

PHOTOCHEMICAL AND PHOTOCATALYTIC DEGRADATION OF DICLOFENAC AND AMOXICILLIN USING NATURAL AND SIMULATED SUNLIGHT

JUTTA KOCKLER, DEVAGI KANAKARAJU, BEVERLEY GLASS AND MICHAEL OELGEMÖLLER*

School of Pharmacy and Molecular Sciences, James Cook University, Townsville, Qld 4811, Australia.

*Corresponding author: michael.oelgemoeller@jcu.edu.au

Abstract: Photochemical and titanium dioxide (TiO₂) photocatalysed degradations of diclofenac and amoxicillin in water, under natural and simulated sunlight, were investigated. Direct photolysis of diclofenac resulted in about 80% degradation after exposure to an irradiation level of 400 W/m² for 4 h, while in the presence of TiO₂, 96% of diclofenac was degraded after the same time period. At the irradiation level of 765 W/m², 99% of the drug was degraded within 1 h exposure. The efficiency of degradation of diclofenac was thus proportional to the level of simulated irradiation. The use of floating solar reactors has resulted in comparable rate of photodegradation by direct natural sunlight to that achieved by the solar simulator. In contrast, amoxicillin remained photostable under direct photolysis, while degrading significantly in the presence of TiO₂.

KEYWORDS: Pharmaceuticals; photocatalysis; photolysis; photochemistry; sunlight; titanium dioxide

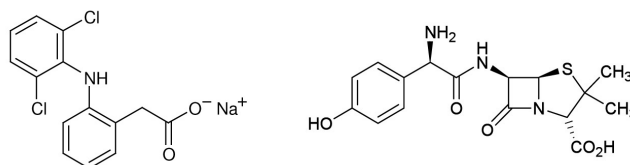
Introduction

Pharmaceutical products contain active pharmaceutical ingredients (APIs) whose presence in surface and ground waters is emerging as a major environmental threat, not only due to their continuous input from various sources, but also from the persistent nature of this class of organic pollutants (Deegan *et al.*, 2011). Their fate in the aquatic environment is relatively unknown as are their effects on both aquatic organisms and humans (Khetan & Collins 2007). The development of effective removal methods of APIs thus requires important consideration.

Two commonly-used APIs, diclofenac (DCF) and amoxicillin (AMX) were selected as model compounds in this study (Figure 1; Table 1). DCF is a readily available over-the-counter non-steroidal anti-inflammatory drug (NSAID) used to treat pain or inflammation. Approximately 15% of DCF is excreted unchanged after administration to humans (Rizzo *et al.*, 2009). DCF was directly correlated with the decline of vulture populations in India in the 1990s (Oaks *et al.*, 2004) and has

been frequently detected in wastewater treatment plant (WWTP) effluents and surface water (Zhang *et al.*, 2008). AMX, a broad-spectrum β -lactam antibiotic is widely used in human and in veterinary prescription medicine. After oral consumption of a 500 mg dose, 86% is excreted renally within 2 hours (Martins *et al.*, 2009). The detection of antibiotics in the environment has been related to the emergence of antibiotic-resistant strains of bacteria (Elmolla and Chaudhuri 2010). Monitoring studies conducted thus far have confirmed the presence of AMX in effluents from WWTPs and other water bodies (Lindberg *et al.*, 2005; Zuccato *et al.*, 2005; Watkinson *et al.*, 2007).

Advanced oxidation processes (AOPs) appear to be a promising destructive tool for the degradation of recalcitrant compounds in wastewater. TiO₂ photocatalytic oxidation in particular occupies a prominent role in the degradation of pharmaceuticals due to their complete mineralisation under mild conditions (Dalrymple *et al.*, 2007; Klavarioti *et al.*, 2009). Solar photocatalysis of pharmaceuticals has been extensively reviewed (Malato *et al.*, 2009; Bernabeu *et al.*, 2011).



Diclofenac sodium

Amoxicillin

Figure 1: Chemical structures of diclofenac sodium (DCF) and amoxicillin (AMX).

Table 1: Properties of diclofenac sodium and amoxicillin.

