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Combined process for removal of tetracycline antibiotic - Coupling pre-treatment with a nickel-modified graphite felt electrode and a biological treatment

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ABSTRACT

Biodegradability improvement of tetracycline-containing solutions after an electrochemical pretreatment was examined. Cyclic voltammetry with a nickel electrode revealed a significant electrochemical activity of tetracycline, in both oxidation and reduction. Electrochemical treatment was therefore performed in a home-made flow cell using a nickel-modified graphite felt electrode as the working electrode. Optimal conditions, namely 100 mg l⁻¹ initial tetracycline, above 0.45 V potential, and between 1 and 6 ml min⁻¹ flow rate, led to a more than 99% conversion yield of tetracycline in oxidation in alkaline conditions, after only a single pass through the percolation cell. However, total organic carbon (TOC) analyses revealed a low mineralization level, i.e., always below 31%, underscoring the importance of a combined electrochemical and biological treatment. This was confirmed by the favorable trends of the COD/TOC ratio, decreasing from 2.7 to 1.9, and the average oxidation state, increasing from 0.044 to 1.15, before and after oxidation pretreatment at 0.7 V and 3 ml min⁻¹ flow rate. Electrolyzed solutions appeared biodegradable, since BOD₅/COD increased from 0 to 0.46 for untreated and pretreated TC at 0.7 V/SCE. Biological treatment showed only biosorption for non-pretreated tetracycline, while after 11.5 days of culture, the mineralization of solutions electrolyzed in oxidation was 54%, leading to a 69% overall TOC decrease during the combined process.

Keywords:

Tetracycline

Carbon felt anode

Combined processes

Biodegradability

1. Introduction

Tetracycline (TC) represents an important group of polyketide antibiotics. It is commonly used in human and veterinary medicine, in aquaculture, and as an additive to animal feeds, and it can also inhibit fungal growth in fruit trees. It is active against a wide range of Gram-positive and Gram-negative bacteria (Chopra and Roberts, 2001). It is widely used in European countries; in Germany, for instance, in 2007, over 17,000 kg of tetracycline were consumed by livestock as antimicrobial substances applied to pigs (Merle et al., 2012).

Only small portions of antibiotics administered to treated species are metabolized or absorbed in the body; most of the unchanged form of the drug is eliminated in faeces and urine (Arikan et al., 2006). Between 30 and 90% is excreted unchanged into the waste system (Hirsch et al., 1999). The presence of low levels of antibiotics and their transformation products in the environment could have adverse effects, such as bacterial resistance and disruption of key cycles critical to aquatic ecology or crop and animal production (Kummerer, 2004; Costanzo et al., 2005; Crane et al., 2006).

Due to their refractory characteristics as well as their antibacterial effects, biological methods are not efficient for antibiotic removal (Reyes et al., 2006). Indeed, biological removal using activated sludge showed only adsorption onto the solid phase without degradation (Prado et al., 2009).

Chemical oxidation could efficiently destroy antibiotics and overcome most of the limitations encountered during other conventional processes; especially the advanced oxidation

processes (AOP), which constitute the most important and widely documented group (Chiron et al., 2000; Oppenländer, 2003; Badawy et al., 2006). The AOP can be divided into three categories: photochemical processes, ozonation combined with UV irradiation and/or hydrogen peroxide (H_2O_2), and in-situ generation of free radicals $\bullet\text{OH}$ by other technologies. They are efficient but can be costly (Mohajerani et al., 2009).

Electrochemical processes also showed a remarkable ability to remove recalcitrant organic contaminants such as antibiotics (Walsh and Mills, 1993). An electrochemical reaction is based on a heterogeneous electronic transfer, and the main reactants are electrons. Weichgrebe et al. (2004) studied the biocide effect during electrochemical oxidation of tetracycline in water at an initial concentration of 1 g l^{-1} . Zhang et al. (2009) investigated the effect of various operating conditions on the electro-oxidation of tetracycline with a Ti/RuO_2 anode; similar studies used gold diamond and platinum anodes (Weichgrebe et al., 2004; Kraft, 2007; Masawat and Slater, 2007; Zhang et al., 2009). Electro-oxidation has appeared efficient for tetracycline degradation but has been carried out mostly on onerous anode materials.

For electroactive target compounds, oxidation or reduction can be carried out for their removal. Direct electrochemical processes are relevant in the case of a specific pollutant owing to the targeted selectivity, and therefore would be appropriate to treat low volumes of highly concentrated pollutants.

Reducing the antibacterial activity of a tetracycline solution does not necessarily require its complete mineralization. All that is needed is to break down the initial tetracycline molecules (Vedenyapina et al., 2008). Effluent mineralization can subsequently be completed during biological treatment; the potential advantages of the strategy of combining physicochemical and

biological processes to treat contaminants in wastewater have previously been described (Scott and Ollis, 1995, 1997; Pulgarin et al., 1999; Farré, et al., 2007).

Biodegradability improvement of solutions of 2,4-dichlorophenoxyacetic acid after a direct electrochemical oxidation in a homemade flow-cell involving a bare graphite felt electrode has been shown (Fontmorin et al., 2012), and complete mineralization (97%) of a pesticide, phosmet, was obtained by coupling an electrochemical reduction by means of the same electrolysis system and an activated sludge culture (Alonso-Salles et al., 2010).

