

1 **Removal of the drug procaine from acidic aqueous solutions**  
2 **using a flow reactor with a boron-doped diamond anode**

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## 13 **Abstract**

14 This article reports the electrochemical advanced oxidation treatment of 2.5 L of acidic aqueous  
15 solutions with 0.320 mM of the drug procaine hydrochloride in 0.050 M Na<sub>2</sub>SO<sub>4</sub> using a pre-  
16 pilot flow plant. This was equipped with a cell, containing a boron-doped diamond (BDD)  
17 anode and an air-diffusion cathode for H<sub>2</sub>O<sub>2</sub> generation, which was connected to an annular  
18 photoreactor with a 160 W UVA lamp for the study of photoelectro-Fenton (PEF) process. Poor  
19 degradation and mineralization was attained by electrochemical oxidation with  
20 electrogenerated H<sub>2</sub>O<sub>2</sub> due to the limited attack of both, hydroxyl radical ( $\bullet$ OH) formed at the  
21 BDD surface from water oxidation and H<sub>2</sub>O<sub>2</sub> on organic matter. The electro-Fenton process  
22 became more effective thanks to the simultaneous oxidation with  $\bullet$ OH formed from Fenton's  
23 reaction in the presence of Fe<sup>2+</sup>. The most powerful process was PEF because of the additional  
24 photolysis of photoactive intermediates by UVA radiation. This method allowed achieving 91%  
25 mineralization after 360 min of electrolysis at 33.3 mA cm<sup>-2</sup>. The effect of current density and  
26 drug concentration on PEF performance was examined. The mineralization current efficiency  
27 and energy consumption were determined for each treatment. Two nitroderivatives were  
28 identified by gas chromatography-mass spectrometry. The quantification of generated  
29 carboxylic acids revealed that the final solution in PEF was composed of a mixture of acetic  
30 and formic acids.

31 *Keywords:* Electrochemical oxidation; Electro-Fenton; Photoelectro-Fenton; Procaine; Water  
32 treatment

## 33 1. Introduction

34 Procaine (2-(diethylamino)ethyl-4-aminobenzoate, see molecular structure in Table 1) is a  
35 local anesthetic drug widely used since its synthesis in 1905 that acts as a sodium channel  
36 blocker. It is commercially available as procaine hydrochloride ( $C_{13}H_{20}N_2O_2 \cdot HCl$ ,  $M = 272.77$   
37  $g\ mol^{-1}$ ). It was first used to diminish the pain upon intramuscular injection of penicillin and  
38 later, in dentistry, although it also possesses therapeutic properties because of its mood- and  
39 perfusion-enhancing, anti-inflammatory, and sympatholytic effects. Procaine can be lethal at  
40 high doses ( $> 10\ mg\ kg^{-1}$  for horses) since it can produce cardiac or respiratory arrests in human  
41 beings and animals, along with intoxication by the metabolites formed [1-3]. 4-Aminobenzoic  
42 acid, ethanolamine, monoethyl-aminoethanol, and diethylaminoethanol are the main  
43 metabolites found in animals such as rats, pigs, and horses [4,5]. Procaine has been detected at  
44 concentrations near  $1\ \mu g\ L^{-1}$  in industrial pharmaceutical wastewater [6,7] and effluents from  
45 wastewater treatment plants (WWTPs) [8]. The high stability of this drug under natural  
46 conditions along with its scarce removal in WWTPs explain its presence in the aquatic  
47 environment, although its potentially toxic effects on aquatic organisms have not been  
48 documented so far. The efficient removal of procaine and its products from industrial  
49 pharmaceutical wastewater by powerful transformation treatments seems necessary to avoid its  
50 discharge into natural water. Nonetheless, no specific technologies have been tested to destroy  
51 this drug. Worth noting, a single work has been reported on procaine hydrochloride degradation,  
52 using *N*-chlorobenzenesulfonamide in acid and alkaline media [9], but no previous studies have  
53 addressed the potential destruction of this compound by strong oxidants like hydroxyl radical  
54 ( $\bullet OH$ ). On the other hand, aqueous solutions with formulations (1:1) of procaine-penicillium G  
55 have been treated by chemical and photochemical advanced oxidation processes (AOPs) such  
56 as ozonation at pH 7 [10] and Fenton-like and photo-Fenton like at pH 3.0 [11]. The strong  
57 oxidant  $\bullet OH$  produced in situ by these methods yielded a partial mineralization (82% as

58 maximal) of such solutions, which contained 600 mg L<sup>-1</sup> chemical oxygen demand (COD) and  
59 450 mg L<sup>-1</sup> total organic carbon (TOC). As an interesting finding, all treated solutions became  
60 biodegradable from acute toxicity tests with *Daphnia magna*, but neither products nor released  
61 inorganic ions were analyzed, and the oxidation of procaine in the complex formulation was  
62 not clarified either. This is an important issue that needs to be addressed in order to limit the  
63 duration of the oxidation method for subsequent combination with a less expensive biological  
64 post-treatment [12].

65 Over the last decade, powerful electrochemical AOPs (EAOPs) are being developed for  
66 the remediation of pharmaceuticals wastewater [12-16]. Among them, Fenton-based treatments  
67 with H<sub>2</sub>O<sub>2</sub> electrogeneration seem the most promising EAOPs for industrial implementation  
68 [12-15]. In these processes, Fe<sup>2+</sup> is added to the solution to react with H<sub>2</sub>O<sub>2</sub> produced at the  
69 cathode of the electrochemical cell, eventually forming homogeneous •OH via the well-known  
70 Fenton's reaction. The continuous production of H<sub>2</sub>O<sub>2</sub> is ensured once O<sub>2</sub> gas is fed into the  
71 solution or through the cathode surface to be cathodically reduced to H<sub>2</sub>O<sub>2</sub> via reaction (1)  
72 [12,14,15]. Carbonaceous cathodes show a high electrocatalytic activity for this reaction.  
73 Examples include carbon nanotubes [17,18], reticulated vitreous carbon [19], carbon and  
74 graphite felt [19-23] and carbon-polytetrafluoroethylene (PTFE) air-diffusion devices [22,24-  
75 27].



77 Other key factors that affect the effectiveness of EAOPs in undivided cells are the anode  
78 material and the electrolyte composition [28,29]. In the absence of chloride ions, boron-doped  
79 diamond (BDD) thin films are the best anodes [12-15]. The weak •OH-BDD interaction and the  
80 large overpotential for water discharge at BDD favor the generation of physisorbed hydroxyl  
81 radical (BDD(•OH)) from reaction (2), which is more active than the radical adsorbed on

82 conventional Pt and dimensionally stable anodes (DSA<sup>®</sup>) [28-32]. In chlorinated media, the  
83 latter anodes become more effective to produce active chlorine, which reacts with organics in  
84 concomitance with heterogeneous  $\bullet\text{OH}$ . However, the preferred anode also in this case is  
85 usually BDD since it possesses greater ability to remove the toxic and recalcitrant  
86 chloroderivatives formed. As a potential drawback, undesirable chlorate and perchlorate ions  
87 may be formed if the electrolysis conditions are not carefully controlled [33-36].



89 This work aims to assess whether the hydroxyl radicals generated by EAOPs, either alone  
90 or in concomitance with UVA light, are able to effectively degrade and mineralize acidic  
91 aqueous solutions of procaine at pH 3.0. Tests were carried out in a 2.5 L pre-pilot flow plant  
92 containing an undivided filter-press cell with a BDD anode and a carbon-PTFE cathode, which  
93 provided  $\text{H}_2\text{O}_2$  to the solution from reaction (1). A typical non-chlorinated medium such as  
94 0.050 M  $\text{Na}_2\text{SO}_4$  was chosen to characterize the oxidation action of hydroxyl radicals produced,  
95 without significant interference of weaker oxidizing agents like persulfate ( $\text{S}_2\text{O}_8^{2-}$ ) and sulfate  
96 radical ion ( $\text{SO}_4^{\bullet-}$ ) coming from sulfate oxidation [12-15]. No other aqueous matrices (e.g.,  
97 urban wastewater) were tested, in order to avoid the interference of active chlorine originated  
98 from the anodic oxidation of  $\text{Cl}^-$  ions [37]. Two Fenton-based EAOPs were compared, namely  
99 electro-Fenton (EF) and photoelectro-Fenton (PEF) under UVA ( $\lambda_{\text{max}} = 360 \text{ nm}$ ) irradiation.  
100 They were operated in the presence of 0.50 mM  $\text{Fe}^{2+}$ , the optimum content for Fenton's reaction  
101 using this kind of cell [38]. A drug concentration of 0.320 mM (i.e., 50 mg  $\text{L}^{-1}$  TOC), much  
102 higher than that found in the environment, was employed in order to determine the  
103 mineralization current efficiencies and energy consumptions related to the procaine removal,  
104 as well as to minimize the error in the analysis of the oxidation products formed and inorganic  
105 ions released. Comparative treatments in the absence of  $\text{Fe}^{2+}$  catalyst, i.e., electrochemical

106 oxidation with electrogenerated  $\text{H}_2\text{O}_2$  (EO- $\text{H}_2\text{O}_2$ ), were also made in order to clarify the  
107 behavior of BDD( $\bullet\text{OH}$ ) and homogeneous  $\bullet\text{OH}$ . For the most powerful process, the effect of  
108 applied current density ( $j$ ) and drug concentration on its performance was assessed to  
109 understand the role of UVA radiation. Gas chromatography-mass spectrometry (GC-MS) was  
110 used to identify the aromatic products produced, whereas high-performance liquid  
111 chromatography (HPLC) was employed for the quantification of the final short-chain aliphatic  
112 carboxylic acids.