Property	Diclofenac sodium	Amoxicillin
Chemical formula	C ₁₄ H ₁₀ Cl ₂ NO ₂ Na	C ₁₆ H ₁₉ N ₃ O ₅ S
Molecular weight (g/mol)	318.13	365.40
pK _a *	4.15	2.4 and 7.2

* Pavlović et al. (2007)

In this study, the aim was to investigate solar photochemical and photocatalytic degradation of DCF and AMX in aqueous medium in a solar simulator (at different doses of irradiation) and a floating solar reactor (under different illumination conditions).

Materials and Methods

Deionised water (Millipore®) was used for the preparation of all the solutions. DCF sodium salt, AMX and titanium (IV) oxide (99.8% metals basis, anatase) were purchased from Sigma Aldrich and used without pre-treatment. Sodium acetate trihydrate (minimum 99.0%) from Sigma Aldrich, high-performance liquid chromatography (HPLC) grade methanol from Scharlau and acetic acid glacial from Univar were used for the preparation of HPLC mobile phase. Concentrations of 200 mg/L of DCF and AMX in deionised water were prepared to which was added TiO₂ (100 mg/L). To eliminate potential photodegradation of the APIs between collection and analysis, samples were wrapped in aluminium foil and refrigerated (5 ± 3°C) and analyses were performed on the same day in triplicate.

The solar simulator (Suntest XLS+, Atlas, Gelhausen, Germany) equipped with a Xenon lamp allowed for variable irradiance from 250 W/m² to 765 W/m². The filter was a Solar ID 65-filter of quartz glass coated with 6 mm window glass

(cut-off 320 nm). The temperature increased with the level of irradiance with 400 W/m² resulting in 38°C and at 765 W/m² up to 46°C, respectively. The API solutions (150 mL) were filled in a glass-petri-dish (Ø = 13.7cm, filling height = ca. 1 cm) and covered with polyethylene wrap (λ > 215 nm) to minimise evaporation. The solution containing the photocatalyst was maintained under slow magnetic stirring.

Figure 2 shows the floating solar reactor used in this study (Zhao *et al.*, 2008) with the sample chambers in the reactor having open sidings to allow free flow of water. A small pool was used as a cooling water reservoir. API solutions with and without TiO₂ (50 mL) were filled in glass-petri-dishes (Ø = 9 cm, filling height = ca. 1 cm) and covered with polyethylene wrap. The petri-dishes were placed in the reactor under direct natural sunlight while half immersed in the water. The TiO₂ suspension was subjected to continuous magnetic stirring with an air-driven magnetic stirrer. Temperatures achieved were not greater than 30°C except on extremely sunny days, where the temperatures reached 34°C. Samples were withdrawn in intervals from the petri-dishes and analysed immediately after collection. All solar outdoor experiments were conducted on the roof of the Molecular Sciences building at James Cook University in Townsville, Australia (19° S, 146° E) in September/October 2009 and July 2010.

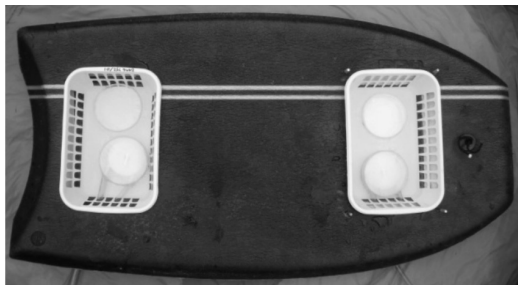


Figure 2: Floating solar reactor set-up.

The concentrations of DCF and AMX in the irradiated samples were quantified using a HPLC instrument (Varian Pro Star) equipped with a photodiode array detector and a C-18 column (μ -bondapak, 4.6 x 250 mm, 10 μ m). The mobile phase for DCF and AMX was methanol/water/acetic acid (60/39/1) and 0.01 M sodium acetate (pH 4)/methanol (95/5) respectively, the flow rate 1 mL/min and the sample injection volume 20 μ l. The degradation of DCF was monitored at a wavelength of 240 nm and AMX at a wavelength of 274 nm. Samples with TiO₂ were filtered using a 0.22 μ m-filter prior to analysis with HPLC. Linearity was established for the developed methods with calibration curves demonstrating excellent correlation coefficients (R^2) of 0.9997 for DCF and 0.9996 for AMX, respectively.