Regarding the target compound, tetracycline, a significant electrochemical activity was shown by cyclic voltammetry with a vitreous carbon electrode, and hence electrochemical treatment was performed in a home-made flow cell with a bare graphite felt electrode. Biodegradability, based on the BOD₅ (five-day biochemical oxygen demand) to COD (chemical oxygen demand) ratio, increased with the oxidation potential until reaching 0.39, namely a biodegradable solution for 1.6 V/SCE, while no biodegradability improvement was observed after electrolysis in reduction, even though the resulting solution was not toxic for activated sludge. In addition, TOC analyses of the electrolyzed solution revealed that the level of mineralization remained low indicating the potential of a combined electrochemical and biological treatment (Belkheiri et al., 2011).

In order to improve the efficiency of the electrolysis pretreatment, especially through attempts to reduce the working potential, modification of the graphite felt electrode by nickel electrodeposition has been considered (Chamoulaud et al., 2001). Indeed, nickel oxidation on the electrode leads to the formation of a nickel oxyhydroxide, NiOOH, known to catalyze the oxidation of some organic molecules (Fleischmann et al., 1971; Vértes and Horányi, 1974). The purpose of this study was therefore to examine the electrochemical behavior of tetracycline with

an electrode modified by nickel electrodeposition and to determine if this improved the biodegradability of the tetracycline.

2. Materials and methods

2.1. Chemicals and reagents

Tetracycline hydrochloride (< 96% HPLC-grade) is displayed in Fig.1 and was obtained from Sigma Aldrich (Saint-Quentin Fallavier, France). Acetonitrile (ACN) was HPLC grade from Fisher Scientific (Illkirch, France), and formic acid (LC-MS grade, 98%) was purchased from J.T. Baker (Deventer, Holland). Standards were prepared with ultra-pure water (Purelab Options- Q7/15, Elga, 18.2 M Ω .cm⁻¹). All other reagents were of analytical grade.

2.2. Materials for the electrochemical pre-treatment

Electrochemical pre-treatment, in a continuous system, was performed in a home-made flow cell (Fig. 2a). The working electrode was obtained by nickel electrodeposition on the surface of the carbon felt. The electrode was made in the laboratory (by Floner and co-workers) at room temperature in an electrochemical cell formed by an open rectangular tank containing 1 L of the electrolyte solution (sodium sulfate and boric acid, 0.25 M each). The mechanism of nickel electrodeposition in acidic medium can be summarized in its simplest form by the reaction: $\text{Ni}_{\text{aq}}^{2+} + 2\text{e}^{-} \rightarrow \text{Ni}$ (Floner and Moinet, 2004; Floner and Geneste, 2007). The electrode was uniformly covered by nickel (around 1 μm thickness). There were no obvious defects and

cracks of the coating layer found on the electrode surface and it had a smooth surface, as shown in the SEM micrograph obtained with a JEOL 6301F (9 kV) microscope (Fig. 2b). Its specific area, measured by the BET method, was $1 \text{ m}^2 \text{ g}^{-1}$ and its density was about 0.37 g cm^{-3} , with a specific surface area related to the volume of $3700 \text{ cm}^2 \text{ cm}^{-3}$. The working electrode was 0.3 cm high and 4 cm in diameter, leading to a volume of 3.768 cm^3 , with a total surface of 1.39 m^2 . The electrode was separated from the two interconnected stainless steel counter-electrode compartments by cationic exchange membranes (Ionac 3470 – Lanxess SAS, Courbevoie, France). A good homogeneity of the potential distribution in the three-dimensional working electrode was obtained when the felt was located between two counter-electrodes (Moinet, 1994). The reference electrode (SCE) was positioned in the middle of the felt. The potential control was performed using an e-daq potentiostat linked to an e-corder 401 converter (AD Instruments Pty Ltd., Castle Hill, Australia). The tetracycline concentration (TC) was 100 mg l^{-1} . The supporting electrolyte used was $0.1 \text{ M Na}_2\text{SO}_4$. The TC solution percolated the porous electrode at a constant flow rate monitored by a Gilson minipuls 2 peristaltic pump (Middleton, WI, USA).

2.3. Analysis

2.3.1 Electrochemical analysis

Electrochemical analysis of tetracycline was performed using a conventional three electrode-cell with a nickel electrode (20 mm^2) as working electrode and a platinum wire as counter electrode. All the electrode potentials were measured with respect to a saturated calomel electrode (SCE) located near the working electrode.

Experiments were performed at ambient temperature under a nitrogen atmosphere. Voltammograms were obtained by cyclic voltammetry (100 mVs^{-1}) using an e-daq potentiostat linked to an e-corder 401 converter. The sense of the potential (E) sweeping is indicated by an arrow.

