

25 mineralization, TOC removal higher than 90 % can be achieved but higher applied
26 electric charges than those required for disinfection have to be applied (around 30 kAh
27 m⁻³).

28 **Keywords:** disinfection; electrolysis; *E. coli*; *P. aeruginosa*; diamond

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34 **Highlights**

35 - *E. coli* and *P. aeruginosa* are completely removed by electrolysis with BDD
36 anodes.

37 - Electrogenerated oxidants are the main responsible of the disinfection process.

38 - High efficiencies for microorganisms and organics removal are obtained at low
39 current densities.

40 - Mineralization higher than 90 % is attained after passing 30 kAh m⁻³.

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50 **1. Introduction.**

51 In last decades, electrochemical disinfection has been widely studied for the treatment of
52 drinking water and reclaimed wastewater (secondary effluents coming from Wastewater
53 Treatment Plants, WWTPs) [1-3]. Specifically, this technology has been proven very
54 efficient for the removal of the *Escherichia coli* (*E. coli*) contained in these effluents,
55 because of the electrochemical production of disinfectants from the oxidation of ions
56 naturally contained in water [4-9]. For this reason, it was not necessary the addition of
57 chemicals to carry out an efficient treatment as occur during conventional disinfection
58 processes and, therefore, the main physical-chemical characteristics of water and
59 wastewater were not significantly altered [10].

60 One of the keys in electrochemical disinfection is the choice of a suitable electrode that
61 favors the potential production of disinfectant species. In this context, Boron Doped
62 Diamond (BDD) can be considered as an appropriate anode material because it allows to
63 generate large amounts of these species in-situ, favoring the disinfection processes, even
64 at low applied electric charges and current densities [11-15]. Likewise, these electrodes
65 promote the generation of significant amounts of hydroxyl radicals by means of water
66 oxidation [16]. These species have a high oxidant capacity which may contribute to the
67 disinfection processes. Therefore, the use of BDD anodes does not only favor efficient
68 disinfection processes but also helps to decrease the energy consumption in the
69 disinfection of water and reclaimed wastewater [17].

70 On the other hand, more recently, the scientific community has begun to focus attention
71 on the disinfection of urine in hospitals and other facilities [18-21]. An important volume
72 of these urines may present high pathogenicity, associated to different diseases and this
73 is becoming a key point because of the appearance of antibiotic-resistant bacteria. In this
74 context, the World Health Organization (WHO) has recently reported a priority list of

75 antibiotic-resistant bacteria and, as an example, WHO considers *Pseudomonas*
76 *aeruginosa* as priority 1 (critical), *Staphylococcus aureus* as priority 2 (high) or
77 *Streptococcus pneumoniae* as priority 3 (medium). Therefore, hospital effluents should
78 be also properly treated in order to preserve not only the human health but also the
79 environment, because there is no currently legislation for this type of hazardous effluents.
80 In literature, it has been recently reported the disinfection of human urine with BDD
81 anodes. Specifically, Raut et al. have studied the removal of *E. coli* in human urine for
82 water-free and additive-free toilets by electrolysis [22]. They evaluated the elimination
83 of microorganisms at different cell voltages (4-12 V), finding that it was possible to attain
84 a complete disinfection at operation times lower than 1 hour. The higher voltage led to
85 the higher removal rate of *E. coli* due to the generation of large amounts of free chlorine.
86 They also evaluated the removal of microorganisms in human urine with fecal pollution
87 at 6 V and they demonstrated that the presence of high concentration of fecal matter was
88 negative for disinfection efficiency. However, the evolution of the organics from urine
89 was not studied in that work. This is an important point taking into account that the
90 electrogenerated free chlorine can react with these organics, favoring the formation of
91 hazardous organochlorinated compounds.

92 With this background, the main aim of the present work is to evaluate the disinfection of
93 urine that can be typically found in hospital wastewater by electrolysis with diamond
94 electrodes, paying special attention not only to the removal of microorganisms but also
95 to the evolution of organics present in wastewater. To do this, synthetic urine was polluted
96 with *E. coli* and, also, *P. aeruginosa*. The last one has been selected because it is one of
97 the bacteria reported by WHO as critical priority, while the first one is the most common
98 indicator of fecal pollution and it is the most frequent pathogen in urine. The influence of

99 the current density (0-100 A m⁻²) has been studied because this parameter is expected to
100 influence on the electrochemical process efficiency.