Results and Discussion

Dark adsorption studies were carried out to evaluate the extent of APIs adsorption onto TiO₂ in the absence of light. Adsorption of 0.5%-3.7% for DCF and 4% for AMX was obtained after 24 hours. Thus, physical adsorption only contributes marginally to the removal of these APIs during exposure to light.

Polyethylene wrap was chosen as a cover for the petri-dishes due to its high transmittance of about 90% at 290 nm, the UV cut-off point for natural direct sunlight. In contrast, Pyrex glass displayed zero transmittance at the same wavelength. Experiments at 400 W/m² were performed in duplicate and showed high reproducibility.

In general, irradiations in the presence of TiO₂ resulted in an increased rate of degradation

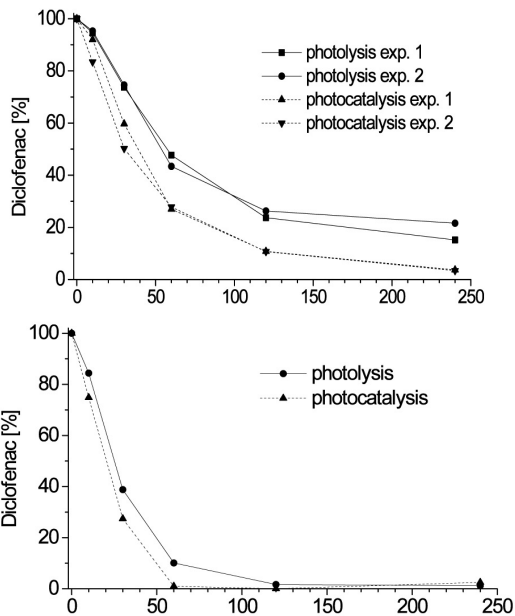


Figure 3: Percentage peak area-time profiles of direct photolysis and photocatalysis of DCF at (a) 400 W/m² and (b) 765 W/m².

of DCF compared to direct photolysis, although this effect was less marked at higher irradiation levels. Irradiation at 400 W/m² resulted in 96% removal after 4 hours in the presence of the catalyst. For the direct photolysis, only about 80% of DCF was degraded over the same irradiation period (Figure 3a). Degradations furthermore showed a good reproducibility under both conditions (experiments 1 and 2). At a higher irradiation level of 765 W/m², both degradation processes were significantly enhanced. The photocatalytic process went almost to completion, as 99% degradation was obtained after 1 hour of irradiation. In contrast, direct photolysis gave rise to 90% DCF degradation after 1 hour and 98% after 2 hours of irradiation (Figure 3b).

The HPLC profiles (Figure 4) revealed a rapid initial degradation and the appearance of additional breakdown products under photocatalytic conditions. This observation is similar to that observed in previous studies on the photodegradation of DCF (Agüera *et al.*, 2005; Bartels & von Tümpling, 2007; Eriksson *et al.*, 2010).

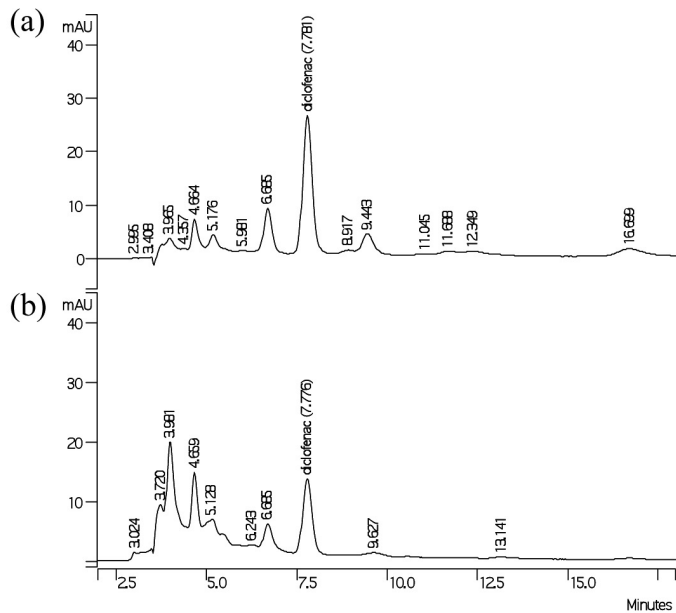


Figure 4: HPLC chromatograms of DCF (a) after direct photolysis and (b) after photocatalysis at 400 W/m² (240 min).