2.3.2. UPLC

The residual tetracycline concentration was determined by a UPLC (ultra-high-pressure liquid chromatography) system involving a Waters Acquity UPLC[®] H-Class gradient pump and a PDA (photo diode array) UV detector. A C₁₈ BEH (bridged ethylene hybrid) column, 1.7 μm (2.1 x 50 mm) was used. A gradient elution was carried out with 0.1% formic acid in ultra-pure water (solvent A) and acetonitrile (solvent B) as follows: 90/10% from 0 to 1 min; from 1 to 4.5 min elution was linearly modified from 90/10 to 2/98%, maintained at 2/98 % from 4.5 to 5 min; from 5 to 5.5 min elution was linearly modified from 2/98 to 90/10%, where it was maintained from 5.5 to 10 min for solvents A and B, respectively.

The flow rate was 0.5 ml. Tetracycline was detected at 360 nm. More detailed information on the UPLC determination can be found in a previous paper (Belkheiri et al., 2011).

2.3.3. Total organic carbon (TOC) and total nitrogen measurements

Total organic carbon and total nitrogen were measured by means of a Shimadzu total organic analyzer (TOC-V_{CPH} TOC-V_{CPN}/TOC-V_{WP}). HCl (2 N) and H₃PO₄ (25%) were considered for CO₂ and NO production. Organic carbon compounds were combusted and converted to CO₂, which was detected by a non-dispersive infrared detector (NDIR). Dissolved nitrogen compounds were combusted and converted to NO, which was then mixed with ozone

chemiluminescence for detection by a photomultiplier. Analyses were run in triplicate.

2.3.4. Chemical oxygen demand (COD) measurements

Chemical oxygen demand (COD) was measured by means of a Test Nanocolor® CSB 40 and 160 from Macherey-Nagel (Düren, Germany). The amount of oxygen required for the oxidation of the organic and mineral matter at 148°C for 2 h was quantified after oxidation with $K_2Cr_2O_7$ at acidic pH and with heating. Analyses were triplicated.

2.3.5. Toxicity

Toxicity was measured by means of the Microtox test (using a Microtox 500 analyser, which is a laboratory-based temperature-controlled photometer [15–27°C] that maintains the luminescent bacteria reagent and test samples at the appropriate temperature. This self-calibrating instrument measures the light production from a luminescent marine bacterial strain, *Vibrio fischeri* NRRL B-11177 (standard ISO 11348-3). The sample toxicity is determined by measuring the effective concentration at which 50% of the light is lost due to compound toxicity (EC_{50}) (Sarria et al., 2002).

2.3.6. Biological oxygen demand (BOD_5) measurements (Delzer and McKenzie 2003)

Biodegradability was deduced from BOD_5 measurements, carried out in an Oxitop IS6 (WTW, Alès, France). Activated sludge from a wastewater treatment plant was used to inoculate the flasks; the initial microbial concentration was 0.5 g l^{-1} .

1 ml of a mineral solution and 2.5 ml of a phosphate solution were added to 164 ml of sample. The composition of the mineral solution was (in g l^{-1}): $MgSO_4 \cdot 7H_2O$, 22.5; $CaCl_2$, 27.5;

FeCl₃, 0.15; NH₄Cl, 2.0; and that of the phosphate solution was (g l⁻¹): Na₂HPO₄, 6.80; KH₂PO₄, 2.80.

The BOD₅ value was initially estimated based on the COD value experimentally measured by means of a Nanocolor test CSB 160 (Macherey-Nagel, Düren, Germany); BOD₅ = COD/1.46. The range of expected BOD₅ values was then deduced and hence led to the volumes of sample of activated sludge solution and of nitrification inhibitor (0.5 ml of 10 mg l⁻¹ solution of *N*-Allylthiourea), which have to be added in the shake flask of the Oxitop apparatus.

Similar protocol was applied for the control flask except that it was replaced by a solution of easily biodegradable compounds, namely glutamic acid (150 mg l⁻¹) and glucose (150 mg l⁻¹). Before use, KOH was added to achieve neutral pH (7.0 ± 0.2). A similar protocol was also considered for the blank solution, for which the sample was replaced by water to deduce the biological oxygen demand corresponding to the endogenous respiration.

All BOD₅ measurements were duplicated.

2.4. Biological treatment

After only one pass through the electrochemical flow-cell, the effluent was collected for subsequent biological treatment. The biological treatment was carried out in aerobic conditions, using activated sludge purchased from a local wastewater treatment plant (Beaurade, Rennes, France). Prior to the experiment, activated sludge was washed four times with tap water and once with distilled water. After each washing, activated sludge was centrifuged at 3000 rpm for five minutes (Jouan, Thermo Fisher Scientific, Saint Herblain, France). The supernatant was then separated from the sludge to dispose of any residual carbon or mineral source.

Duplicate experiments were carried out in 600-ml Erlenmeyer flasks containing 450 ml of medium. Each sample was run in triplicate, stirred at 200 rpm, and kept at 25°C. The following mineral basis was used for each sample:

- 1 ml of the following solution (g l^{-1}): KH_2PO_4 , 8.5; K_2HPO_4 , 20.8; $\text{Na}_2\text{HPO}_4 \cdot 2\text{H}_2\text{O}$, 33.4.
- 0.4 ml of the following solutions (g l^{-1}): CaCl_2 , 27.6; $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 22.6; $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, 0.26.
- 1 ml of a trace elements solution containing (g l^{-1}): $\text{CuSO}_4 \cdot 7\text{H}_2\text{O}$, 1.36; $\text{ZnSO}_4 \cdot 5\text{H}_2\text{O}$, 0.25; $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$, 0.11; $\text{MnSO}_4 \cdot \text{H}_2\text{O}$, 1.01; H_3BO_3 , 0.10; and H_2SO_4 , 1 ml l^{-1} .

