Photocatalytic degradation of amoxicillin, ampicillin and cloxacillin antibiotics in aqueous solution using UV/TiO2 and UV/H2O2/TiO2 photocatalysis

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Degradation of amoxicillin, ampicillin and cloxacillin antibiotics in aqueous solution by TiO2 photocatalysis under UVA (365 nm) irradiation was studied. Enhancement of photocatalysis by addition of H2O2 was also evaluated. The results showed that no significant degradation occurred by 300-min UVA irradiation per se and pH had a great effect on antibiotic degradation. Photocatalytic reactions approximately followed a pseudo-first order kinetics and the rate constants (k) were 0.007, 0.003 and 0.029 min−1 for amoxicillin, ampicillin and cloxacillin, respectively. Addition of H2O2 at ambient pH −5 and TiO2 1.0 g/L resulted in complete degradation of amoxicillin, ampicillin and cloxacillin in 30 min. Dissolved organic carbon (DOC) removal, and nitrate (NO3−), ammonia (NH3) and sulphate (SO42−) formation during degradation indicated mineralization of organic carbon, nitrogen and sulphur. UV/H2O2/TiO2 photocatalysis is effective for degradation of amoxicillin, ampicillin and cloxacillin in aqueous solution.

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1. Introduction

Pharmaceutical compounds including antibiotics have been observed in the aqueous environment. These compounds have been observed in surface water [1–3], ground water [3], sewage effluent [4,5] and even in drinking water [6]. Pharmaceutical compounds can reach the aquatic environment through various sources such as pharmaceutical industry, hospital effluent and excretion from humans and livestock [5,7,8]. Among all the pharmaceutical compounds that cause contamination of the environment, antibiotics occupy an important place due to their high consumption rate in both veterinary and human medicine. A problem that may be created by the presence of antibiotics in low concentration in the environment is the development of antibiotic resistant bacteria [9]. In recent years, the incidence of antibiotic resistant bacteria has increased and many people believe that the increase is due to the use of antibiotics [10]. Furthermore, the presence of antibiotics in wastewaters has also increased and their abatement will be a challenge in the near future.

It is useful to apply various treatment technologies to purify effluents containing pharmaceutical compounds. The advanced oxidation processes (AOPs) appear as interesting tools in comparison with other techniques such as activated carbon adsorption, air stripping and reverse osmosis. Indeed, many of these techniques only transfer the pollutants from one phase to another without destroying them. Biological treatment is limited to wastewaters which contain biodegradable substances and which are not toxic to the biological culture. Among the different advanced oxidation processes, TiO2 photocatalysis has emerged as a promising wastewater treatment technology. The main advantages of the process are lack of mass transfer limitations and operation at ambient conditions, and the catalyst is inexpensive, commercially available, non-toxic and photochemically stable [11].

Reaction mechanisms of photocatalytic processes have been discussed in the literature [12–17]. Illumination of a semiconductor such as titanium dioxide (TiO2) by photons having an energy level that exceeds its band gap energy (hv>Eg=3.2 eV in the case of anatase TiO2) excites electrons (e−) from the valence band to the conduction band and holes (h+) are produced in the valence band (Reaction (1)). The photogenerated valence band holes react with either water (H2O) or hydroxyl ions (OH−) adsorbed on the catalyst surface to generate hydroxyl radicals (•OH) which are strong oxidants (Reactions (2) and (3)). The hydroxyl radical reacts readily with surface adsorbed organic molecules, either by electron or hydrogen atom abstraction, forming organic radical cations, or by addition reactions to unsaturated bonds [17] (Reaction (4)). Since the reaction of the holes on the particle interface is faster than electrons, the particles under illumination contain an excess of electrons. Removal of these excess electrons is necessary to complete the oxidation reaction by preventing the recombination of electrons with holes. The most easily available electron acceptor is molecular oxygen and in the presence of oxygen the predominant reaction of electrons is that with O2 to form radicalic superoxide ions (•O2−) as in Reaction (5). In acidic condition, superoxide ion combines with proton to form a hydroperoxide radical and it reacts with conduction band electron to form...
hydroperoxide ion. The hydroperoxide ion reacts with proton to form hydrogen peroxide. Cleavage of hydrogen peroxide by the conduction band electrons yields further hydroxyl radicals and hydroxyl ions (Reaction (6)). The hydroxyl radicals can then react with the valence band holes to form additional hydroxyl radicals. Recombination of the photogenerated electrons and holes may occur and indeed it has been suggested that preadsorption of substrate (organic substance) onto the photocatalyst is a prerequisite for highly efficient degradation.