The effect of TiO₂ on the degradation of AMX was significant compared to direct photolysis (Figure 5). After 6 hours of direct photolysis (400 W/m²), only about 10% of AMX degradation was obtained, without any notable photodegradants in the HPLC chromatogram (Figure 6a). Photocatalysis with TiO₂ resulted in over 70% degradation of AMX, similar to that achieved by Klauson *et al.*, (2010), with notable photodegradants detected (Figure 6b). Under both conditions, degradations again showed excellent reproducibility (experiment 1 and 2). Increasing the irradiation dosage to 765 W/m² had almost no influence on the degradation of AMX under both conditions (not shown).

Experiments were also carried out by exposing DCF and AMX solutions to direct natural sunlight. DCF degradation under solar exposure was conducted in duplicate on sunny days in September 2009 at different UV levels. In the first experiment, 96% degradation under direct sunlight photolysis and 99% under photocatalysis occurred after 4 hours of exposure (Figure 7a). The UV level recorded for the day was 10 (ARPANSA). As shown in Figure 7b, a similar

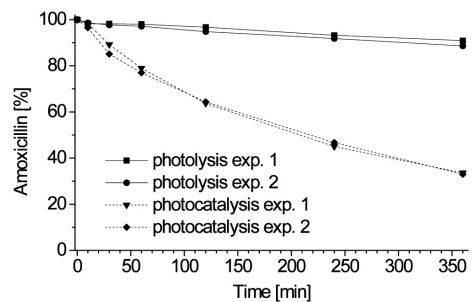


Figure 5: Percentage peak area-time profiles of direct photolysis and photocatalysis of AMX at 400 W/m².

period of exposure during the second experiment yielded 89% DCF degradation under sunlight photolysis, while photocatalysis produced 97% degradation. The UV level recorded for the day of the experiment was 13. In line with irradiations at different irradiation levels in the solar simulator, the amount of sunlight thus corresponds directly with their degradation or removal levels. The results confirm that DCF can be degraded by sunlight photolysis (Packer *et al.*, 2003; Calza *et al.*, 2006) although the photocatalyst unambiguously accelerates the overall degradation process.

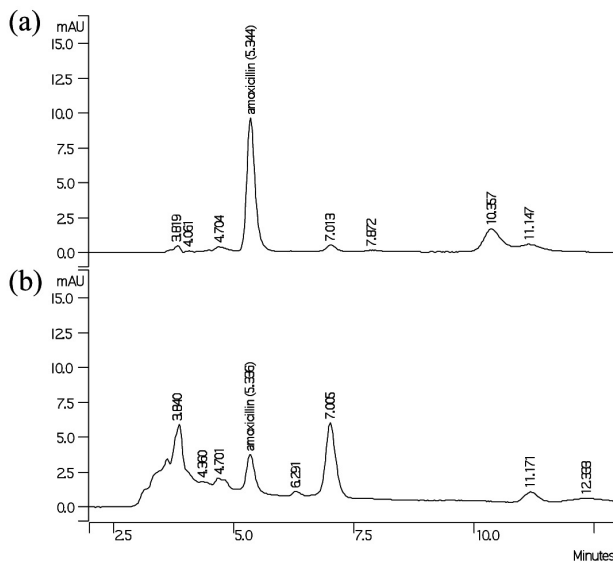


Figure 6: HPLC chromatograms of AMX (a) after direct photolysis and (b) after photocatalysis at 400 W/m² (360 min).