## 113 **2. Materials and methods**

### 114 *2.1. Reagents*

115 Procaine hydrochloride (99% purity) was provided by Sigma-Aldrich and used as received.  
116 The supporting electrolyte ( $\text{Na}_2\text{SO}_4$ ) and Fenton's catalyst ( $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ ) were of analytical  
117 grade purchased from Fluka and Panreac. Analytical grade standard carboxylic acids were  
118 purchased from Merck and Panreac. The solutions treated in the 2.5 L pre-pilot flow plant were  
119 prepared with deionized water, whereas analytical solutions were prepared with Millipore  
120 Milli-Q ultrapure water (resistivity  $> 18.2 \text{ M}\Omega \text{ cm}$ ). Other reagents and chemicals were either  
121 of HPLC or analytical grade from Merck, Panreac and Prolabo.

### 122 *2.2. Pre-pilot flow plant*

123 The electrochemical assays were carried out in a 2.5 L pre-pilot flow plant constructed in  
124 our laboratory and containing the same basic elements as previously reported [39]. Briefly, the  
125 electrochemical cell was an undivided filter-press reactor with two electrodes of  $20 \text{ cm}^2$  of  
126 exposed area, separated 1.2 cm. The cell was connected to a reservoir containing the solution  
127 through two heat-exchangers, which were fed with external water at constant temperature  
128 regulated with a Digiterm 3000542 thermostat from J.P. Selecta, a flowmeter and a peristaltic  
129 pump. The outlet of the cell was connected to an annular glass photoreactor of 640 mL, which

130 was either covered with an opaque cloth in EO-H<sub>2</sub>O<sub>2</sub> and EF or equipped with a 27 E 160-W  
131 UVA lamp (320–400 nm,  $\lambda_{\text{max}} = 360$  nm) from Omnilux to illuminate the solution in the PEF  
132 process. This lamp provided an irradiance of 134 W m<sup>-2</sup>, as detected with a Kipp & Zonen CUV  
133 5 radiometer. The anode was a BDD thin film on a Si wafer from NeoCoat (Le-Chaux-de-  
134 Fonds, Switzerland) and the cathode was a carbon-PTFE air-diffusion electrode from E-TEK  
135 (Somerset, NJ, USA), which was fed with air pumped at 8.6 kPa of overpressure to continuously  
136 produce H<sub>2</sub>O<sub>2</sub> from reaction (1). An N5746A System DC power from Agilent Technologies  
137 was used to provide constant current to the cell, also measuring the potential difference between  
138 electrodes ( $E_{\text{cell}}$ ). Before the trials, the two fresh electrodes were cleaned and activated in 0.050  
139 M Na<sub>2</sub>SO<sub>4</sub> at  $j = 100$  mA cm<sup>-2</sup> for 240 min. All the electrochemical assays were carried out in  
140 duplicate and the corresponding mean values of the parameters measured are reported in this  
141 work. The error bars with 95% confidence interval are included in figures.

### 142 2.3. Analytical methods

143 The solution pH was adjusted to 3.0 with analytical grade H<sub>2</sub>SO<sub>4</sub> (Merck) and monitored  
144 during all the trials using a 2000 pH-meter from Crison. The H<sub>2</sub>O<sub>2</sub> accumulated in the solution  
145 was measured by the standard metavanadate method using a 1800 UV/Vis spectrophotometer  
146 from Shimadzu set at  $\lambda = 450$  nm [40].

147 For the degradation experiments, the samples were diluted (1:1) with acetonitrile to stop  
148 the oxidation and filtered with 0.45  $\mu\text{m}$  PTFE filters from Whatman before HPLC analysis.  
149 This was made by injecting 10  $\mu\text{L}$  aliquots into a 600 LC coupled to a 996 photodiode array  
150 detector (PDA) selected at  $\lambda = 290$  (the maximum wavelength for procaine), both from Waters.  
151 The LC contained an ODS Hypersil 5  $\mu\text{m}$ , 150 mm  $\times$  3 mm (i.d.), column from Thermo Electron  
152 Corporation at 25 °C. A 60:40 (v/v) acetonitrile/water (10 mM KH<sub>2</sub>PO<sub>4</sub>, pH 3) mixture was  
153 circulated at 1 mL min<sup>-1</sup> as mobile phase. Under these conditions, the procaine peak in the  
154 chromatograms appeared at a retention time  $t_r = 4.2$  min, with L.O.D. = 0.085 mg L<sup>-1</sup> and L.O.Q.

155 = 0.290 mg L<sup>-1</sup>. Generated carboxylic acids were detected by injecting 20 µL samples into the  
156 same LC with an Aminex HPX 87H, 300 mm × 7.8 mm (i.d.), column from Bio-Rad at 35 °C,  
157 and the PDA set at λ = 210 nm. A 4 mM H<sub>2</sub>SO<sub>4</sub> solution at 0.6 mL min<sup>-1</sup> was employed as  
158 mobile phase. Oxalic (t<sub>r</sub> = 6.9 min), formic (t<sub>r</sub> = 14.1 min) and acetic (t<sub>r</sub> = 15.4 min) acids were  
159 quantified. NH<sub>4</sub><sup>+</sup>, NO<sub>3</sub><sup>-</sup>, and Cl<sup>-</sup> contents in solution were measured following the procedures  
160 previously described [25,36].

161 TOC of solutions was measured on a TOC VCSN analyzer from Shimadzu upon injection  
162 of filtered 50 µL samples after immediate withdrawal from treated solutions. Reproducible  
163 values with ±1% accuracy were always obtained using the non-purgeable organic carbon  
164 (NPOC) method, with L.O.D. = 0.215 mg L<sup>-1</sup> and L.O.Q. = 0.713 mg L<sup>-1</sup>.

165 The stable organic components accumulated in 0.320 mM drug solutions with 0.050 M  
166 Na<sub>2</sub>SO<sub>4</sub> at pH 3.0 upon EO-H<sub>2</sub>O<sub>2</sub> treatment at j = 33.3 mA cm<sup>-2</sup> were identified by GC-MS  
167 using a NIST05 library. Several samples of 100 mL were withdrawn at different electrolysis  
168 times and, for each one, the remaining organics were extracted with dichloromethane (3 × 25  
169 mL) and further treated for volume reduction to about 2 mL. A 6890 N GC coupled to a 5975C  
170 inert XL MS, both from Agilent Technologies, was used for the GC-MS analysis. Organics  
171 were detected using a non-polar Sapiens-X5ms 0.25 µm, 30 m × 0.25 mm (i.d.), column from  
172 Teknokroma, as reported elsewhere [36].

### 173 **3. Results and discussion**

#### 174 *3.1. Comparative treatment of procaine solutions by EAOPs*

175 Preliminary assays were performed to ensure the photostability of procaine in acidic aqueous  
176 medium and the ability of the electrolytic cell to generate H<sub>2</sub>O<sub>2</sub> in the pre-pilot flow plant. A  
177 solution of 2.5 L of 0.320 mM procaine hydrochloride in 0.050 M Na<sub>2</sub>SO<sub>4</sub> at pH 3.0 was  
178 recirculated through the plant equipped with a BDD/air-diffusion cell (20 cm<sup>2</sup> of exposed area



179 each) and connected to an annular glass photoreactor (irradiated volume of 640 mL) with a 160-  
180 W UVA lamp in its center. After 8 h at a liquid flow rate of 180 L h<sup>-1</sup> and with intermittent 2-h  
181 exposure to UVA radiation, no change of absorbance in the UV spectrum of drug solution at  
182  $\lambda_{\max} = 290$  nm was found, thus confirming its stability under the experimental conditions tested.

183 Another series of trials was made by electrolyzing 2.5 L of 0.050 M Na<sub>2</sub>SO<sub>4</sub> at pH 3.0 in  
184 the above pilot plant at different  $j$  values without UVA irradiation, i.e., under EO-H<sub>2</sub>O<sub>2</sub>  
185 conditions. Fig. 1 evidences a progressive increase in accumulated H<sub>2</sub>O<sub>2</sub> at each  $j$  for 360 min,  
186 attaining final contents of 13.4, 25.7 and 31.1 mM at raising  $j$  values of 33.3, 66.7 and 100 mA  
187 cm<sup>-2</sup>, respectively. Such enhancement can be related to the concomitant increase in rate of  
188 reaction (1). It is noticeable that each profile tended to a maximum value as a result of the  
189 gradual destruction of H<sub>2</sub>O<sub>2</sub> in solution and, pre-eminently, at the anode surface where it was  
190 oxidized to O<sub>2</sub> via hydroperoxyl radical (HO<sub>2</sub>•) production [12,14]. However, the amount of  
191 H<sub>2</sub>O<sub>2</sub> accumulated was not proportional to the increase of current density, which is also due to  
192 the enhancement of H<sub>2</sub>O reduction to H<sub>2</sub> gas at the cathode. This loss in current efficient was  
193 more significant as  $j$  was increased, and hence, current densities > 100 mA cm<sup>-2</sup> were not useful  
194 in practice for H<sub>2</sub>O<sub>2</sub> production. Despite this, the amount of H<sub>2</sub>O<sub>2</sub> produced was high enough  
195 in all cases to generate a large quantity of homogeneous •OH via Fenton's reaction during the  
196 EF and PEF treatments, which was also favored by the fast Fe<sup>2+</sup> regeneration from Fe<sup>3+</sup>  
197 reduction at the cathode [14-16].