The culture medium also contained NH_4Cl , 75 mg l^{-1} , as nitrogen source; as well as either the tetracycline concentration at 100 mg l^{-1} , or a solution of 100 mg l^{-1} TC electrolyzed in oxidation at -0.7 V at a flow rate of 3 ml min^{-1} . A primary carbon source, glucose 100 mg l^{-1} , was also added as a carbon co-substrate. The pH of each sample was then adjusted to 7.0 ± 0.2 with 1 mol l^{-1} NaOH.

Samples (5 ml) were taken every 2 or 3 days and filtered on 0.45 μm . Measurements of pH were carried out using a Hanna pH meter with a combined micro-electrode probe (Thermo Spectronic, Rochester, NY). Samples were then diluted for TOC and TC measurements.

3. Results and discussion

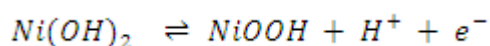
3.1. Electrochemical behaviour of tetracycline

The electroactivity of tetracycline (1 g l^{-1}) was examined in oxidation in alkaline medium (NaOH 0.1 mol l^{-1}) and in reduction in acidic medium (phosphate buffer 0.25 mol l^{-1}) by cyclic voltammetry on a nickel electrode. Alkaline conditions were established for oxidation, since it is

well-known that under these conditions, oxyhydroxide NiOOHs are formed, leading to electrocatalysis of organic compounds, mainly alcohols (Fleischmann et al., 1971; Vértes and Horányi, 1974). Reduction tests were carried out in an acidic medium (pH = 2.2 phosphate buffer 0.25 mol l⁻¹), since it favors the electrocatalytic hydrogenation (ECH) of compounds (Martel et al., 1997; Vilar et al., 2010).

3.1.1. Oxidation tests

Voltammograms obtained in the presence of only NaOH display a quasi-reversible system around 0.38 V_{SCE} (Fig.3 a). This signal has to be related to the reversible couple nickel hydroxide / nickel oxyhydroxide (Ni(OH)₂/ NiOOH). This couple is known to appear above pH 12 (Hahn et al., 1987).

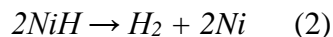


The voltammogram of the target compound showed an increase of the anodic signal of the quasi-reversible system, showing that in alkaline conditions tetracycline can be oxidized on nickel. It seems that the formation of NiOOH on the electrode allows the oxidation of tetracycline, probably by a reaction with the alcohols groups of the molecule. Interestingly, the oxidation potential (around 0.5 V_{SCE}) was significantly lower than those observed on the graphite-felt electrode (1 V/SCE – (Belkheiri et al. 2011)), due to the catalytic properties of nickel.

Owing to the high concentration of tetracycline that can be achieved in some effluents, experiments were also carried out for tetracycline concentrations of 0.1 g l⁻¹ (not shown). The electrochemical oxidation of tetracycline was still observed at this concentration, underscoring the importance of the electrochemical process on nickel.

3.1.2. Reduction tests

The electrochemical behavior of tetracycline in reduction in buffered acidic medium at pH 2.2 is displayed in Fig.3b. The presence of tetracycline induces a slight anodic shift of the reduction of water in dihydrogen. The reduction of water on the nickel electrode in acidic medium proceeds as follows (Martel et al., 1997; Vilar et al., 2010):



The anodic shift of the electrochemical signal shows that adsorbed dihydrogen (NiH) is involved in a reaction with adsorbed tetracycline, favouring reaction (1). Thus, cyclic voltammetry analyses seem to show an electrocatalytic hydrogenation reaction of tetracycline on the nickel electrode, which should be confirmed by electrolysis.

3.2. TC electrolysis

Since cyclic voltammetry showed the feasibility of an electrochemical pre-treatment, electrolysis of tetracycline were studied at 0.1 g l⁻¹ in both oxidation and reduction.

3.2.1. Reduction

Cathodic reduction was performed in phosphate buffered acidic medium (pH 2.1) at 1 ml min⁻¹ at different potentials (Table 1). The TC concentration was followed by HPLC. The results show that TC removal yield increased for increasing negative potentials. However, even at -1.0 V, the residual amount of TC remained high (17.5 mg l⁻¹ – Table 1), whereas the hydrogen evolution rate becomes more significant with increasing polarization potential. Since more cathodic potentials should even more enhance reaction (2), we considered the oxidation of tetracycline rather than the reduction as a possible pretreatment.

3.2.2. Oxidation

Oxidation was examined for a TC concentration of 100 mg l^{-1} , in alkaline medium (pH 13) at 1 ml min^{-1} .