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102 **2. Material and methods.**

103 **2.1. Chemicals and microorganisms.**

104 Urea, creatinine, uric acid, potassium chloride, magnesium sulfate, calcium phosphate,
105 sodium carbonate and diammonium hydrogen phosphate were analytical grade and used
106 as received (Sigma Aldrich, Spain). Acetonitrile and formic acid HPLC grade (Sigma
107 Aldrich, Spain) were used for the mobile phase to determine uric acid. p-
108 dimethylaminobenzaldehyde and hydrochloric acid (Sigma Aldrich, Spain) were
109 analytical grade and used for the determination of urea concentration. Acetone, 2,6-
110 pyridinedicarboxylic acid and nitric acid (Sigma Aldrich, Spain) were used for the mobile
111 phase to determine creatinine and ions concentration. Double deionized water (Millipore
112 Milli-Q system, resistivity: 18.2 MΩ cm at 25°C) was used to prepare all solutions.

113 The bacterial strains used in this work were *E. coli* ATCC 25922 and *P. aeruginosa*
114 NCIMB 8626 (CECT, Spain).

115 **2.2. Analytical techniques.**

116 The concentration of *E. coli* and *P. aeruginosa* was estimated by filtration with membrane
117 according to ISO 9308-1 and ISO 16266, respectively. Sodium thiosulphate was added to
118 the samples for the determination of microorganisms in order to avoid their death by the
119 attack of the electrogenerated oxidants after the treatment. Measurements were done in
120 triplicate. Samples were diluted with 0.9 % NaCl aqueous solution and 50 cm³ were
121 filtered by 0.45 μm. Then, membranes were spread in plates with selective agar for each

122 microorganism (Scharlau, Spain) and were incubated at 37°C during 24 h. Finally,
123 colonies were counted.

124 Uric acid concentration was measured by chromatography using an Agilent 1200 series
125 chromatograph equipped with a DAD detector and a ZORBAX Eclipse Plus C18
126 analytical column. The mobile phase consisted of 98:2 v/v aqueous solution with 0.1 %
127 of formic acid/acetonitrile (flow rate: 1 cm³ min⁻¹). The DAD detection wavelength was
128 235 nm, the temperature was kept at 25°C and the injection volume was 10 µL. Urea
129 concentration was determined by a spectrophotometric method using the Cary Series UV-
130 Vis Spectrophotometer (Agilent Technologies). It is based on the yellow-green color
131 produced when p-dimethylaminobenzaldehyde is added to urea in dilute hydrochloric
132 acid solution [23]. The concentration of trihalomethanes (THMs) was measured by gas
133 chromatography using a Young Lin GC 6100 series chromatograph equipped with an
134 ECD detector and a SPB-5 column (30m x 0.25mm). Nitrogen was used as carrier gas
135 and the temperature ramp was 50°C for 5 min, 6°C min⁻¹ up to 150°C and hold time 5
136 minutes. The injection volume was 1 µL.

137 Total Organic Carbon (TOC) was monitored using a Multi N/C 3100 Analytik Jena
138 analyzer. Inorganic ions were measured by ion chromatography using a Metrohm 930
139 Compact IC Flex coupled to a conductivity detector. A Metrosep A Supp 7 column was
140 used to determine the anions and a Metrosep A Supp 4 column was used to analyze the
141 cations. The mobile phase consisted of 85:15 v/v 3.6 mM Na₂CO₃/acetone solution for
142 the determination of anions (flowrate: 0.80 cm³ min⁻¹) and 1.7 mM HNO₃ and 1.7 mM
143 2,6-pyridinedicarboxylic acid solution for the determination of cations (flowrate: 0.90
144 cm³ min⁻¹). The temperature of the oven was 45 and 30°C for the determination of anions
145 and cations, respectively. The volume injection was 20 µL. The same system of cations
146 determination was used for the quantification of creatinine concentration. Oxidants were

147 determined iodometrically according to Kolthoff & Carr [24]. The pH and conductivity
148 were measured using a CRISON pH25+ and CRISON CM35+, respectively

149 **2.3. Experimental procedure.**

150 Electrolyses were carried out in a single compartment electrochemical cell working under
151 batch-operation mode [25]. Circular boron doped diamond (BDD) plates (purchased from
152 WaterDiam, France) with a geometric area of 78 cm² were used as electrodes, and the
153 inter-electrode gap between both electrodes was 9 mm. A Delta Electronika ES030-10
154 power supply (0-30V, 0-10A) provided the electric current.

155 All experiments were carried out under galvanostatic conditions and the current densities
156 applied were within the range 0-100 A m⁻². The synthetic urine was stored in a glass tank
157 (1 dm⁻³) and its composition is detailed in Table 1.