198 Once studied the H<sub>2</sub>O<sub>2</sub> production in the system, 0.320 mM drug solutions were  
199 electrolyzed under the above conditions by EO-H<sub>2</sub>O<sub>2</sub>, EF and PEF at  $j = 33.3$  mA cm<sup>-2</sup>. The  
200 two latter trials were carried out in the presence of 0.50 mM Fe<sup>2+</sup> as catalyst. No significant pH  
201 change, close to 3.0, was found after 360 min of such electrolyses. Fig. 2a depicts a very slow  
202 decay of drug concentration upon EO-H<sub>2</sub>O<sub>2</sub> treatment, attaining only 45% removal at 60 min.  
203 This informs about the very small reaction rate of procaine with physisorbed BDD(•OH)

204 originated from reaction (2). At the same treatment time, total drug removal was reached by EF  
205 due to its much faster reaction with homogeneous  $\bullet\text{OH}$  formed from Fenton's reaction (3) with  
206  $\text{Fe}^{3+}$  production [12,41,42].



208 Fig. 2a also highlights the slightly quicker abatement of the drug by PEF, which  
209 disappeared in 45 min. In this process, a greater amount of homogeneous  $\bullet\text{OH}$  is generated to  
210 more rapidly destroy the photostable procaine molecule. This can be accounted for by the  
211 occurrence of reaction (4), in which  $[\text{Fe}(\text{OH})]^{2+}$ , the most stable  $\text{Fe}^{3+}$  species at pH 3.0,  
212 originated from reaction (3), is photoreduced by UVA light to  $\bullet\text{OH}$  and  $\text{Fe}^{2+}$  with the consequent  
213 acceleration of the catalytic  $\text{Fe}^{3+}/\text{Fe}^{2+}$  cycle [14,27,37].



215 The procaine concentration profiles show an exponential trend in both Fenton-based  
216 EAOPs (Fig. 2a), which can then be interpreted considering a pseudo-first-order reaction  
217 kinetics, as presented in Fig. 2b. From the linear regression, the apparent rate constants ( $k$ ) for  
218 procaine removal were determined. Table S1 shows  $k$ -values of  $(7.55 \pm 0.36) \times 10^{-2} \text{ min}^{-1}$  in EF  
219 and  $(7.99 \pm 0.42) \times 10^{-2} \text{ min}^{-1}$  in PEF, with good  $R^2$ -values. This suggests the formation of a small  
220 and steady concentration of  $\bullet\text{OH}$  from reactions (3) and/or (4) to destroy the target molecule. A  
221 different behavior can be observed in Fig. 2b in the case of EO- $\text{H}_2\text{O}_2$ , since a non-linear  $\ln(c_0/c)$   
222 vs. time plot was found. This is due to a progressive decay of the procaine removal rate as  
223 the treatment was prolonged, probably because the oxidant BDD( $\bullet\text{OH}$ ) attacked more rapidly  
224 its products, lowering its availability to oxidize the drug.

225 The percentage of mineralization in the above assays was monitored by determining the  
226 TOC abatement for 360 min, a time much longer than that required for degradation because of

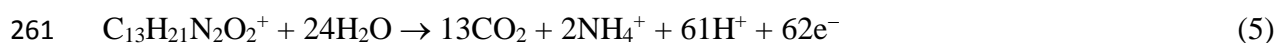
227 the great recalcitrance of the oxidation products generated. Fig. 3a depicts a gradual TOC  
228 disappearance in all cases. Table S1 also depicts a decreasing oxidation ability of the EAOPs  
229 in the order: PEF >> EF > EO-H<sub>2</sub>O<sub>2</sub>. The less powerful treatment was EO-H<sub>2</sub>O<sub>2</sub> and hence, all  
230 organics were quite refractory even to BDD( $\bullet$ OH) since only 26% TOC removal was achieved  
231 after 360 min of electrolysis. In the presence of Fe<sup>2+</sup>, i.e., under EF conditions, the additional  
232 attack of homogeneous  $\bullet$ OH caused a more rapid mineralization of organics, attaining 54%  
233 TOC decay. The PEF treatment had the greatest mineralization power, giving rise to 91% TOC  
234 abatement at 360 min (see Table S1). This corroborates the huge impact of UVA radiation on  
235 the process performance, thanks to photolysis of some by-products, whereas these species are  
236 slowly attacked by BDD( $\bullet$ OH) and  $\bullet$ OH, as revealed by EO-H<sub>2</sub>O<sub>2</sub> and EF profiles. Fig. 3a also  
237 shows that in PEF, TOC decreased quickly until 240 min, whereupon its decay was strongly  
238 decelerated, suggesting the formation of highly persistent products that are very slowly  
239 removed [14,27-29].

240 For each mineralization process, the conversion of the two *N* atoms of procaine in 0.320  
241 mM solutions into inorganic ions was assessed. Analysis of treated solutions only allowed  
242 detecting the release of NH<sub>4</sub><sup>+</sup> ion. Neither NO<sub>2</sub><sup>-</sup> nor NO<sub>3</sub><sup>-</sup> ions were found. The time course of  
243 NH<sub>4</sub><sup>+</sup> concentration obtained in all the above treatments is shown in Fig. 3b. This ion was  
244 quickly released at the beginning of all treatments, progressively decreasing its accumulation  
245 rate at longer time. The final amount of NH<sub>4</sub><sup>+</sup> was increased at a greater oxidation ability of the  
246 EAOPs because larger quantities of *N*-derivatives were mineralized. Final values of 0.261 mM  
247 (40.8% of initial N) in EO-H<sub>2</sub>O<sub>2</sub>, 0.288 mM (45.0% of initial N) in EF, and 0.332 mM (51.9%  
248 of initial N) in PEF were obtained. Taking into account that 91% TOC was removed by the  
249 latter process (Fig. 3a), the loss of volatile *N*-products, e.g., N<sub>2</sub> and N<sub>x</sub>O<sub>y</sub>, can be inferred, as  
250 previously proposed for other *N*-compounds [24,27,36,37].

251 The evolution of  $\text{Cl}^-$  ion during the EAOPs tested was determined as well. Fig. 3c reveals  
252 that, in all cases, the initial  $\text{Cl}^-$  concentration (0.320 mM) was slowly removed by less than 9%,  
253 as expected from the very low content of active chlorine formed from the anodic oxidation of  
254 this ion [34-36]. That confirms that the main oxidizing agents in the EAOPs are heterogeneous  
255 BDD( $\bullet\text{OH}$ ) formed from reaction (2) and/or homogeneous  $\bullet\text{OH}$  generated from Fenton's  
256 reaction (3) and reaction (4), with additional photolytic reactions induced by UVA light in PEF.

### 257 3.2 Mineralization current efficiency and energy consumption

258 From the findings reported in subsection 3.1, the following reaction can be written for the  
259 total mineralization of protonated procaine molecule, the species present in solution,  
260 considering the formation of  $\text{NH}_4^+$  ion:



262 Reaction (5) shows that the number ( $n$ ) of transferred electrons for procaine mineralization is  
263 62. Based on this, the percentage of mineralization current efficiency (MCE) was estimated for  
264 all trials as follows [37]:

$$265 \text{MCE} = \frac{n F V \Delta\text{TOC}}{4.32 \times 10^7 m I t} 100 \quad (6)$$

266 where  $\Delta\text{TOC}$  is the TOC abatement (in  $\text{mg L}^{-1}$ ) at applied current  $I$  (in A) for a given time  $t$  (in  
267 h). The constant values in Eq. (6) are the Faraday constant  $F$ , the solution volume  $V$  (2.5 L), a  
268 conversion factor ( $= 3600 \text{ s h}^{-1} \times 12,000 \text{ mg C mol}^{-1}$ ) and the number of carbon atoms ( $m = 13$ ).

269 Fig. 4a shows the MCE values calculated from Eq. (6) for the tests of Fig. 3a. The EO-  
270  $\text{H}_2\text{O}_2$  process showed a steady MEC value near 8-9% from 180 min of electrolysis (see Table  
271 S1), suggesting that all organic molecules are mineralized at similar rate under such conditions.  
272 This behavior is not observed in EF and PEF, which present maximum MCE values of 28.0%  
273 and 76.8% between 60 and 120 min, respectively, i.e., when the maximum mineralization rate

274 was achieved. This means that the destruction of readily oxidizable compounds was accelerated  
275 until the maximum MCE value was attained. At longer time, the MCE decayed gradually,  
276 although more dramatically in PEF down to 29.2%, still greater than 17.5% determined in EF  
277 at 360 min (see Table S1) This loss of current efficiency can be related to two factors [14,16]:  
278 (i) the abatement of the dissolved organic load, and (ii) the generation of final products, being  
279 so highly recalcitrant that they can only be very slowly removed by the different oxidizing  
280 agents and UVA photons.