Tetracycline concentration degradation appeared almost negligible for potentials below 0.4 V (Table 1). These results confirmed cyclic voltammetry analyses, since the oxidation signal became noticeable from about 0.4 V, corresponding to the formation of nickel oxyhydroxides (NiOOH). Above this potential, an almost total TC removal was always observed, showing the efficiency of the catalytic system. To optimize the electrochemical process, the flow rate effect was also examined at 0.7 V, corresponding to a total TC removal for a flow rate of 1 ml min^{-1} (Table 1). Interestingly, for all the studied flow rates, total TC degradation was achieved, as confirmed by TC determination by HPLC. However, mineralization yield decreased for increasing flow rates (Table 2) and was almost stable (around 15%) from 3.5 ml min^{-1} . This can be explained by further oxidation of byproducts occurring at low flow rates, leading to higher degradation yields.

Even if tetracycline was completely degraded after oxidation, the mineralization level remained low; it increased from 13.3% for 6 ml min^{-1} to 31% for 1 ml min^{-1} (Table 2). It should be noted that the electrochemical process was carried out in order to selectively degrade the target compound to obtain byproducts that were expected to be biologically assimilated by microorganisms from activated sludge. Therefore, such electrochemical pretreatment seems to be relevant for the tetracycline molecule, owing to the important amount of residual organic carbon available for a subsequent biological treatment.

3.3. COD measurements

Generally COD decrease involves a chemical oxidation of the target molecule and therefore a modification of its chemical structure that could lead to a decrease of its toxicity, while low mineralization is desired to ensure sufficient residual organic carbon for a subsequent biological treatment (Bandara et al., 1997; Sarria et al., 2003; Oller et al., 2007). Consequently, a favorable trend is a decrease of the COD/TOC ratio (Chebli et al., 2010) or an increase of the average oxidation state (AOS) (Pulgarin et al., 1999; Sarria et al., 2002):

$$AOS = \frac{4 * (TOC - COD)}{TOC}$$

with TOC and COD expressed in molar carbon per liter and molar oxygen per liter, respectively.

The TOC and COD values for the untreated tetracycline were 55.5 and 145 mg l⁻¹. From this, mineralization and oxidation yields varied in the range 9.7 to 33.5% and 19.3 to 31.7% for flow rates between 1 and 5 ml min⁻¹, respectively (Table 3). Hence, the COD to TOC ratio increased only slightly from 2.6 for the untreated tetracycline to 3.2 for a 1 ml min⁻¹ flow rate, while it decreased significantly for 3 and 5 ml min⁻¹ (Table 3), thus showing a favorable trend. Regarding AOS, it also decreased for a 1 ml min⁻¹ flow rate, while it followed a favorable trend for higher flow rates, 3 and 5 ml min⁻¹ (Table 3). The oxidation on nickel electrodes at flow rates above 1 ml min⁻¹ therefore seemed advantageous for electrolysis prior to a biological treatment.

3.4. Toxicity and biodegradability

Pure tetracycline at a concentration of 100 mg l⁻¹ was toxic for activated sludge, since the toxicity threshold is 18 mg l⁻¹ (Prado et al., 2010); this was illustrated by the BOD₅ value, which

was below that of the blank sample, and was confirmed by the Microtox test, since the EC₅₀ value was 13% (corresponding to 50% cell death, *Vibrio fischeri*).

Toxicity decreased after electrolysis since an EC₅₀ value of 52% was obtained for a 3 ml min⁻¹ flow rate. Biodegradability was checked by determination of the BOD₅ to COD ratio, since for values above 0.4, the effluent can be considered as biodegradable (Pulgarin et al., 1999; Sarria et al., 2002). The favorable trend was confirmed, since after electrolysis the BOD₅ to COD ratio was above the biodegradability threshold for 1 and 3 ml min⁻¹ and close to the threshold for 5 ml min⁻¹ (Table 3), showing the biodegradability of the byproducts from TC oxidation.

3.5. Biological treatment

In the absence of electrochemical pretreatment, the initial decrease observed for tetracycline (Fig.4) should be related to biosorption on activated sludge. Indeed, the adsorbed amount corresponded to 37.5% of the initial amount (not shown), and this was correlated with the TOC decrease (35.5%; Fig.4). This high amount of adsorbed TC was in agreement with previous findings, i.e., 39.8% TC and 41% TOC biosorption on activated sludge for Yahiat et al. (2011), as well as with the trend observed by Prado et al. (2009) who showed that adsorption is the most likely fate for tetracycline in a biological system. Throughout culturing, the TC concentration remained constant within the limits of experimental error (Fig.4), in agreement with the absence of TC biodegradability (Prado et al., 2009) and its potential toxicity for activated sludge remained, since TC concentration remained always above the threshold level of 18 mg l⁻¹ (Prado et al., 2010). Owing to TC toxicity, the weak TOC increase observed from about 50 h of culture may be attributed to cell lysis.