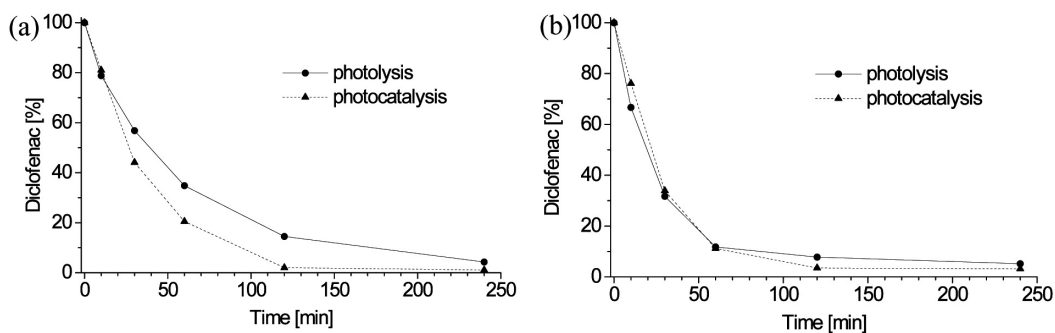


Figure 7: Percentage peak area-time profiles of direct photolysis and photocatalysis of DCF under natural sunlight in September 2009 (a) UV level of 10 and (b) UV level of 13.

The AMX degradation study was conducted in July 2010 with 6 hours of exposure to direct natural sunlight (UV level of 7). Similarly to the results in the solar simulator, the degradation of AMX in the photocatalytic reaction exceeded that of the experiment in the absence of catalyst. A photocatalytic degradation of 78% was achieved after 6 hours of illumination (Figure 8). An increase of 7% upon direct photolysis after 6 hours was attributed to a concentration effect caused by condensation of water on the polyethylene wrap covering the petri-dish. The results therefore confirm that AMX is stable on exposure to direct natural sunlight in aqueous solution (Andreozzi *et al.*, 2004) and that a photocatalyst is needed to

initiate its photochemical degradation.

The different reactivity to direct photolysis can be best explained by the UV-absorption properties of the two APIs (Cantarelli *et al.*, 2011). AMX remained resistant due to its missing absorption in the near UV region (300-350 nm) as depicted in the UV-spectrum (Figure 9). In contrast, direct photolysis under natural sunlight is possible for DCF as it shows a strong absorption at 290 nm with some absorption above 320 nm to initiate degradation in the solar simulator. Solar degradations of DCF have also been reported by other groups (Agüera *et al.*, 2005; Bartels & von Tümpling, 2007; Eriksson *et al.*, 2010).

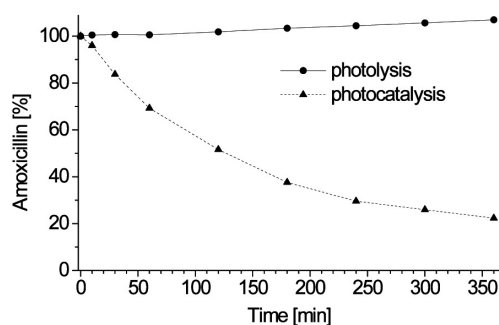


Figure 8: Percentage peak area-time profiles of direct photolysis and photocatalysis of AMX under direct natural sunlight.

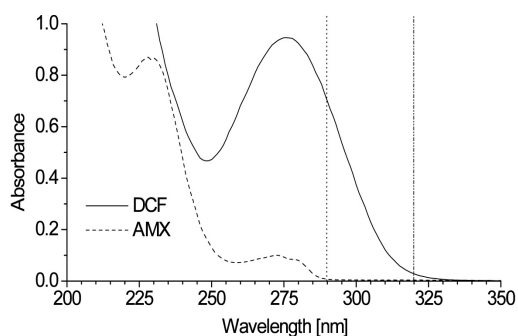


Figure 9: UV-spectra of DCF and AMX; vertical lines represent the cut-off wavelength of the solar simulator (320 nm) and of natural sunlight (290 nm).

Conclusion

The results obtained from this work suggest that DCF and AMX can be efficiently degraded by photocatalysis in water. Direct photolysis, while efficient in the reduction of DCF, does not induce any significant degradation for AMX. This behaviour could be explained on basis of the UV-absorption of both APIs. Due to its poor absorption in the UV range, the addition of a photocatalyst is essential for AMX removal. Photocatalysis in natural sunlight can also be used for the sustainable degradation of the chosen active pharmaceutical ingredients.

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