the variability of real effluents and the low initial concentrations did not allow determination of reliable time resolved data. The solution (5 l) was irradiated in the solar plant in the presence of 0.2 g/l of titanium dioxide. Fig. 3 shows that under those reproducible conditions the following order of reactivity was observed: diclofenac > thiabendazole > caffeine > acetaminophen > trimethoprim > acetamiprid. The apparent differences between the elimination of the studied EPs in the spiked solution and the real sample is attributable to their very different initial concentrations; for instance thiabendazole and acetamiprid were systematically below the limits of quantification, and in the other cases the final concentrations were below this limit; hence, the percentages of removal in the real samples were strongly influenced by the initial concentrations as nearly complete removal of the EPs was accomplished.

Blank experiments carried out in the absence of TiO_2 showed that photolysis of the EPs was in general negligible after $t_{30\,W}$ = 60 min and only for diclofenac and acetominophene was

Table 3
Concentration of eleven emerging pollutants at the outlet of a wastewater treatment plant and after 3 h and 6 h of solar irradiation in the presence of 0.5 g/l of TiO_2.

	Sample 1			Sample 2		
	0 h	3 h	6 h	0 h	3 h	6 h
Erythromycin	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Trimethoprim	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ofloxacin	0.154	0.046	0.043	0.102	0.043	0.043
Enrofloxacin	0.103	0.034	0.013	0.055	0.017	0.012
Clarithromycin	0.012	<0.01	<0.01	0.011	«0.01	<0.01
Acetaminophen	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Diclofenac	0.135	0.027	0.013	0.082	0.020	0.012
Carbamazepine	0.035	<0.01	<0.01	0.022	<0.01	<0.01
Caffeine	1.11	<0.05	<0.05	0.43	<0.05	<0.05
Thiabendazole	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Acetamiprid	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

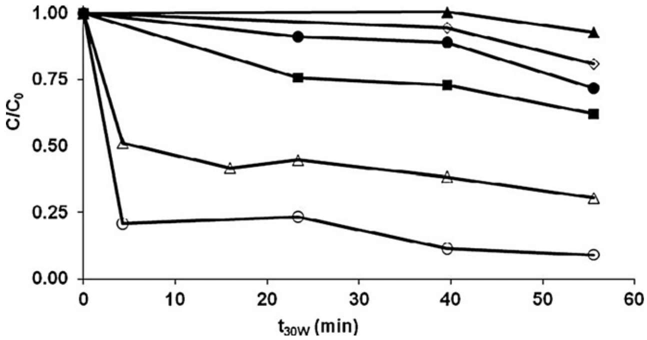


Fig. 3. Plot of the relative concentration of six emerging pollutants vs. irradiation intensity (t_{30W}) of a solution which was spiked with 5 mg/l of each pollutant: (▲) acetamiprid, (●) acetaminophen, (■) caffeine, (△) thiabendazole, (○) diclofenac and (△) trimethoprim.

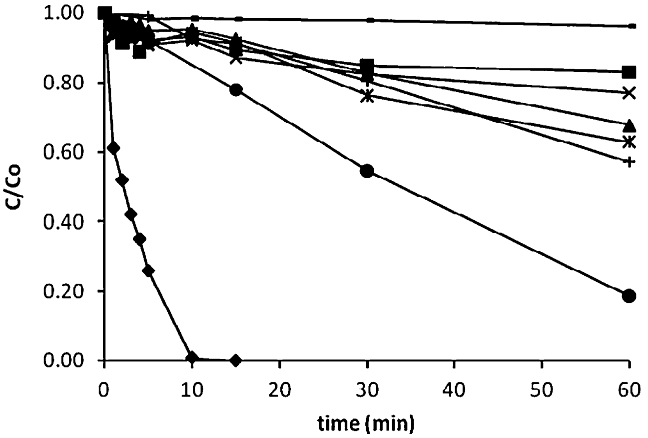


Fig. 5. Relative concentration of caffeine (50 mg/l) vs. irradiation time in the presence of different photocatalytic systems: (♦) photo-Fenton, pH = 2.8; (■) photo-Fenton, pH = 7, distilled water; (▲) photo-Fenton, pH = 7, humic acids, distilled water; (×) photo-Fenton, pH = 7, tap water; (✳) photo-Fenton, pH = 7, humic acids, tap water; (●) TiO_2, distilled water; (+)TiO_2, tap water; (-) blank control (photolysis).

slightly above 10%. Dark controls showed that absorption of the EPs onto the photocatalyst was systematically below 10%; again in this case, absorption of diclofenac was slightly higher (ca. 20%); these results demonstrate that the TiO_2 photocatalysis plays a major role in the EPs removal.