158 **Table 1.** Synthetic urine composition.

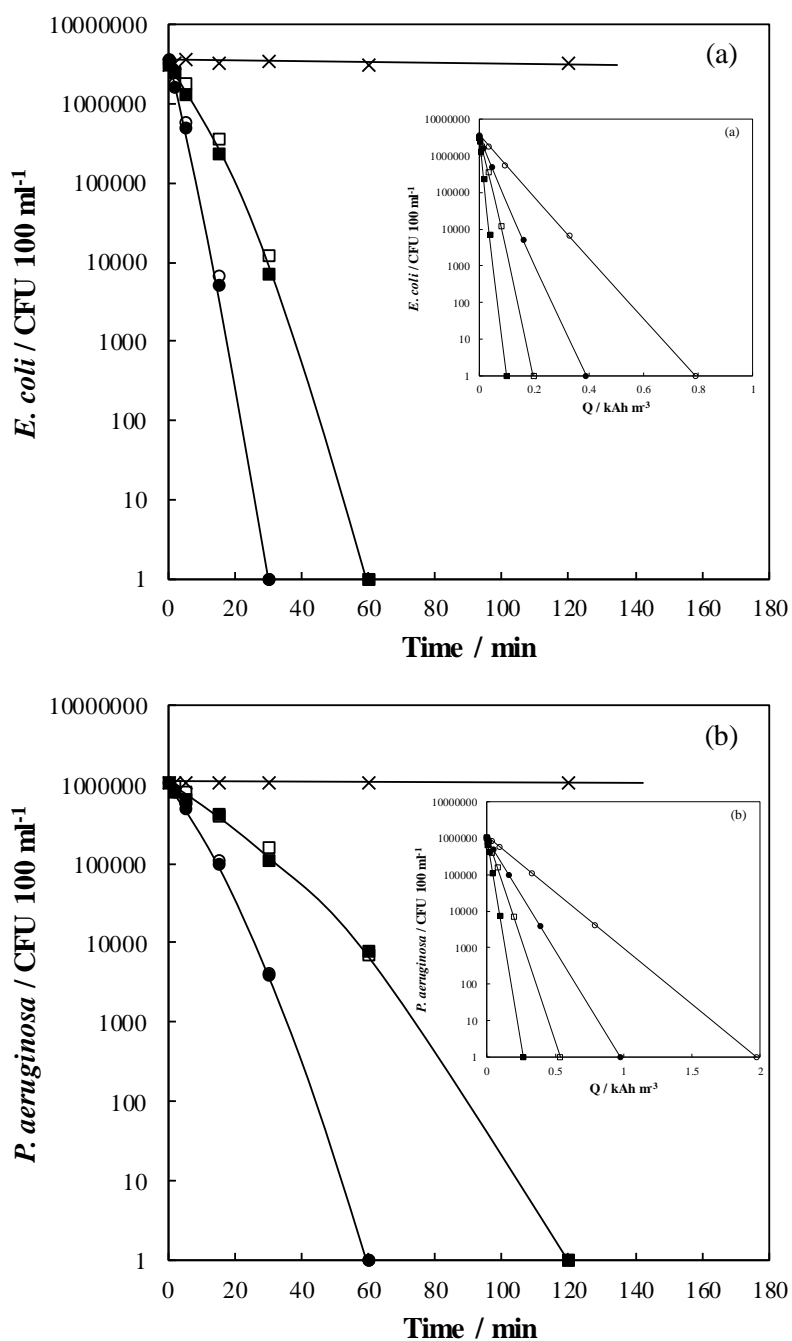
Compound	Concentration (mg dm⁻³)
CH ₄ N ₂ O	3333.34
C ₄ H ₇ N ₃ O	166.67
C ₅ H ₄ N ₄ O ₃	50.00
KCl	1000.00
MgSO ₄	170.00
(Ca) ₃ (PO ₄) ₂	28.34
Na ₂ CO ₃	166.67
(NH ₄) ₂ HPO ₄	83.34

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160

161 **3. Results and discussion.**

162 Figure 1 shows changes in concentration of *E. coli* (Figure 1a) and *P. aeruginosa* (Figure
163 1b) with the operation time and the applied electric charge (onset) during the
164 electrochemical disinfection of synthetic urine using diamond electrodes.