\[
\text{TiO}_2 + h_v \rightarrow \text{TiO}_2(e^- + h^+) \tag{1}
\]

\[
h^+ + H_2O \rightarrow H^+ + 'OH \tag{2}
\]

\[
h^+ + OH^- \rightarrow 'OH \tag{3}
\]

Organics + 'OH \rightarrow Degradation Products \tag{4}

c^- + O_2 \rightarrow O_2\tag{5}

\[
H_2O_2 + c^- \rightarrow 'OH + OH^- \tag{6}
\]

The photocatalytic processes have been reported to be effective for degradation of many organic pollutants such as carboxylic acids [18,19], chloroanilines [20], mono-chlorocarboxylic acids [21], chlorophenols [22–24], dyes [25–28], fungicides [29], herbicides [30], ketones [31], phenolics [32] and pharmaceuticals [8,33]. Degradation of lincomycin and sulfamethoxazole antibiotics by TiO2 photocatalysis have been reported [33,34].

Amoxicillin, ampicillin and cloxacillin are semi-synthetic penicillin obtaining their antimicrobial properties from the presence of a β-lactam ring. They are widely used in human and veterinary medicine. Some authors have found amoxicillin and cloxacillin in wastewater [35,36]. There are some reported studies on degradation of amoxicillin by different AOPs. Zhang et al. [37] studied the treatment of amoxicillin wastewater by combination of extraction, Fenton oxidation and reverse osmosis. Also, different AOPs (O3/OH, H2O2/UV, Fe2+/H2O2, Fe3+/H2O2, Fe2+/H2O2/UV and Fe3+/H2O2/UV) were evaluated as a pretreatment process for real penicillin formulation wastewater [38]. The degradation of amoxicillin by ozonation [39] and photo-Fenton [40] has been reported. In our previous work, we studied the degradation of amoxicillin, ampicillin and cloxacillin antibiotics using Fenton [41], photo-Fenton [42] and ZnO photocatalysis [43]. However, no study on degradation of amoxicillin, ampicillin and cloxacillin antibiotics in aqueous solution by TiO2 photocatalysis has been reported.

The present study was undertaken to examine the degradation of amoxicillin, ampicillin and cloxacillin antibiotics in aqueous solution by UV/TiO2 photocatalysis and the enhancement of photocatalysis by hydrogen peroxide addition.

2. Materials and methods

2.1. Chemicals

Analytical grades of amoxicillin (AMX) and ampicillin (AMP) were purchased from Sigma and cloxacillin (CLX) from Fluka and they were used to construct HPLC analytical curves for determination of antibiotic concentration. AMX, AMP and CLX used to prepare antibiotic aqueous solution were obtained from a commercial source (Farmaniage Company). The commercial products were used as received without any further purification. Sodium hydroxide and sulphuric acid were purchased from HACH Company USA. Potassium dihydrogen phosphate (KH2PO4) was purchased from Fluka and acentonitrile HPLC grade from Sigma. TiO2 powder (anatase, purity >99%) was purchased from Fluka. Hydrogen peroxide (30% w/w) was purchased from R & M Marketing, Essex, U.K. Fig. 1 shows the chemical structure and HPLC chromatograph of amoxicillin, ampicillin sodium and cloxacillin sodium.

2.2. Antibiotic aqueous solution

Antibiotic aqueous solution was prepared by dissolving specific amounts of AMX, AMP and CLX in distilled water (dissolved oxygen 8.4 mg/L at 22 °C). The aqueous solution characteristics were AMX, AMP and CLX concentrations 104, 105 and 103 mg/L, respectively. pH 5, COD 520 mg/L, BOD5/COD ratio ~0 and DOC 145 mg/L. The antibiotic aqueous solution was prepared weekly and stored at 4 °C.