281 The energy consumption per unit TOC mass ( $EC_{TOC}$ , in kWh (g TOC)<sup>-1</sup>) for each  
282 experiment was calculated from Eq. (7) [37]:

$$283 \quad EC_{TOC} = \frac{E_{cell} I t}{V \Delta TOC} \quad (7)$$

284 where  $E_{cell}$  denotes the potential difference between the electrodes of the cell (in V) and the rest  
285 of parameters have been defined above. Note that this equation has also been employed for  
286 calculation in PEF treatment, but without considering the energy related to the 160-W lamp.  
287 For the real application at a larger scale, the solar PEF (SPEF) process using free sunlight could  
288 be alternatively utilized. Under such conditions, no additional energy consumption from light  
289 irradiation should be considered and Eq. (7) would give an idea of the energy requirements for  
290 the treatment [14,27,37].

291 The  $EC_{TOC}$  values present an opposite tendency as compared to the MCE ones, thus  
292 reaching minimal values as the MCE became maximal. Fig. 4b shows the high energy  
293 consumption of about 1 kWh (g TOC)<sup>-1</sup> determined for EO-H<sub>2</sub>O<sub>2</sub> treatment at times  $\geq 120$  min,  
294 which is due to its very low mineralization ability (see also Table S1). At shorter time, much  
295 higher  $EC_{TOC}$  values were obtained, e.g., 5.71 kWh (g TOC)<sup>-1</sup> at 40 min. As expected, the  $EC_{TOC}$   
296 in EF and PEF was drastically smaller, with minimal values of 0.292 kWh (g TOC)<sup>-1</sup> at 120  
297 min and 0.106 kWh (g TOC)<sup>-1</sup> at 90 min, respectively, which gradually rose up to 0.468 and  
298 0.279 kWh (g TOC)<sup>-1</sup> at the end of treatments (see Table S1). According to these results, the

299 most powerful EAOP, i.e., PEF process, was not only the most efficient but also the less  
300 expensive treatment, disregarding the energy associated with the UVA lamp. If the electric  
301 energy from the lamp was taken into account, the energy consumption of  $8.81 \text{ kWh (g TOC)}^{-1}$   
302 would be excessively high for industrial application. Hence, its alternative use with sunlight  
303 can be envisaged as the best method for the decontamination of wastewater containing procaine.

### 304 *3.3 Effect of current density and drug concentration on PEF performance*

305 Once established that PEF was the best method for procaine mineralization, the influence  
306 of key variables on its performance was assessed in order to know the role of generated  
307 hydroxyl radicals and UVA radiation during the process. The first variable to be tested was  $j$ ,  
308 since it limits the concentration of physisorbed BDD( $\bullet\text{OH}$ ) and homogeneous  $\bullet\text{OH}$  produced in  
309 the electrolytic system. Trials were then carried out between  $33.3$  and  $100 \text{ mA cm}^{-2}$  and the  
310 evolution of normalized TOC decay with time is depicted in Fig. 5a. Surprisingly, very similar  
311 profiles can be observed for TOC abatement as  $j$  was increased, reaching final removals  
312 between 91% and 94% from  $33.3$  to  $100 \text{ mA cm}^{-2}$ , respectively (see Table S1). This means that  
313 the mineralization process is mainly controlled by the action of UVA radiation over the  
314 photoactive intermediates. Therefore, the excess of BDD( $\bullet\text{OH}$ ) and  $\bullet\text{OH}$  generated upon  
315 enhancement of reactions (1)-(4), as  $j$  was increased, was mainly wasted in their non-oxidizing  
316 parasitic reactions. These include, for example, the anodic oxidation of BDD( $\bullet\text{OH}$ ) to BDD and  
317  $\text{O}_2$  and the attack of homogeneous  $\bullet\text{OH}$  over  $\text{H}_2\text{O}_2$  and  $\text{Fe}^{2+}$  [14,15,24]. The results suggest that  
318 the enhancement of such parasitic reactions occurs because a large proportion of products are  
319 photoactive and then, more rapidly photodecomposed by UVA light than oxidized by hydroxyl  
320 radicals. Moreover, it seems that at the end of treatment (times longer than 240 min) the  
321 remaining products are so highly recalcitrant that can only be very slowly removed by the  
322 different oxidizing agents and UVA photons.

323 The profiles of MCE and  $EC_{TOC}$  vs. electrolysis time for the above tests are presented in  
324 Fig. 5b and 5c, respectively. As can be seen, the rise of  $j$  did not favor the PEF treatment,  
325 because MCE gradually decreased and  $EC_{TOC}$  underwent a high growth because of the increase  
326 of  $E_{cell}$ . Regarding MCE, Fig. 5b highlights that maximum values of 76.8%, 42.7% and 28.6%  
327 at about 90 min were found at 33.3, 66.7 and 100  $mA\ cm^{-2}$ , respectively, whereas they dropped  
328 to final values from 29.2% to 10.2% (see Table S1). The fact that the maximum of MCE was  
329 reached at a similar time with increasing  $j$  can be explained by the quicker mineralization of the  
330 easily oxidizable products in the presence of the greater amounts of BDD( $\bullet OH$ ) and  $\bullet OH$   
331 produced. However, the generation of recalcitrant photoactive products caused that the overall  
332 process was subsequently limited by their photodecomposition, with little influence of hydroxyl  
333 radicals and hence, of  $j$ . This can also explain the minimum values of 0.106, 0.305 and 0.650  
334  $kWh\ (g\ TOC)^{-1}$  determined at the same time. Fig. 5c evidences that at longer time, the energy  
335 consumption always increased, reaching a value as high as 1.867  $kWh\ (g\ TOC)^{-1}$  at  $j = 100\ mA$   
336  $cm^{-2}$ , in contrast to 0.279  $kWh\ (g\ TOC)^{-1}$  determined at  $j = 33.3\ mA\ cm^{-2}$  (see Table S1).

337 All the above findings indicate that the lowest  $j$  of 33.3  $mA\ cm^{-2}$  was preferable under the  
338 present experimental conditions because it allowed a high TOC removal (91%) with much  
339 greater MCE and lower  $EC_{TOC}$  than higher  $j$  values.

340 Another critical variable is the initial drug concentration, since it allows evaluating the  
341 ability of PEF to mineralize highly concentrated organic products from the parent molecule.  
342 This was studied by electrolyzing from 0.064 to 0.320 mM procaine hydrochloride at the best  $j$   
343 = 33.3  $mA\ cm^{-2}$ . Fig. 6a shows a similar TOC removal at all organic loads, slightly increasing  
344 as the drug content was decreased but always attaining final reductions of 90-91% (see Table  
345 S1). This means that a growing quantity of TOC was destroyed with increasing drug content,  
346 being about 9.1  $mg\ L^{-1}$  for solutions with 0.064 mM, 22.6  $mg\ L^{-1}$  at 0.160 mM and 45.0  $mg\ L^{-1}$   
347 at 0.320 mM. Since the same contents of BDD( $\bullet OH$ ) and  $\bullet OH$  are expected to be formed

348 because the same  $j$  was applied in all cases, one can infer that their parasitic reactions are  
349 gradually inhibited and larger quantities of both reactive radicals are actually available to react  
350 with organic molecules. This behavior is confirmed from the enhancement of the MCE values,  
351 as shown in Fig. 6b. Maximum values of 24.9% after 40 min starting with 0.064 mM, 43.0%  
352 after 60 min at 0.160 mM and 76.8% after 70 min at 0.320 mM were obtained, decreasing to  
353 5.9%, 14.8%, and 29.2% at 360 min, respectively (see Table S1). The opposite tendency was  
354 followed by  $EC_{TOC}$ , as can be seen in Fig. 6c. The most expensive treatment was then obtained  
355 when treating 0.064 mM, since the  $EC_{TOC}$  value rose from about  $0.35 \text{ kWh (g TOC)}^{-1}$  within  
356 the first hour of treatment to  $1.372 \text{ kWh (g TOC)}^{-1}$  at 360 min. These energy consumptions  
357 decreased drastically at higher drug concentrations because of the greater efficiency of the PEF  
358 treatment, attaining  $0.551$  and  $0.279 \text{ kWh (g TOC)}^{-1}$  after 360 min at 0.160 and 0.320 mM,  
359 respectively (see Table S1). Although it is clear that the performance of the treatment was  
360 improved at a higher organic content, it is noticeable the great ability of the system to effectively  
361 destroy low initial procaine concentrations, making it suitable for all kinds of initial conditions.