165

166 **Figure 1.** Variation of microorganisms as function of the operation time and the applied
167 electric charge during the electrochemical disinfection of synthetic urine with diamond

168 electrodes. (a) *E. coli*; (b) *P. aeruginosa*; (x) 0 A m⁻²; (■) 5 A m⁻²; (□) 10 A m⁻²; (●) 50
169 A m⁻²; (○) 100 A m⁻².

170 As it can be observed, the concentration of both microorganisms remains constant during
171 the reference test (process without electric power). These results reveal that the complex
172 matrix of synthetic urine (inorganic and organic compounds) does not affect to *E. coli*
173 and *P. aeruginosa* concentration within the experimental period evaluated. On the
174 contrary, it is possible to attain a complete disinfection of the urine for all the tests carried
175 out applying current densities within the range 5-100 A m⁻². Nonetheless, the process is
176 clearly influenced by this parameter and the initial bacteria concentration. In this context,
177 the removal rate of both microorganisms increases when working at current densities
178 higher than 50 A m⁻². Opposite to that, if results are plotted against the electric charge
179 (onset), it can be seen that the disinfection efficiency increases when the current density
180 decreases. Specifically, the highest efficiency is achieved at 5 A m⁻² for both *E. coli* and
181 *P. aeruginosa* removal. This is an expected behavior in electrochemical processes which
182 are typically more efficient at lower current densities because of the prevention of side
183 reactions at these softer operation conditions [26].

184 On the other hand, it is important to point out that the removal of *E. coli* is faster than that
185 obtained for *P. aeruginosa*, despite the concentration of the first one is higher.
186 Specifically, *E. coli* is depleted before 60 minutes for all the current densities studied
187 whereas *P. aeruginosa* requires operation times higher than 60 minutes to achieve a
188 complete removal. This fact may be directly related to the higher initial concentration of
189 *E. coli* present in the urine. Likewise, *P. aeruginosa* could give more resistance to the
190 electrochemical treatment due to its characteristics since it is important to highlight that
191 this bacterium is considered as antibiotic-resistant bacteria.

192 For comparison purposes, the results obtained for both microorganisms were fitted to first
 193 order kinetics and the resulting constants (k) are presented in Table 2. These values clearly
 194 reveal the rapid removal of *E. coli* in comparison with *P. aeruginosa*.

195 **Table 2.** Kinetic constants for the electrochemical disinfection with BDD anodes.

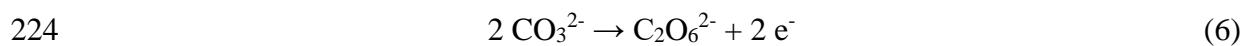
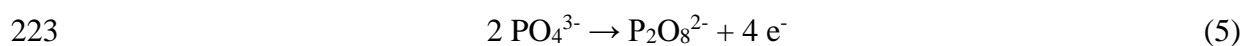
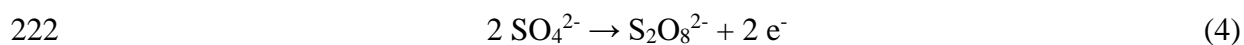
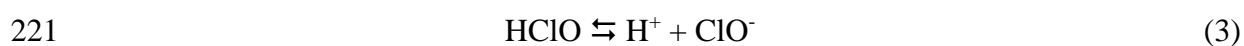
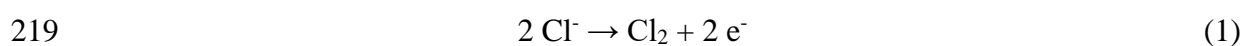
Microorganism	j (A m ⁻²)	k (min ⁻¹)
<i>E. coli</i>	5	0.1956
	10	0.1768
	50	0.4314
	100	0.4055
<i>P. aeruginosa</i>	5	0.0802
	10	0.0785
	50	0.1803
	100	0.1757

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197 The kinetic constants calculated for the *E. coli* are approximately two times the values
 198 obtained for the *P. aeruginosa*. Hence, the higher initial concentration of microorganisms,
 199 the higher is the removal rate. On the other hand, it can be seen that the resulting constants
 200 for low (5 and 10 A m⁻²) and high (50 and 100 A m⁻²) current densities are similar between
 201 them for each microorganism. Furthermore, the values for 50 and 100 Am⁻² are about two
 202 times higher than that obtained during the electrochemical disinfection at 5 and 10 A m⁻²,
 203 regardless the bacteria studied.