2.3. Analytical methods

Antibiotic concentration was determined by a High Performance Liquid Chromatograph (HPLC) (Agilent 1100 Series) equipped with a micro-vacuum degasser (Agilent 1100 Series), quaternary pump, diode array and multiple wavelength detector (DAD) (Agilent 1100 Series) at wavelength 204 nm. The data was recorded by a chemstation software. The column was ZORBAX SB-C18 (4.6 mm×150 mm, 5 µm) and its temperature was 60 °C. The mobile phase was 60% 0.025 M KH2PO4 buffer solution in ultra pure water and 40% acentonitrile at a flow rate of 0.50 mL/min. Chemical oxygen demand (COD) was measured according to the Standard Methods [44]. When hydrogen peroxide was present in the sample, pH was increased to above 10 to decompose hydrogen peroxide and minimize interference in COD measurement [45]. A pH meter (HACH Sension 4) and a pH electrode (HACH platinum series pH electrode model 51910, HACH Company, USA) was used for pH measurement. Biodegradability was measured by 5-day biochemical oxygen demand (BOD5) test according to the Standard Methods [44]. Dissolved oxygen (DO) was measured by a YSI 5000 dissolved oxygen meter. Bacterial seed was obtained from a municipal wastewater treatment plant. TOC analyzer
Model 1010, O & I analytical) was used for determining dissolved organic carbon (DOC). Ammonia (NH₃) concentration was measured by Nessler Method (Method 8038) [46], and nitrate (NO₃⁻) and sulphate (SO₄²⁻) by Hach Powder Pillow [46].

2.4. Experimental procedure

A 500 mL aliquot of the antibiotic aqueous solution was placed in a 600 mL reactor with the required amount of TiO₂ and was stirred magnetically at room temperature (22 ± 2 °C). pH of the mixture was adjusted to the required value by 1 N H₂SO₄ or 1 N NaOH and the mixture was kept in the dark for 30 min for dark adsorption before subjecting to UV irradiation. The source of UV irradiation was a UV lamp (Spectroline Model EA-160/FE; 230V, 0.17A, Spectronics Corporation, New York, USA) with a nominal power of 6 W, emitting radiation at 365 nm and it was placed above the reactor. Samples were taken at pre-selected time intervals using a syringe and filtered through a 0.45 µm PTFE syringe filter for COD, BOD₅ and DOC measurement, and through a 0.20 µm PTFE syringe filter for determination of antibiotic concentration by HPLC.

3. Results and discussion

3.1. Effect of UV irradiation

To observe the effect of photolysis of antibiotics due to UVA irradiation, experiment was conducted at initial AMX, AMP and CLX concentrations 10⁴, 10⁵, 10³ mg/L, respectively and pH 5. By 300-min UV irradiation, degradation was 2.9, 3.8 and 4.9% for AMX, AMP and CLX, respectively (data not shown). Amoxicillin and cloxacillin show maximum absorbance at 245 and 250 nm, respectively and they can absorb light below 300 nm (Fig. 2). Therefore, no significant degradation was expected due to UV 365 nm irradiation per se and presumably the degradation was due to antibiotic hydrolysis. The hydrolysis reaction would proceed through the attack of the nucleophile H₂O to the β-lactam ring followed by ring opening [39]. Consequently, degradation of the studied antibiotics when subjected to TiO₂ photocatalysis will be mainly due to the active species produced during the photocatalytic process (e.g., hydroxyl radical, hole and superoxide ion).

3.2. Effect of TiO₂ concentration

To observe the effect of TiO₂ concentration, initial TiO₂ concentration was varied in the range 0.5–2.0 g/L. The experimental conditions were: AMX, AMP and CLX concentrations 10⁴, 10⁵ and 10³ mg/L, respectively and pH 5. Fig. 3 shows the degradation of AMX, AMP and CLX. Degradation percent after 300 min irradiation were 42.3, 54.8, 55.8 and 58.7 for AMX (Fig. 3(A)), 33.3, 52.4, 54.3 and 52.4 for AMP (Fig. 3(B)) and 46.6, 58.3, 59.2 and 60.2 for CLX (Fig. 3(C)) at TiO₂ concentrations 0.5, 1.0, 1.5 and 2.0 g/L, respectively. Degradation of antibiotics increased with increasing TiO₂ concentration in the range 0.5–1.0 g/L. Further increase of TiO₂ concentration above 1 g/L did not produce significant improvement in antibiotic degradation. This may be due to the decreasing light penetration, increasing light scattering [47], agglomeration, and sedimentation of TiO₂ under high catalyst concentration [48,49]. The degradation of the antibiotics may decrease in case of real wastewater due to the presence of interfering anions (e.g., chloride, bromide, sulphate, phosphate) and/or due to decrease of light density in turbid wastewater. These results agree well with previous studies on degradation of bisphenol [50], chloramphenicol [51], hymatoxylin [33] and paracetamol [8]. Based on the results, the optimum titanium dioxide concentration for degradation of amoxicillin, ampicillin and cloxacillin antibiotics in aqueous solution is 1.0 g/L and it will be used to study the effect of other parameters. It is worth noting that dissolved oxygen decreased under the experimental condition from initial value 8.4 to 6.8 mg/L in 300 min. This may be due to the reaction of oxygen with conduction band electrons to form superoxide ions (·O₂⁻) as in Reaction (5). The role of dissolved oxygen in photocatalytic degradation is dual. It accepts a photogenerated electron from the conduction band and thus promotes the charge separation (minimizing the electron-hole pair recombination) and it also forms ·OH radical via superoxide ion (Reactions (5) and (6)). COD removal percent after 300 min