### 362 *3.4 Detection of oxidation products*

363 The primary stable oxidation products originated from the attack of hydroxyl radicals on  
364 the drug were identified in 0.320 mM procaine hydrochloride solutions electrolyzed by the less  
365 powerful EAOP, namely EO- $H_2O_2$ , at  $j = 33.3 \text{ mA cm}^{-2}$ . Table 1 collects the characteristics of  
366 the three organic compounds detected, including the parent molecule of procaine (**1**) that was  
367 very slowly removed by this method. The nitration of the  $-NH_2$  group leads to compound **2**,  
368 which is subsequently oxidized to compound **3** with loss of the diethylamino group. The  
369 generation of these products could suggest the release of  $NO_3^-$  ion from the cleavage of the  
370 C(4)-N bond of the aromatic moiety. However, this ion was not detected in the treated solutions,  
371 as expected if its main release occurs via  $NH_4^+$  and volatile  $N_xO_y$  species.



372 Another interesting aspect to be considered to clarify the fate of contaminants treated by  
373 EAOPs is the identification and quantification of the final products. It is expected that benzenic  
374 products are transformed into smaller aliphatic molecules, including short-chain carboxylic  
375 acids [12,14,15]. This possibility was explored by analyzing the electrolyzed solutions under  
376 the same conditions described in Fig. 3a by ion-exclusion HPLC. In the case of EO-H<sub>2</sub>O<sub>2</sub>, only  
377 small contents of oxalic acid (< 0.08 mM) were found between 150 and 360 min of electrolysis,  
378 which is not surprising taking into account the limited mineralization ability of this method. A  
379 very different behavior was observed in EF and PEF treatments, in which three carboxylic acids,  
380 namely acetic, formic and oxalic, were detected. In these EAOPs, a large proportion of iron is  
381 in the form of Fe<sup>3+</sup> ion when an air-diffusion cathode is used and hence, most of the above acids  
382 are complexed with Fe(III) [14]. These species are not attacked by homogeneous •OH, are  
383 slowly mineralized by physisorbed BDD(•OH), and some of them can be photodecarboxylated.  
384 Note that acetic acid is converted into oxalic and formic acids, which are final products that are  
385 directly transformed into CO<sub>2</sub> [14,27,39].

386 Fig. 7a and 7b present the profiles of the concentration of each carboxylic acid found in EF  
387 and PEF treatments, respectively. In the former treatment, a large and continuous accumulation  
388 of oxalic acid up to 17.8 mM can be observed. A smaller accumulation occurred for formic  
389 acid, reaching 9.5 mM as maximum concentration and finally dropping to 5.02 mM, whereas  
390 acetic acid disappeared from the medium after reaching a maximal of 4.8 mM at 240 min. A  
391 simple mass balance of the EF treatment revealed that all carboxylic acids contributed with 6.1  
392 mg L<sup>-1</sup> TOC to the final solution, only accounting for 26.5% of the remaining 23.0 mg L<sup>-1</sup> of  
393 TOC (Fig. 3a). This means that, after the EF process, the solution still contained 16.9 mg L<sup>-1</sup> of  
394 TOC related to other undetected and persistent products. Regarding the PEF treatment, Fig. 7b  
395 highlights that oxalic acid was not present in solution because of the rapid photolysis of Fe(III)-  
396 oxalate complexes. In contrast, high contents of acetic and formic acids were accumulated,

397 indicating that a large proportion of recalcitrant products that were not destroyed in EF could  
398 be photolyzed, thus largely enhancing the mineralization process in PEF. This can also be  
399 inferred from the mass balance of the final acetic and formic acids, with concentrations of 7.5  
400 and 9.9 mM. This corresponded to 5.6 mg L<sup>-1</sup> TOC, a value that agrees with the 100% of the  
401 TOC found for the final treated solution (Fig. 3a). In fact, this was already verified at 240 min,  
402 when the solution was already hardly mineralized. At that time, the sum of all acids yielded 7.0  
403 mg L<sup>-1</sup> TOC, very close to 7.5 mg L<sup>-1</sup> of the TOC experimentally determined. This informs  
404 about the pre-eminent conversion of procaine hydrochloride into a mixture of acetic and formic  
405 acids in PEF. Therefore, for practical implementation, the duration of PEF could be shortened  
406 to be subsequently combined with a biological post-treatment. This would become a more cost-  
407 effective solution for industrial application. It should be noted that the complete conversion of  
408 an aromatic pollutant into carboxylic acids has been rarely reported in the literature. To our  
409 knowledge, this has been described for the SPEF treatment of the herbicide mecoprop at pH  
410 3.0, yielding a final solution composed of acetic acid [39], which was hardly oxidized as also  
411 occurs here for the PEF treatment of procaine.

#### 412 **4. Conclusions**

413 Hydroxyl radicals generated by EAOPs, pre-eminently those combined with UVA  
414 radiation, were very effective to treat acidic water contaminated with procaine. The PEF process  
415 had much greater oxidation ability than EF to decontaminate 2.5 L of 0.320 mM procaine in  
416 0.050 M Na<sub>2</sub>SO<sub>4</sub> with 0.50 mM Fe<sup>2+</sup> at pH 3.0. At  $j = 33.3 \text{ mA cm}^{-2}$ , 91% TOC removal was  
417 attained after 360 min of PEF with 29.2% MCE and 0.279 kWh (g TOC)<sup>-1</sup> of energy  
418 consumption. In contrast, only 54% TOC was abated using EF, meaning that a large proportion  
419 of recalcitrant species to BDD(<sup>•</sup>OH) and <sup>•</sup>OH are photoactive and can be photodecomposed by  
420 UVA light in PEF. Procaine concentration dropped at similar rate in the two Fenton-based

421 methods, following a pseudo-first-order kinetics, owing to the action of •OH as main oxidant.  
422 In EO-H<sub>2</sub>O<sub>2</sub>, much slower procaine and TOC decays were obtained, as expected if the drug and  
423 its products are hardly attacked by BDD(•OH). NH<sub>4</sub><sup>+</sup> was the only dissolved nitrogenated ion  
424 detected, which was accompanied by two N-containing derivatives identified by GC-MS. Ion-  
425 exclusion HPLC analysis of treated solutions revealed that the final solution upon PEF  
426 treatment was composed of a mixture of only Fe(III)-acetate and Fe(III)-formate complexes,  
427 because of the total photodecarboxylation of Fe(III)-oxalate complexes.