204 According to literature, the removal of microorganisms may take place by different
 205 mechanisms during the electrochemical treatment: direct and mediated disinfection.
 206 During the first one, an electroadsorption of microorganisms takes place on the electrode

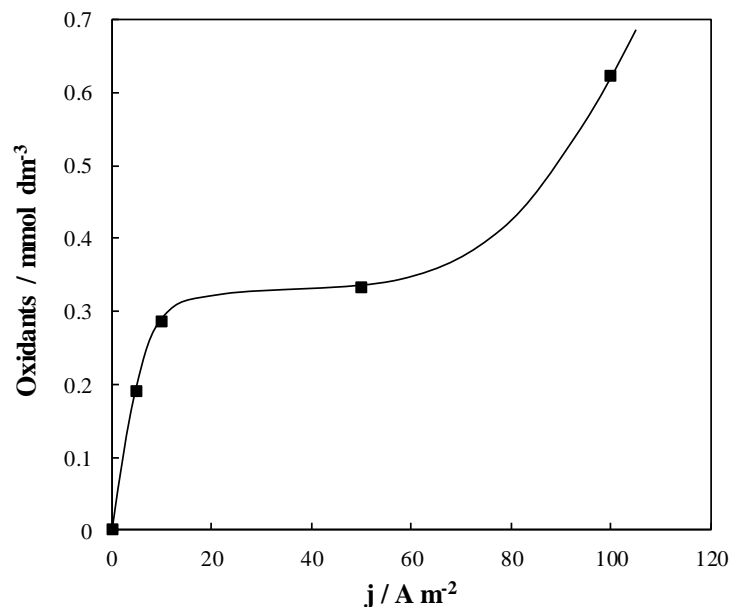
207 surface, causing their death by electrocution. However, this mechanism is expected in
 208 porous materials such as carbon felt, foams, cloth [27] and, therefore, it can be discarded
 209 for the electrochemical disinfection with diamond electrodes. The second mechanism,
 210 indirect disinfection, consists of the attack of disinfectant species (usually chlorine
 211 derivatives) to microorganisms contained in wastewater. These species can be directly
 212 added to the effluent or be generated in situ during the treatment [28-30]. In this context,
 213 the composition of the synthetic urine used in this work presents large amounts of
 214 chlorides which can be electrooxidized, favoring the production of chlorine and
 215 hypochlorite [Eqs. (1)-(3)] [4, 31]. Furthermore, other ions can be found in synthetic urine
 216 (sulfate, phosphate, carbonate,...) which can be also electrochemically oxidized,
 217 generating powerful oxidants such as persulfate [Eq. (4)], peroxodiphosphate [Eq. (5)]
 218 and percarbonate [Eq. (6)] [32].



225 These compounds can significantly contribute to the removal of the pathogens contained
 226 in urine. Figure 2 shows the oxidants electrogenerated at the end of the electrochemical
 227 disinfection of synthetic urine as function of the applied current density.

228 As it can be observed, the concentration of oxidants increases with the applied current
 229 density. This behavior may be directly related to the higher removal rate of
 230 microorganisms when working at higher current densities (Figure 1). Hence, the higher

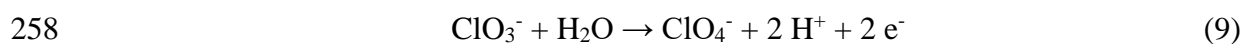
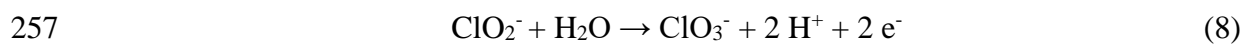
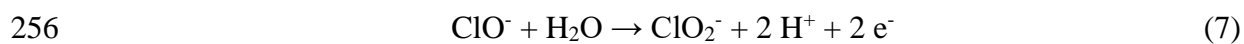
231 the concentration of oxidants produced, the higher is the removal rate of microorganisms.
232 On the other hand, it is important to point out that the cocktail of oxidants
233 electrogenerated during the treatment of synthetic urine leads to a more efficient
234 disinfection process than that observed, for example, during the disinfection of secondary
235 effluents from Wastewater Treatment Plants (WWTP) [14]. In that case, the disinfection
236 is mainly produced by the generation of chlorine disinfectants because of chloride is the
237 primary ion contained in those effluents whereas the concentration of others such as
238 phosphate, or sulfate is negligible. Therefore, the presence of other ions in urine and,
239 consequently, in hospital effluents may significantly contribute to a more efficient
240 disinfection. This has been also recently reported by the authors for the efficiency of the
241 electro-oxidation during the treatment of soil washing effluents [33]. Finally, the results
242 obtained shows that the final concentration of oxidants at 10 and 50 A m^{-2} are very similar.
243 This suggests that these species are wasted not only in disinfection but also in other
244 oxidation processes when working at current densities higher than 50 A m^{-2} .