![Fig. 2. Absorption spectra of AMX and CLX.](image)

![Fig. 3. Effect of TiO₂ concentration on (A) AMX, (B) AMP and (C) CLX degradation.](image)
irradiation were 6.2, 9.2, 10.0 and 9.6, respectively. No significant improvement in biodegradability (BOD5/COD ratio) occurred and the maximum DOC removal was 2%.

3.3. Effect of pH

To study the effect of initial pH on degradation of AMX, AMP and CLX, experiments were conducted by varying the pH in the range 3–11. The experimental conditions were AMX, AMP and CLX concentrations 10^4, 10^5 and 10^3 mg/L, respectively, TiO2 1.0 g/L and initial COD 520 mg/L. Fig. 4 shows the effect of pH on degradation of AMX, AMP and CLX. Degradation percent after 300 min irradiation were 61.2, 54.8, 59.2 and 70.9 for AMX (Fig. 4(A)), 78.1, 52.4, 74.3 and 91.4 for AMP (Fig. 4(B)) and 95.2, 58.3, 81.7 and 100 for CLX (Fig. 4(C)) at pH 3, 5, 8 and 11, respectively.

The effect of pH on antibiotic degradation in terms of COD removal was also studied. COD removal after 300 min irradiation was 11.7, 9.2, 10.2 and 11.2%, respectively. No significant improvement in BOD5/COD ratio occurred and the maximum DOC removal was 3%.

The effect of pH on antibiotic degradation can be explained by taking into consideration the properties of both catalyst and antibiotics at different pH. For TiO2, as pH increases overall surface charge of TiO2 changes from positive (pK_a1 = 2.6) to negative (pK_a2 = 9.0) with point of zero charge being pH 6.4 [52]. Chemie [53] reported that ionic amoxicillin species change from positive charge at acidic pH to negative charge at alkaline pH as shown in Schematic 1. At acidic pH, both TiO2 and amoxicillin are positively charged and hence, the adsorption on the surface of TiO2 is limited. The high degradation of antibiotics at acidic pH compared to that at neutral pH may be due to the hydrolysis of antibiotics as reported by Hou and Poole [54]. At alkaline pH, both amoxicillin and the TiO2 are negatively charged and so repulsive forces between the catalyst and the antibiotics are developed. High degradation of antibiotics in alkaline condition may be due to two facts. First is the enhancement of hydroxyl radical formation at high pH due to the availability of hydroxyl ions on TiO2 surface that can easily be oxidized to form hydroxyl radical as in Reaction (3) [8,55,56]. Second is the hydrolysis of the antibiotics due to instability of the β-lactam ring at high pH [57].

3.4. Kinetics of photocatalytic degradation of amoxicillin, ampicillin and cloxacillin

To study the kinetics of photocatalytic degradation of amoxicillin, ampicillin and cloxacillin, experiments were conducted at TiO2 concentration 1.0 g/L, irradiation time 300 min and pH 11. The concentration of AMX, AMP and CLX after 30 min dark adsorption was taken as the initial AMX, AMP and CLX concentration for kinetic analysis. Fig. 5 shows the plots of ln ([Antibiotic]/[Antibiotic]_0) versus irradiation time for amoxicillin, ampicillin and cloxacillin. The linearity of the plots as shown in Fig. 5 suggests that the photocatalytic degradation approximately followed the pseudo-first order kinetics. Degradation of cloxacillin exhibited the highest rate constant.