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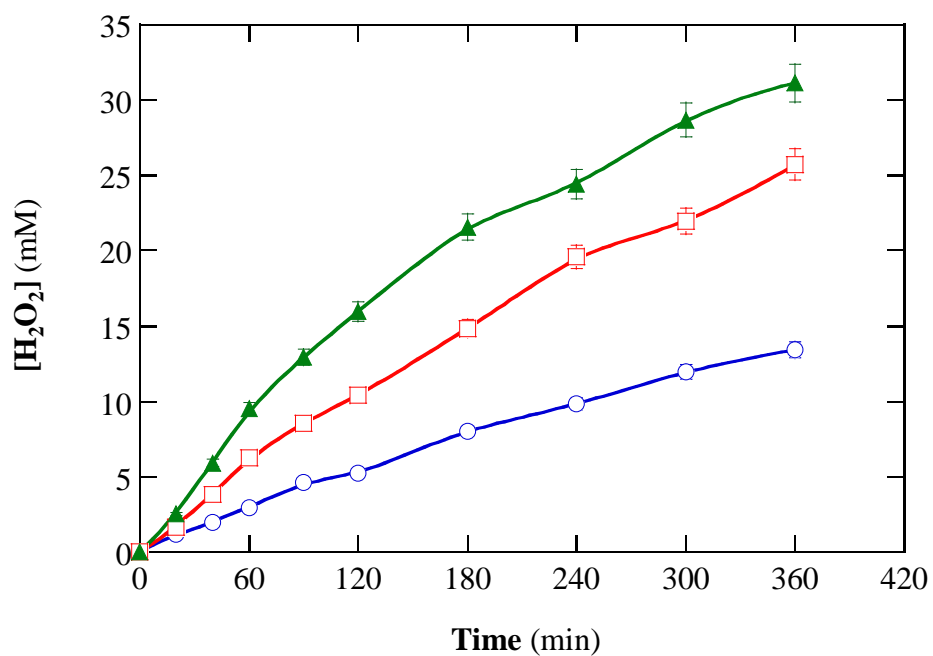
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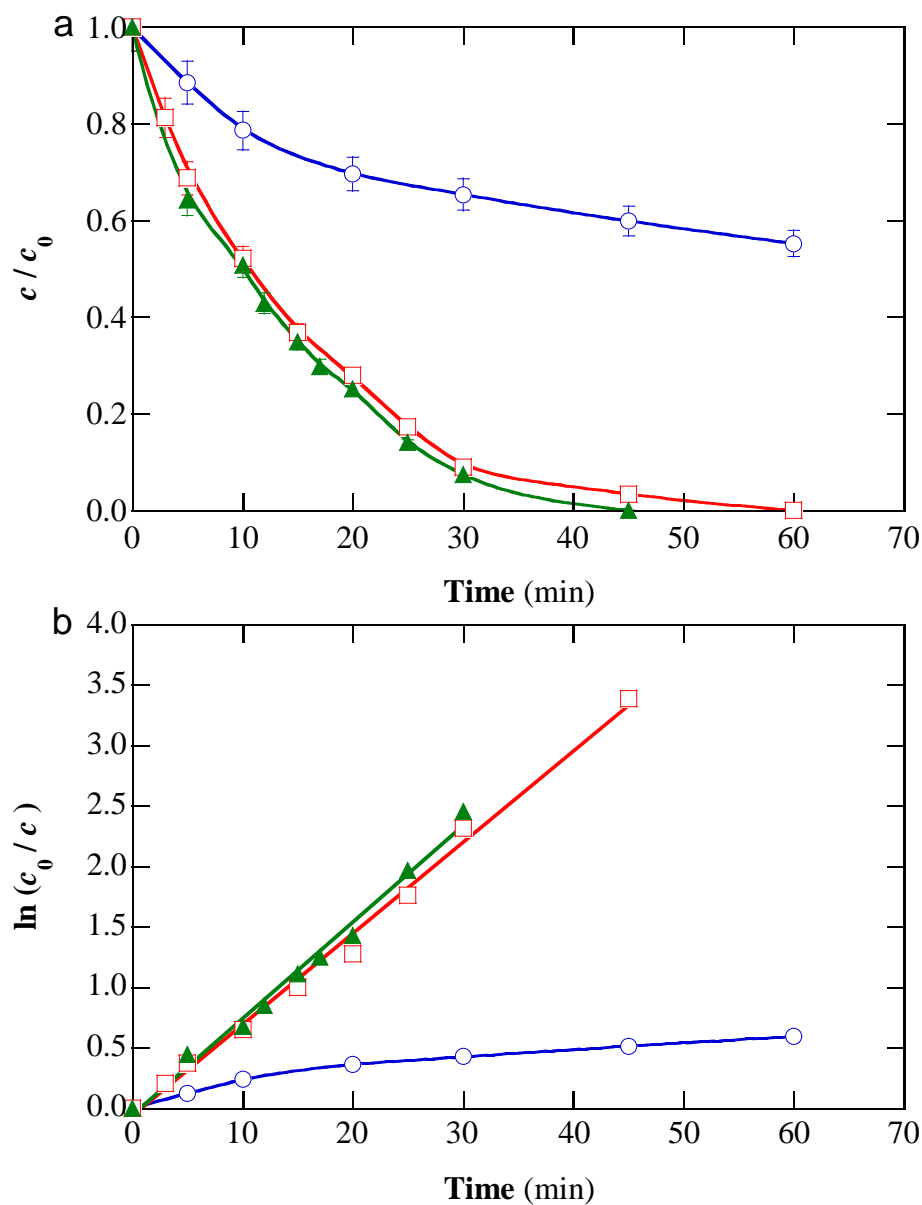
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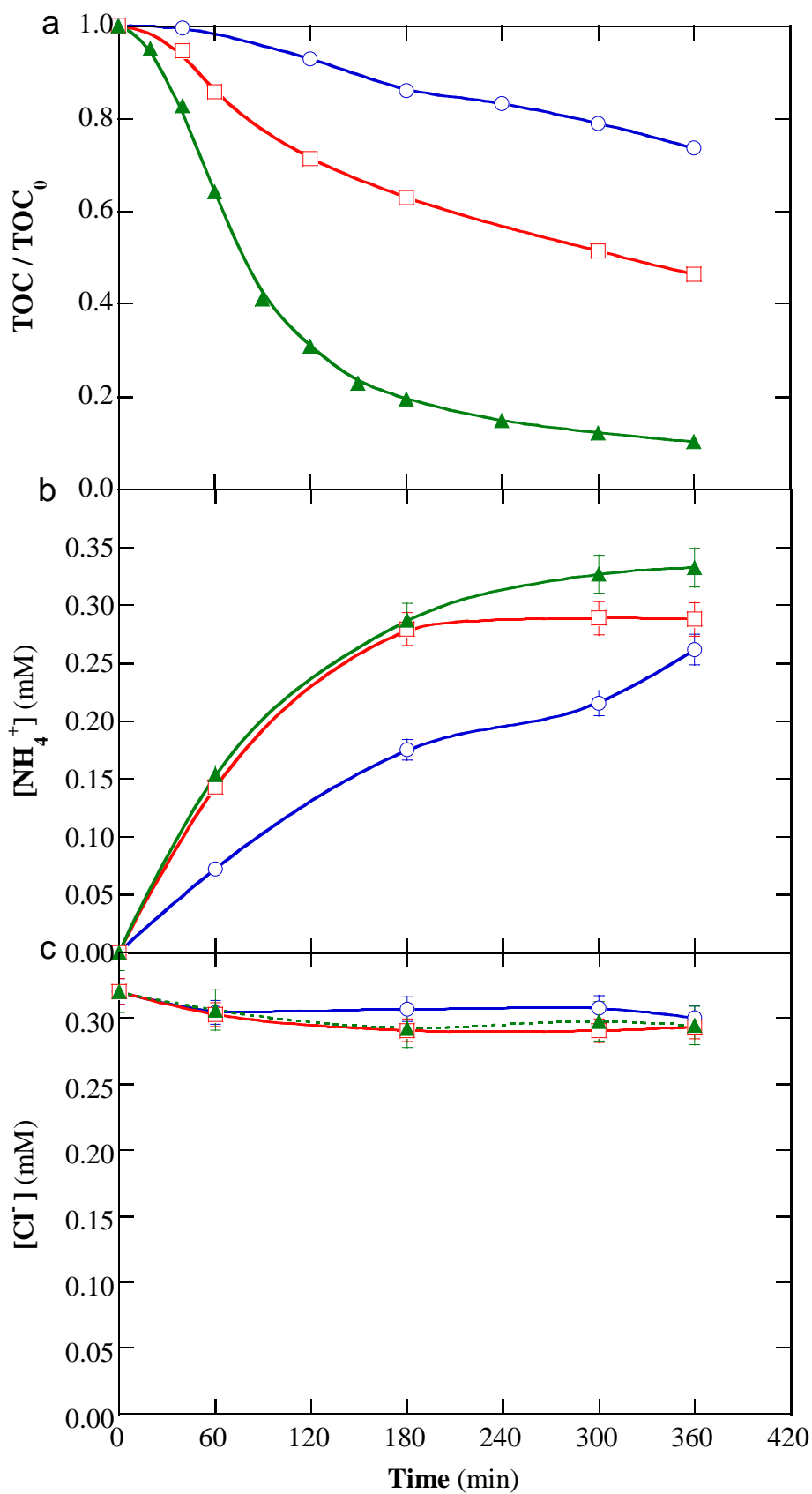




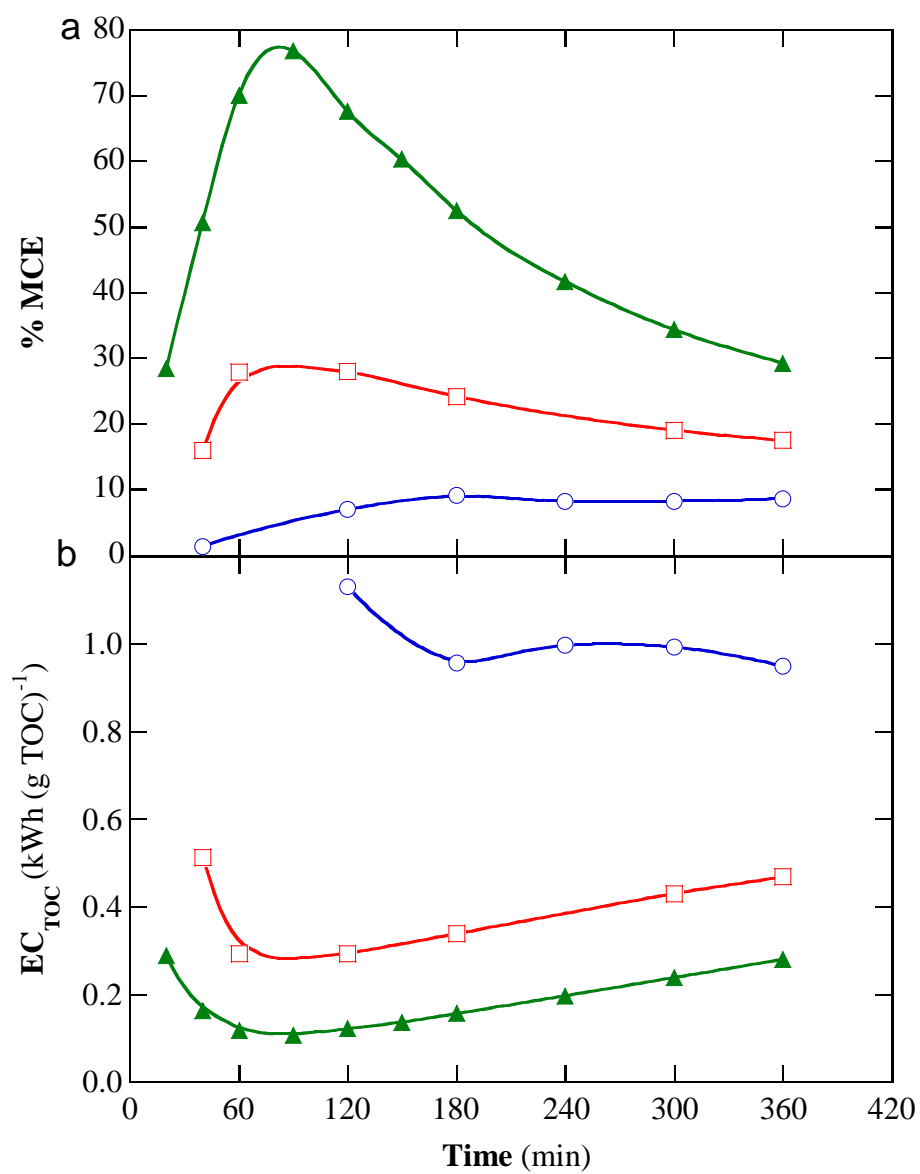
**Fig. 1.** Concentration of accumulated  $H_2O_2$  vs. electrolysis time in 2.5 L of 0.050 M  $Na_2SO_4$  at pH 3.0 and 35 °C using a pre-pilot flow plant with an electrochemical reactor containing a BDD anode and an air-diffusion cathode, both of 20 cm<sup>2</sup>, at liquid flow rate of 180 L h<sup>-1</sup>. Current density: (○) 33.3 mA cm<sup>-2</sup>, (□) 66.7 mA cm<sup>-2</sup> and (▲) 100 mA cm<sup>-2</sup>.