The TOC decreased during biological treatment with an electrolyzed TC solution. This showed a continuous decrease of the residual TOC amount over the period of culture (Fig.4), which obviously cannot be attributed to the biosorption of byproducts which is a rapid mechanism which take only a few hours (Prado et al., 2009). It should be remembered that TC was completely oxidized after only one pass through the percolation cell, so no residual TC was expected after biological treatment. Decrease in TOC was observed until about 11.5 days of culture, leading to about 54% mineralization; then the TOC level remained nearly constant until the end of culture (Fig.4). From this the overall TOC decrease during the combined process was 69%, corresponding to the abatement from the initial TOC value, before electrolysis pretreatment (55.5 mg l⁻¹ for untreated TC – Table 3) to the final value observed at the end of the activated sludge culture (close to 17 mg l⁻¹ – Figure 4). The significant residual TOC amount showed that some degradation byproducts in the oxidized effluent samples could not be assimilated by microorganisms even after 18 days of culture. An incomplete mineralization was also previously observed during the coupling of electrochemical pretreatment on a non-modified graphite-felt electrode and a biological treatment for the degradation of a pesticide, 2,4-dichlorophenoxyacetic acid (Fontmorin et al., 2013). However, the proposed combined process appeared especially promising considering the inefficiency of a widely used AOP, photocatalysis, to improve the biodegradability of TC solutions, owing to the presence of non-biodegradable byproducts (Yahiat et al., 2011, 2012; Maroga Mboula et al., 2012). To continue this study, research is in progress in the laboratory to examine the relevance of the proposed combined process to treat synthetic solutions of a widely used macrolide antibiotic, tylosin.

4. Conclusions

The electroactivity of tetracycline (1 g l^{-1}) was examined under oxidation conditions in alkaline medium ($\text{NaOH } 0.1 \text{ mol l}^{-1}$) and under reduction in an acidic medium (phosphate buffer 0.25 mol l^{-1}) using cyclic voltammetry with a nickel electrodeposition-modified graphite felt electrode. To our knowledge, such an electrode has never been studied for TC degradation. Tetracycline can be oxidized in alkaline conditions on nickel at an oxidation potential of only $0.5 \text{ V}_{\text{SCE}}$, which is significantly lower than possible with a graphite-felt electrode (1 V/SCE – (Belkheiri et al., 2011)). An electrocatalytic hydrogenation reaction of tetracycline on the nickel electrode was also shown; however, that reaction remained limited even at a potential of -1.0 V . An oxidation pretreatment was therefore considered.

For 0.7 V , the COD on the TOC followed a favorable trend since it decreased significantly for 3 and 5 ml min^{-1} ; a similar trend was also recorded for AOS. The favorable trend was confirmed since toxicity decreased after electrolysis; an EC_{50} value of 52% was obtained for 3 ml min^{-1} while it was initially 13% , and the BOD_5 to COD ratio was above the biodegradability threshold for 1 and 3 ml min^{-1} and close to this threshold for 5 ml min^{-1} . Confirming these results, activated sludge culture led to 54% mineralization of solutions electrolyzed in oxidation, leading to a 69% overall TOC decrease during the combined process.

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Tables**Table 1**

Effect of the oxidation potential on tetracycline degradation on nickel / carbon felt electrode.

(Flow rate: 1 ml min⁻¹)

	Reduction					Oxidation				
E (V)	-0.6	-0.7	-0.8	-0.9	-1.0	0.3	0.4	0.5	0.7	0.8
Removal yield (%)	36.47	49.98	51.05	56.95	82.50	5.50	96.43	99.10	100	100

Table 2

Tetracycline degradation by oxidation and mineralization yields.

Flow rate (ml min ⁻¹)	1.00	2.25	3.50	4.75	6.00
([TC] ₀ -[TC])/ [TC] ₀ (%)	100	100	100	100	100
(TOC ₀ -TOC)/TOC ₀ (%)	31.0 ± 2.5	22.4 ± 2.5	14.83 ± 2.5	13.3 ± 1.4	13.3 ± 1.4

Table 3

Oxidation, mineralization, and biodegradability of tetracycline electrolyzed on nickel / carbon felt electrode in oxidation in alkaline medium (NaOH 0.1 M) at 0.7 V.

	Flow rate (mL min ⁻¹)			
	Untreated TC	1	3	5
TOC (mg l ⁻¹)	55.5 ± 0.9	36.9 ± 0.9	50.1 ± 0.7	46.8 ± 0.4
COD mg O ₂ l ⁻¹	145 ± 1	117 ± 4	99 ± 5	111 ± 4
COD/TOC	2.61 ± 0.05	3.17 ± 0.17	1.98 ± 0.11	2.37 ± 0.13

AOS	0.08 ± 0.01	-0.76 ± 0.04	1.04 ± 0.09	0.44 ± 0.03
BOD ₅ mg O ₂ l ⁻¹	0 ± 0	52.5 ± 2.5	48 ± 4	31 ± 3
BOD ₅ /COD	0 ± 0	0.45 ± 0.01	0.48 ± 0.02	0.28 ± 0.02

Figure captions

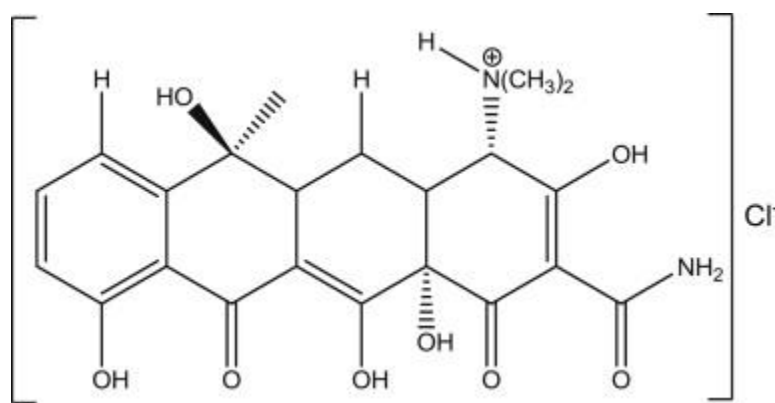


Fig. 1. Chemical structure of hydrochlorated tetracycline.