![Fig. 4. Effect of pH on (A) AMX, (B) AMP and (C) CLX degradation.](image)

![Schematic 1. Anionic species of amoxicillin at different pH (Chemie [53]).](image)
(0.029 min\(^{-1}\)) followed by amoxicillin (0.007 min\(^{-1}\)) and ampicillin (0.004 min\(^{-1}\)).

### 3.5. Effect of H\(_2\)O\(_2\) addition

Addition of H\(_2\)O\(_2\) to TiO\(_2\) suspensions is a well-known procedure and in many cases leads to an increase in the rate of photocatalytic oxidation [58,59]. In order to keep the efficiency of the added H\(_2\)O\(_2\), it is necessary to choose the optimum concentration of H\(_2\)O\(_2\) according to the type and concentration of the pollutants. H\(_2\)O\(_2\) is considered to have two functions in the photocatalytic oxidation. It accepts a photogenerated electron from the conduction band of the semiconductor to form \(\cdot\)OH radical (Reaction (6)). In addition, it forms \(\cdot\)OH radicals according to Reaction (7) [60].

\[ \text{H}_2\text{O}_2 + \text{O}_2^- \rightarrow \text{OH} + \text{OH}^- + \text{O}_2 \]  

(7)

In order to investigate the effect of H\(_2\)O\(_2\) addition, experiments were conducted by varying the initial H\(_2\)O\(_2\) concentration in the range 50–300 mg/L. The experimental conditions were AMX, AMP and CLX concentrations 10^4, 10^5 and 10^3 mg/L respectively, TiO\(_2\) 1.0 g/L, ambient pH ∼5 and initial COD 520 mg/L. Ambient pH ∼5 was chosen because H\(_2\)O\(_2\) decomposes at alkaline pH [45]. Fig. 6 shows the effect of H\(_2\)O\(_2\) addition on antibiotic degradation in terms of COD removal, BOD\(_5\)/COD ratio and DOC removal, respectively. COD removal percent after 300 min illumination was 14.8, 26.3, 23.1, 16.3 and 12.3 at H\(_2\)O\(_2\) concentrations 50, 100, 150, 200 and 300 mg/L, respectively (Fig. 6(A)). BOD\(_5\)/COD ratio after 300 min illumination was 0.05, 0.10, 0.09, 0.07 and 0.06 at H\(_2\)O\(_2\) concentrations 50, 100, 150, 200 and 300 mg/L, respectively (Fig. 6(B)). DOC removal percent after 300 min illumination was 6.4, 13.9, 9.6, 6.9 and 5.3 at H\(_2\)O\(_2\) concentrations 50, 100, 150, 200 and 300 mg/L, respectively (Fig. 6(C)). Maximum COD and DOC removal percent were achieved at H\(_2\)O\(_2\) concentration 100 mg/L. Degradation increased as the concentration of H\(_2\)O\(_2\) increased and it reached the highest value at H\(_2\)O\(_2\) concentration 100 mg/L. Further increase in H\(_2\)O\(_2\) concentration caused a decrease in COD and DOC removal and BOD\(_5\)/COD ratio. This may be due to the fact that excess H\(_2\)O\(_2\) reacts with \(\cdot\)OH and contributes to the \(\cdot\)OH and hole scavenging to form HO\(_2^-\) as in Reactions (8) and (9) [61,62]. This agrees well with other reported studies such as degradation of chloramphenicol [51]. Based on these results, the optimum H\(_2\)O\(_2\) concentration for antibiotic degradation is 100 mg/L.

\[ \text{\'OH} + \text{H}_2\text{O} \rightarrow \text{H}_2\text{O} + \text{HO}_2^- \]  

(8)

\[ \text{H}_2\text{O}_2 + \text{h}^+ \rightarrow \text{H}^+ + \text{HO}_2^- \]  

(9)