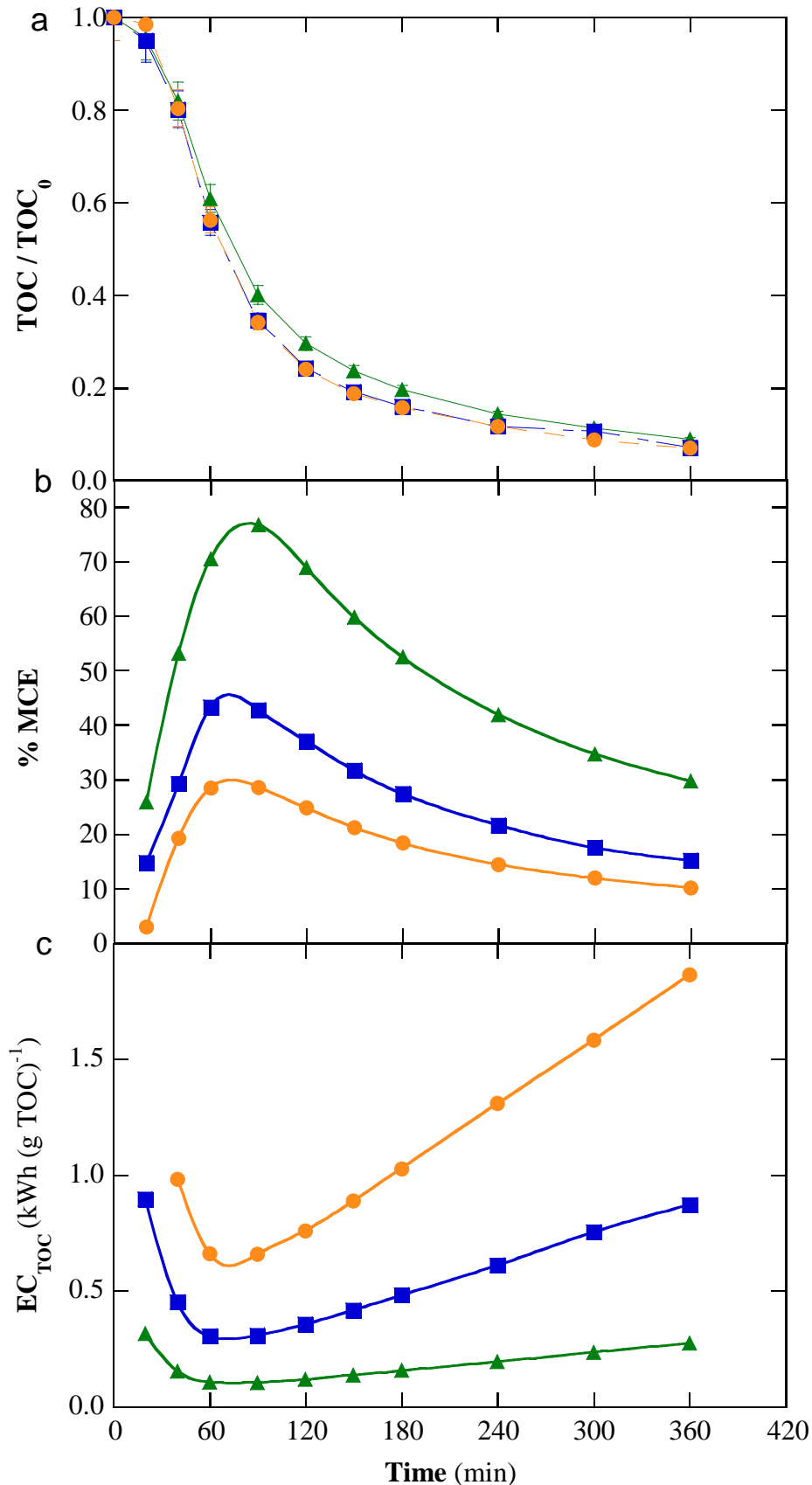
**Fig. 2.** (a) Normalized drug concentration decay vs. electrolysis time and (b) pseudo-first-order kinetic analysis for the degradation of 2.5 L of a 0.320 mM procaine hydrochloride solution with 0.050 M Na<sub>2</sub>SO<sub>4</sub> at pH 3.0 and 35 °C using a pre-pilot flow plant with a BDD/air-diffusion cell (20 cm<sup>2</sup> electrode area) at current density ( $j$ ) of 33.3 mA cm<sup>-2</sup> and liquid flow rate of 180 L h<sup>-1</sup>. Method: (○) Electrochemical oxidation with electrogenerated H<sub>2</sub>O<sub>2</sub> (EO-H<sub>2</sub>O<sub>2</sub>), (□) electro-Fenton (EF) and (▲) photoelectro-Fenton (PEF). The two latter trials were made with 0.50 mM Fe<sup>2+</sup>. The PEF treatment was performed under irradiation with a 160-W UVA lamp.



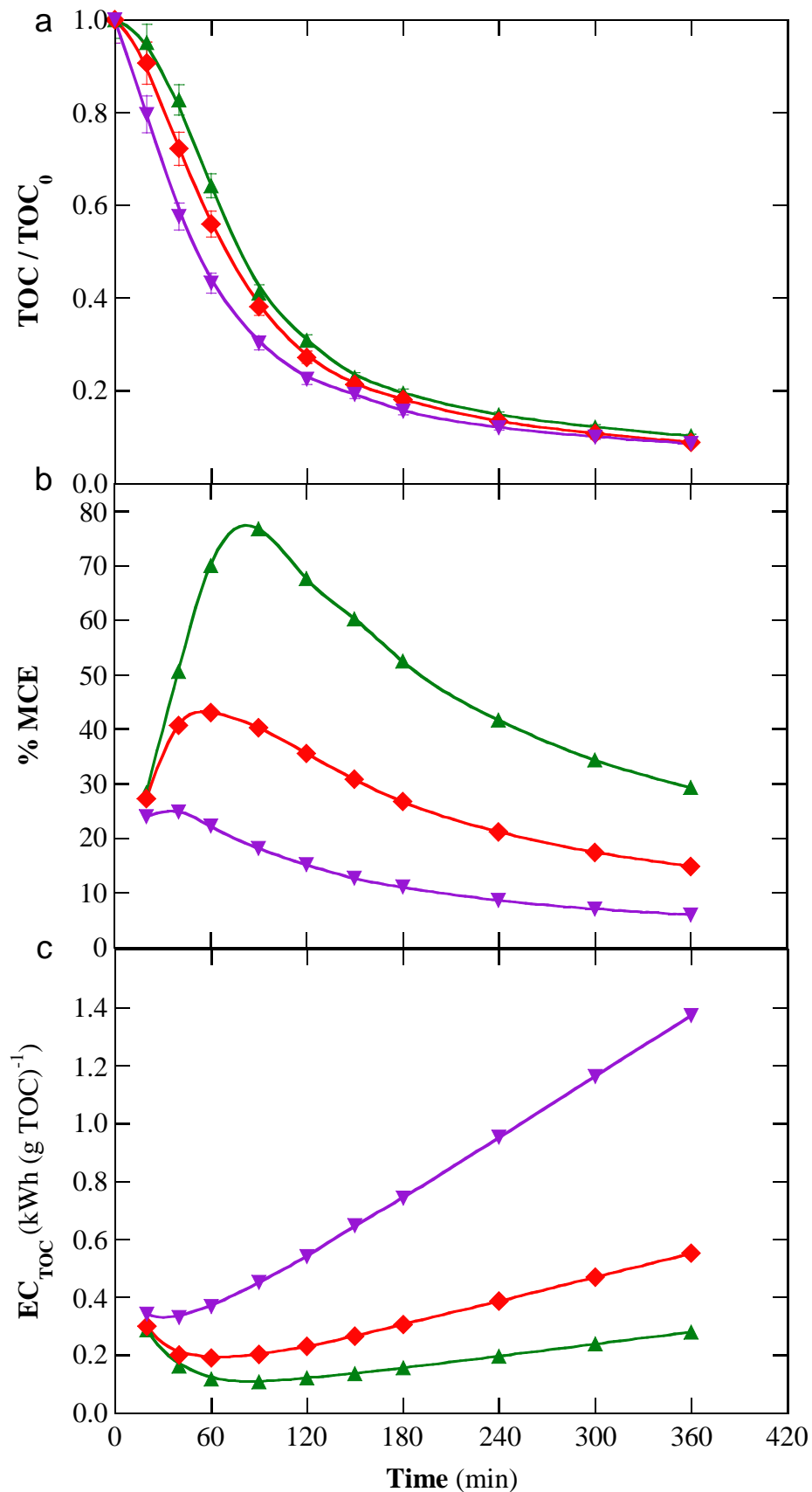
**Fig. 3.** (a) Normalized TOC decay vs. electrolysis time for the assays of Fig. 2 (initial TOC of 50 mg L<sup>-1</sup>). Concentration of (b) accumulated ammonium ion and (c) chloride ion during the same trials. Method: (○) EO-H<sub>2</sub>O<sub>2</sub>, (□) EF and (▲) PEF.