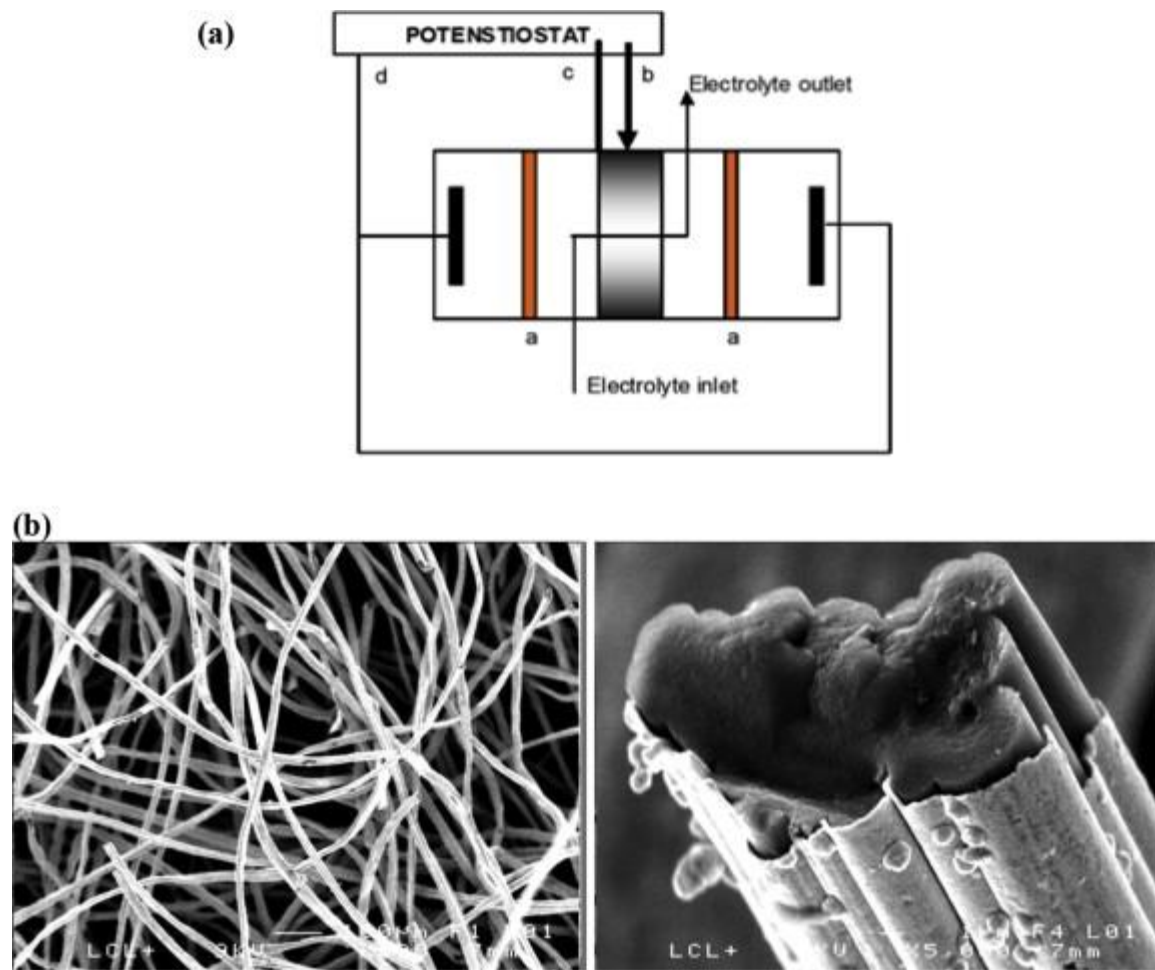


Fig. 2. (a) Schematic diagram of the percolation cell: a: cationic membranes; b: saturated calomel electrode (SCE); c: working electrode (disc of graphite covered with nickel felt: 10 mm diameter, 10 mm thickness); d: auxiliary counter electrodes. (b) SEM images of a nickel coating graphite felt (thickness 3 mm).