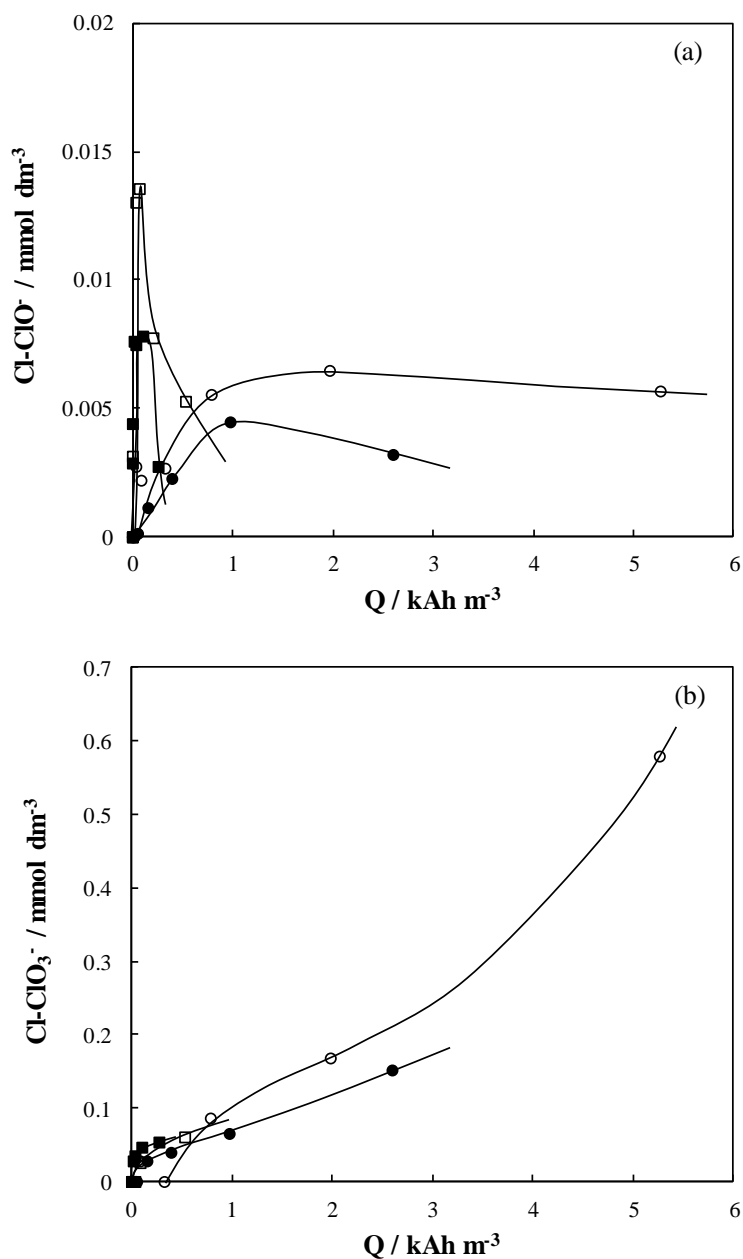


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246 **Figure 2.** Final concentration of oxidants electrogenerated as function of the current
247 density during the electrochemical disinfection of synthetic urine with diamond
248 electrodes.

249 The electrooxidation of chlorides contained in the synthetic urine ($[\text{Cl}^-]_0$: 475.53 mg dm⁻³)
250 ³) does not only lead to the generation of hypochlorite during electrolysis with diamond
251 anodes but, unfortunately, it is also possible to produce electrochemically other chlorine
252 compounds in high oxidation state such as chlorate and perchlorate [Eqs. (7)-(9)] [34,
253 35]. These species are harmful to human health and environment, and hence, they should
254 be avoided. For this reason, the concentration of chlorine compounds was monitored
255 during the process and results are shown in Figure 3.





259

260 **Figure 3.** Inorganic chlorine speciation during the electrochemical disinfection of
 261 synthetic urine with diamond anodes. (a) ClO⁻; (b) ClO₃⁻; (■) 5 A m⁻²; (□) 10 A m⁻²; (●)
 262 50 A m⁻²; (○) 100 A m⁻².