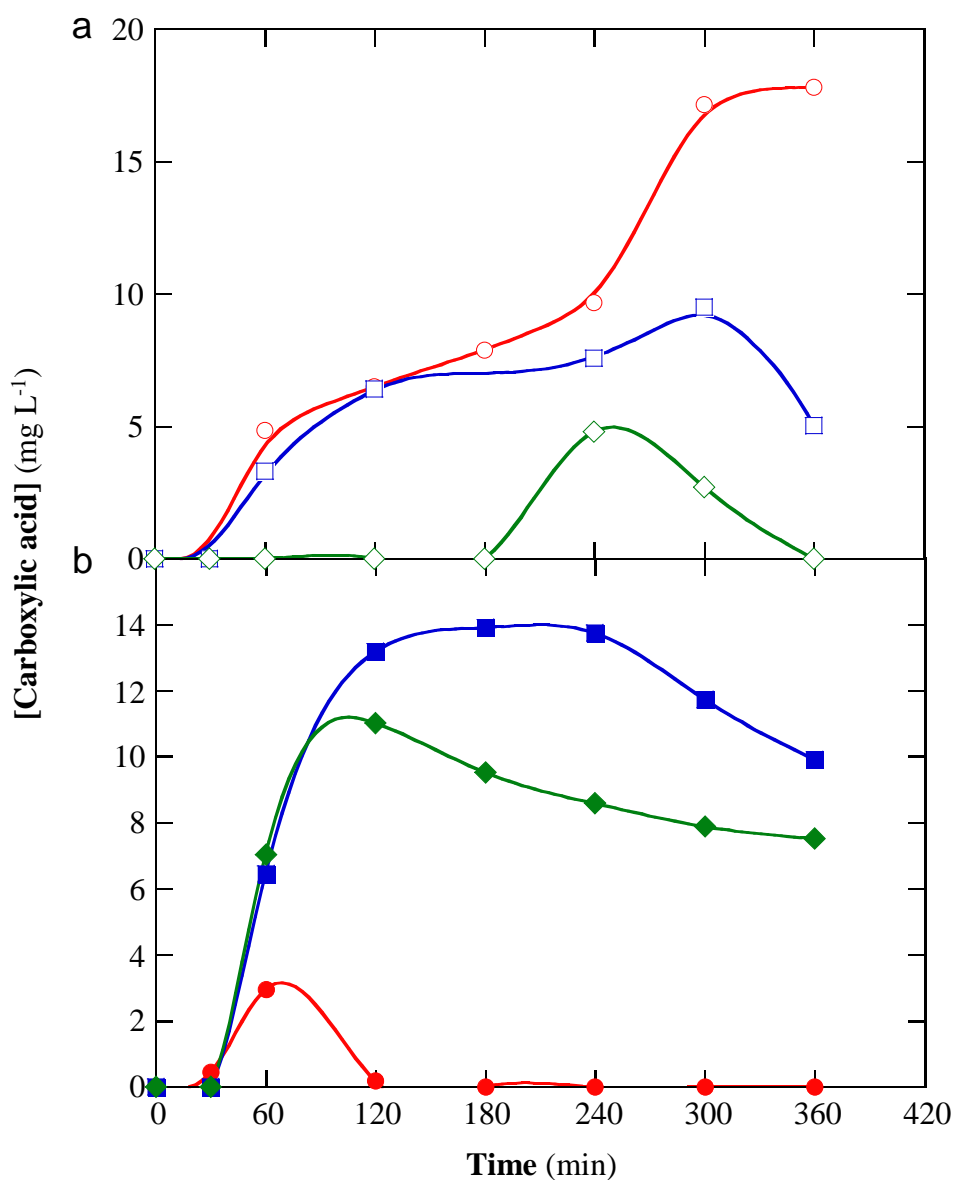
**Fig. 4.** Change of (a) percentage of mineralization current efficiency and (b) energy consumption per unit TOC mass with electrolysis time for the experiments of Fig. 3a. Method: (○) EO-H<sub>2</sub>O<sub>2</sub>, (□) EF and (▲) PEF.



**Fig. 5.** Effect of current density on the time course of (a) normalized TOC, (b) percentage of mineralization current efficiency and (c) energy consumption per unit TOC mass for the PEF treatment of 2.5 L of a 0.320 mM procaine hydrochloride solution with 0.050 M Na<sub>2</sub>SO<sub>4</sub> and 0.50 mM Fe<sup>2+</sup> at pH 3.0 and 35 °C using a pre-pilot flow plant with a BDD/air-diffusion cell at liquid flow rate of 180 L h<sup>-1</sup>. Applied  $j$ : (▲) 33.3 mA cm<sup>-2</sup>, (■) 66.7 mA cm<sup>-2</sup> and (●) 100 mA cm<sup>-2</sup>.

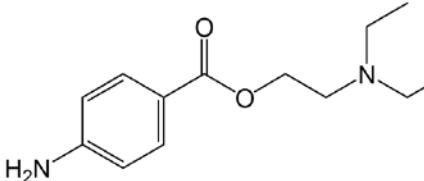
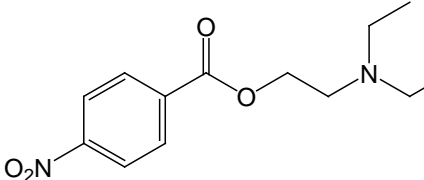
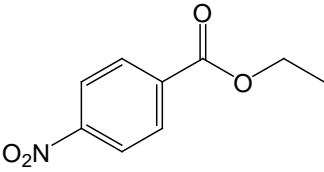


**Fig. 6.** Influence of drug concentration on the time course of (a) normalized TOC, (b) percentage of mineralization current efficiency and (c) energy consumption per unit TOC mass for the PEF treatment of 2.5 L of procaine hydrochloride solutions with 0.050 M Na<sub>2</sub>SO<sub>4</sub> and 0.50 mM Fe<sup>2+</sup> at pH 3.0 and 35 °C using a pre-pilot flow plant with a BDD/air-diffusion cell at  $j = 33.3 \text{ mA cm}^{-2}$  and liquid flow rate of 180 L h<sup>-1</sup>. Drug content: (▼) 0.064 mM, (◆) 0.160 mM and (▲) 0.320 mM.



**Fig. 7.** Change of the concentration of (○,●) oxalic, (□,■) formic and (◇,◆) acetic acids detected during the (a) EF and (b) PEF treatments of 2.5 L of 0.320 mM procaine hydrochloride solutions with 0.050 M Na<sub>2</sub>SO<sub>4</sub> and 0.50 mM Fe<sup>2+</sup> at pH 3.0 and 35 °C using a pre-pilot flow plant with a BDD/air-diffusion cell at  $j = 33.3 \text{ mA cm}^{-2}$  and liquid flow rate of 180 L h<sup>-1</sup>.

**Table 1.** Characteristics of the aromatic compounds detected by GC-MS with a non-polar column during the EO-H<sub>2</sub>O<sub>2</sub> treatment of 2.5 L of a 0.320 mM procaine hydrochloride solution in 0.050 M Na<sub>2</sub>SO<sub>4</sub> at pH 3.0 and 35 °C using a pre-pilot flow plant with a BDD/air diffusion cell at  $j = 33.3 \text{ mA cm}^{-2}$  and liquid flow rate of 180 L h<sup>-1</sup>.

Number	Chemical name	Molecular structure	Retention time (min)	Main fragmentation ions ( $m/z$ )
1	2-(Diethylamino)ethyl-4-aminobenzoate (Procaine)		36.92	235, 164, 137, 120, 99, 86
2	2-(Diethylamino)ethyl-4-nitrobenzoate		35.88	266, 194, 150, 120, 86, 76
3	Ethyl-4-nitrobenzoate		38.95	195, 150, 120, 104, 92, 76