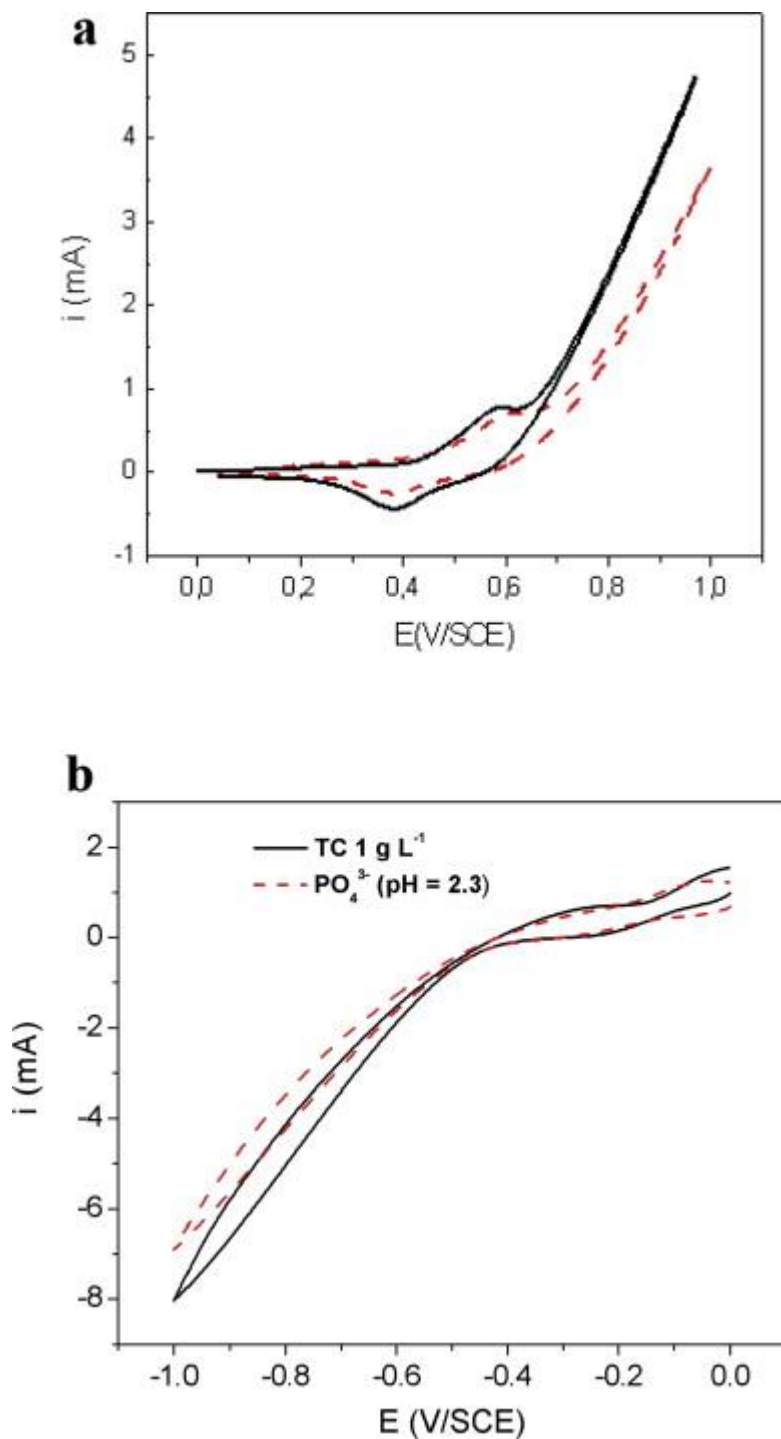


Fig. 3. Current-potential curve obtained in oxidation by cyclic voltammetry (100 mVs^{-1}) with a nickel electrode ($S = 20 \text{ mm}^2$), under nitrogen atmosphere and $T = 298 \text{ K}$, 0.1 g l^{-1} TC in 0.1 mol l^{-1} NaOH (a) and 1 g l^{-1} TC in 0.1 mol l^{-1} phosphate buffer (b). Current-potential curve in the absence (red) and in the presence of TC (black line).

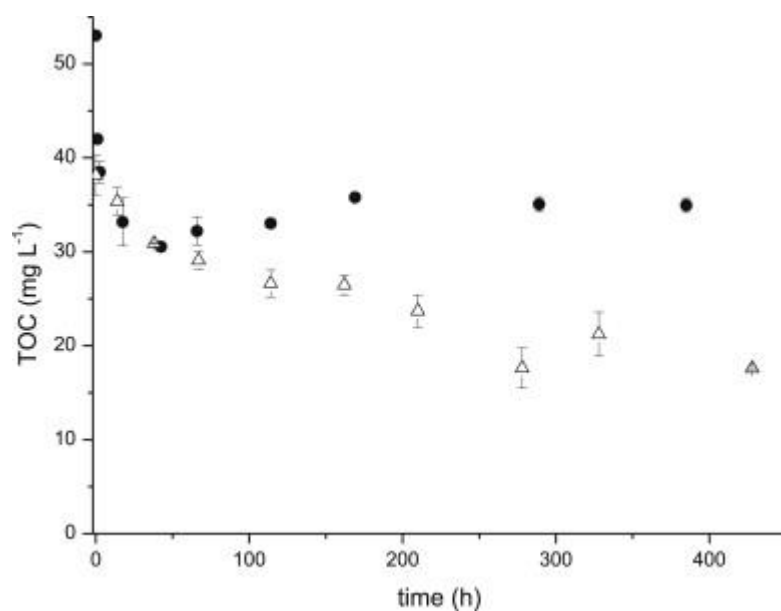


Fig. 4. Time-courses of the total organic carbon concentration during activated sludge culture on tetracycline (100 mg l^{-1}) non-pretreated (●) and after oxidation in a single pass through the percolation cell at a flow rate of 3 ml min^{-1} at 0.7 V in 0.1 mol l^{-1} NaOH (Δ).