263 As expected, the concentration of hypochlorite (Figure 3a) increases with the applied
 264 electric charge during all the tests carried out, regardless the current density applied. The
 265 trend observed clearly indicates that there are two different zones: an initial increase
 266 followed by a further decrease. The first one (increase) is due to the electrolysis of

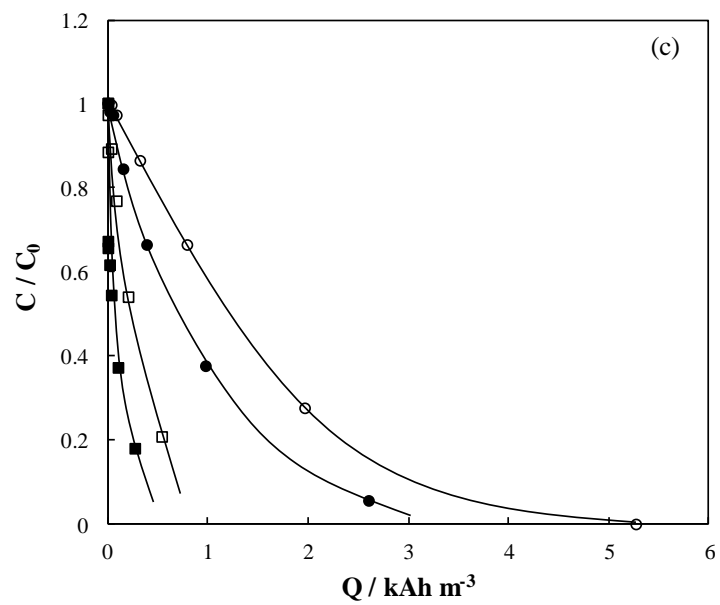
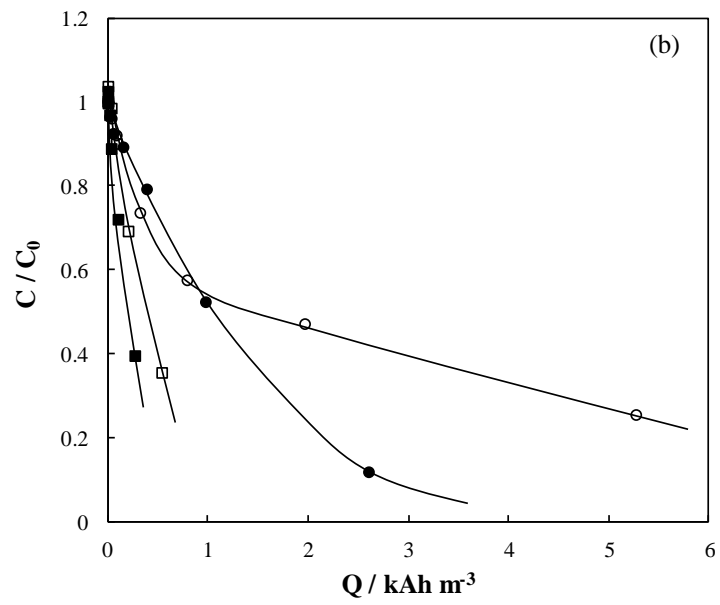
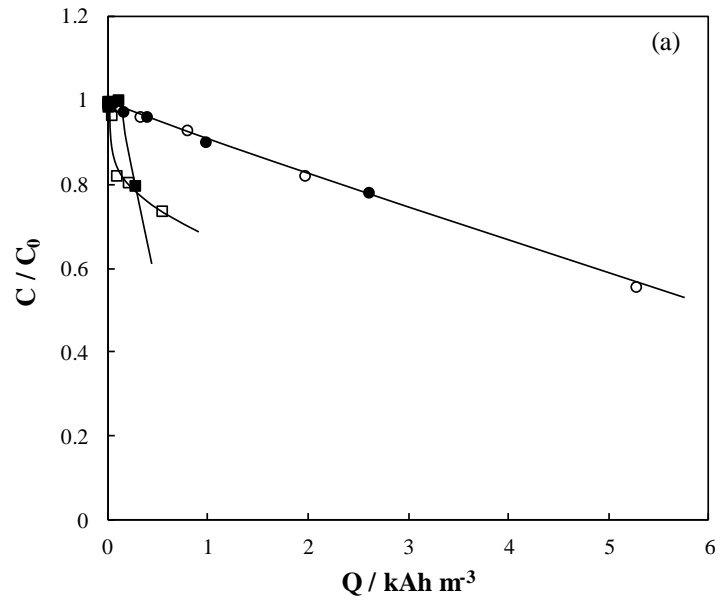
267 chlorides present in synthetic urine [Eqs. (1)-(3)] and the decrease observed is related to
268 different processes that can take place simultaneously during the electrochemical
269 treatment:

- 270 - The promotion of hypochlorite to other chlorine compounds in higher oxidation
271 state [Eqs. (7)-(9)].
- 272 - The reaction of hypochlorite with other compounds contained in the effluent,
273 including microorganisms.