In addition to the elimination of emerging pollutants, photocatalysis might also be useful to deal with faecal contamination present at the outlet of wastewater treatment plant, as TiO_2-based solar processes have been demonstrated to be useful methods for disinfection, as recently reviewed by Malato et al. [15]. Hence, monitoring this parameter seems meaningful if the final goal of the process is obtaining a final water quality compatible with agricultural and industrial reuse. Fig. 4 shows the amount of coliforms (expressed as *E. coli* colony-forming units, CFU) present in the effluent of the wastewater treatment plant after different irradiation times in the presence of 0.2 g/l of TiO_2, 0.5 g/l of TiO_2 and in the absence of the photocatalyst. More than 99% disinfection was achieved after ca. 1 h irradiation in the presence of 0.5 g/l of TiO_2, while it took around 100 min with 0.2 g/l; this indicates that, in addition of the removal of chemical pollutants below their limits of quantification, this process is also able to accomplish important disinfection, clearly showing the potential benefits of this procedure. Although apparently important disinfection was also reached in the absence of TiO_2, it was observed some re-growth of the *E. coli* (samples taken from the plant 2 h after the irradiation was ceased showed the presence of colonies of this bacteria) hence indicating that the photocatalyst was necessary to achieve a complete removal of faecal contamination.

An alternative approach to eliminate emerging pollutants from the outlet of biological reactors using sunlight is the photo-Fenton process. The use of these homogeneous reagents could represent a technical advantage vs. heterogeneous TiO_2, as the elimination of this semiconductor after the process is not simple. However, as indicated in Section 1, a strategy has to be used to keep iron in solution at this pH. In this context, humic acids were tested. A series of laboratory scale experiments were carried out under simulated sunlight irradiation in order to compare TiO_2 and neutral photo-Fenton under different reaction conditions, using caffeine (50 mg/l) as model pollutant (see Section 2 for details). The following trend was observed for the reaction rates under the studied conditions (Fig. 5): photo-Fenton (pH = 2.8) > TiO_2 (distilled water) > TiO_2 (tap water) > photo-Fenton (pH = 7, humic acids, distilled water) ≈ photo-Fenton (pH = 7, humic acids, tap water) > photo-Fenton (pH = 7, distilled water) ≈ photo-Fenton (pH = 7, distilled water). Dark controls were also performed with TiO_2 and the Fenton system at acidic and neutral media. Only in the case of dark Fenton at pH = 2.8 some degradation of caffeine was observed (ca. 20%); nevertheless, it was less efficient than the corresponding solar driven process; finally, photolysis in the absence of photocatalytic systems was proven to be negligible.

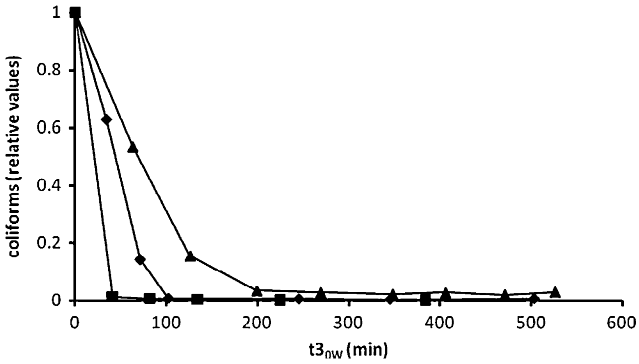


Fig. 4. Elimination of faecal contamination at the outlet of a wastewater treatment plant. Relative amount of coliforms vs. t_{30W} in the presence of TiO_2: 0.5 g/l (■), 0.2 g/l (♦) and in the absence of photocatalyst (▲).

All these results clearly shows that although the most efficient method was the photo-Fenton at acidic media, some reaction was also measured in photo-Fenton at neutral pH in the presence of humic acid; in fact, humic acids seemed to play a more relevant role in the process than salts present in tap water, and carbonates in particular, which have been claimed to play as disfavourable role in the neutral photo-Fenton, probably acting as radical scavengers [32]. This could probably due to the stabilization of iron in the media, which allowed continuous formation of the reactive species. In fact when no humic acids were present, reactions were nearly stopped after the early stages of the process. This result seems especially interesting as significant amounts of dissolved organic matter, and in particular humic acids, have been detected at the outlet of biological reactors [33]. Preliminary experiments performed with real wastewaters indicate that final concentrations of emerging pollutants after neutral photo-Fenton were only slightly higher than those reached with TiO_2 and significant amounts of iron can be detected in the liquid sample throughout the reaction. Hence, the use of neutral photo-Fenton process for this purpose deserves further research to show its real applicability.

4. Conclusions

Solar photocatalysis using TiO_2 has been demonstrated as an efficient tertiary treatment. Concentrations of emerging pollutants has been decreased to reach in most cases values below to their limit of quantification, after 3 h of irradiation. Furthermore, significant disinfection of the effluent has also been observed (more than 99% inactivation of faecal coliforms in 1 h of treatment).

Experiments carried out using caffeine as model compound indicate that a neutral photo-Fenton process can also be performed if humic acids are present in the media. Although preliminary results indicate that this process might be less efficient than TiO_2 photocatalysis, further research to optimize and to determine its real applicability is meaningful, as the use of homogeneous iron and hydrogen peroxide at low concentration seems more advantageous from the technical point of view than TiO_2 in slurry.

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