### 3.6. Degradation of antibiotics and mineralization

To study the effect of H\(_2\)O\(_2\) addition on the degradation of AMX, AMP and CLX, an experiment was conducted under the following experimental conditions: TiO\(_2\) 1.0 g/L, H\(_2\)O\(_2\) 100 mg/L and pH 5. Initial AMX, AMP and CLX concentrations were 10^4, 10^5 and 10^3 mg/L, respectively and initial COD was 520 mg/L. Fig. 7 shows the effect of H\(_2\)O\(_2\) addition on AMX, AMP and CLX degradation. Complete degradation of amoxicillin and cloxacillin were achieved in 20 min, whereas complete degradation of ampicillin was achieved in 30 min. TiO\(_2\) photocatalysis would result in the mineralization of organic carbon, and release of nitrogen and sulphur from the antibiotic molecule. To assess the degree of mineralization, dissolved organic carbon (DOC), nitrate (NO\(_3^-\)), ammonia (NH\(_3\)) and sulphate (SO\(_4^{2-}\)) in the solution were measured. The final degradation products were measured as NO\(_3^-\), NH\(_3\) and SO\(_4^{2-}\) concentrations, whereas the small organic molecules were measured as COD, BOD\(_5\) and DOC. The experimental conditions were TiO\(_2\) concentration 1.0 g/L, H\(_2\)O\(_2\) concentration 100 mg/L, pH 5, initial AMX, AMP and CLX concentrations 104, 105 and 103 mg/L, respectively and initial COD 520 mg/L. Mineralization of organic carbon, and nitrogen and sulphur compounds are verified.
by the results presented in Figs. 8 and 9. Fig. 8 shows the increase of organic carbon release with irradiation time (DOC removal percent 24.3 and 41.0 at 10 and 24 h, respectively). Fig. 9 shows the evolution of the ionic species ($\text{NO}_3^-$, $\text{NH}_4^+$, $\text{SO}_4^{2-}$) formed during the degradation of AMX, AMP and CLX. According to the structure of the antibiotics, each antibiotic has three nitrogen atoms and one sulphur atom. Photocatalytic transformation of the nitrogen moieties to $\text{N}_2$, $\text{NH}_4^+$, $\text{NO}_3^-$, or $\text{NO}_2^-$ depends on the initial oxidation state of nitrogen and on the structure of the organic molecules [63]. Low et al. [64] reported that ammonium to nitrate concentration ratio in aliphatic amines is higher than that in compounds containing ring nitrogen. For amoxicillin and ampicillin, each molecule contains three nitrogen atoms, two of them in aliphatic bond and the other in aromatic bond, and for cloxacillin, only one atom in aliphatic bond. This indicates that mineralization of organic nitrogen in case of cloxacillin is more complex than that of amoxicillin and ampicillin. The results show that the initial $\text{NH}_4^+$ concentration was 6.1 mg/L and slightly increased to 7.6 mg/L. $\text{NO}_3^-$ ions gradually increased from zero (initial value) to 1.2 mg/L in 24 h. Sulphate ions were not detected in the first 6 h, but were detected in small amount in the time between 6–10 h and in high concentration of 39 mg/L after 24 h. This indicates that the release of sulphur atoms needs long irradiation time. The results indicate that degradation of AMX, AMP and CLX antibiotics presumably involves cleavage of $\beta$-lactam ring followed by subsequent reactions to form carbon dioxide, water, nitrate, ammonia and sulphate.

4. Conclusions

Degradation of amoxicillin, ampicillin and cloxacillin antibiotics in aqueous solution by TiO$_2$ photocatalysis under UVA (365 nm) irradiation was studied. No significant degradation occurred by 300-min UVA irradiation per se. pH had a great effect on antibiotic degradation and the highest degradation was achieved at pH 11. Photocatalytic reactions approximately followed a pseudo-first order kinetics and the rate constants ($k$) were 0.007, 0.003 and 0.029 min$^{-1}$ for amoxicillin, ampicillin and cloxacillin, respectively.

Addition of H$_2$O$_2$ at ambient pH ~5 and TiO$_2$ 1.0 g/L resulted in complete degradation of amoxicillin, ampicillin and cloxacillin in 30 min. Dissolved organic carbon (DOC) removal, and nitrate ($\text{NO}_3^-$), ammonia ($\text{NH}_4^+$) and sulphate ($\text{SO}_4^{2-}$) formation during degradation indicated mineralization of organic carbon, nitrogen and sulphur. UV/ H$_2$O$_2$/TiO$_2$ photocatalysis is effective for degradation of amoxicillin, ampicillin and cloxacillin in aqueous solution.

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References


Fig. 7. Effect of $\text{H}_2\text{O}_2$ addition on AMX, AMP and CLX degradation.

Fig. 8. Effect of irradiation time on DOC concentration and removal.

Fig. 9. Effect of irradiation time on $\text{NH}_4^+$, $\text{NO}_3^-$ and $\text{SO}_4^{2-}$ formation.