274 The evolution of chlorine compounds in higher oxidation state than hypochlorite is
275 presented in Figure 3b, specifically, the concentration of chlorate. At this point it is
276 important to highlight that the presence of perchlorate was not detected for all the tests
277 carried out. This fact can be explained in terms of the low current densities used in this
278 work in comparison to those required for the electrochemical production of perchlorates
279 with diamond anodes [36].

280 As it can be seen, the concentration of chlorate increases with the applied electric charge,
281 being significantly influenced by the current density: the higher current density, the
282 higher concentration of chlorate. This result indicates that the production of this
283 compound takes mainly place by an electrochemical process. At low current densities,
284 the maximum concentration of chlorate reached was 0.054 (5 A m^{-2}) and 0.060 (10 A m^{-2})
285 mmol Cl dm^{-3} whereas 0.151 and 0.579 mmol Cl dm^{-3} were obtained when working at
286 50 and 100 A m^{-2} , respectively. These latter data (high current densities) are more
287 negative due to their high concentrations ($> 0.1 \text{ mmol Cl dm}^{-3}$) and could limit the
288 application of electrolysis with diamond anodes for the disinfection of hospital effluents.
289 Nonetheless, the applied electric charge required to attain these values are higher than
290 those necessary to completely disinfect the effluent and, hence, the potential production
291 of these hazardous chlorine compounds could be avoided.

292 The second process that could explain the decrease observed in hypochlorite
293 concentration is its reaction with other compounds present in the effluent. In this context,
294 urine matrix contains different organics which are susceptible to react with hypochlorite
295 and with other electrogenerated oxidants. For this reason, the concentration of urine-
296 organic-compounds was monitored during the process. It is important to pay attention to
297 the evolution of these compounds not only for their possible reaction with hypochlorite
298 but also because, as organics, it is necessary to decrease their concentration in the
299 effluents. Thus, Figure 4 shows the concentration of urea, creatinine and uric acid with
300 the applied electric charge during the electrolysis of synthetic urine with diamond anodes.
301 As it can be observed, the concentration of organics decreases with the applied electric
302 charge for all the current densities studied. However, as previously commented on
303 disinfection (Figure 1), the process efficiency is higher when working at low current
304 densities [26]. On the other hand, the removal rate is higher in uric acid followed by
305 creatinine and, finally, urea.

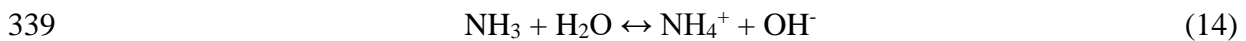
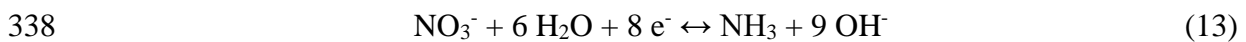
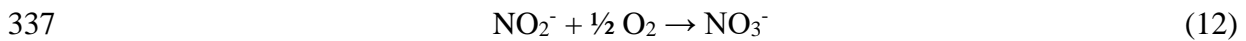
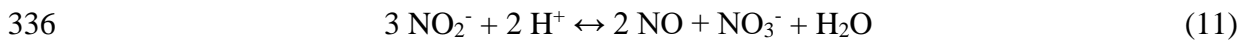
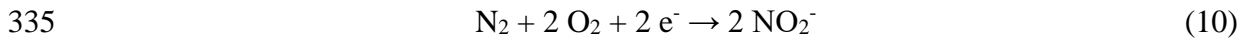


307 **Figure 4.** Influence of the current density on organic compounds during the
308 electrochemical disinfection of synthetic urine with diamond anodes. (a) urea; (b)
309 creatinine; (c) uric acid; (■) 5 A m⁻²; (□) 10 A m⁻²; (●) 50 A m⁻²; (○) 100 A m⁻².

310 This fact may be related to the different initial concentration of each one in urine: the
311 concentration of uric acid and creatinine is about 67 and 20 times lower than that of urea,
312 respectively. These results disagree the previous obtained for microorganisms removal
313 where the higher concentration of *E. coli* as compared to *P. Aeruginosa* led to the higher
314 disinfection efficiency. Nevertheless, in this case, the differences between both
315 microorganisms was only around 3 times (Figure 1). Regarding the data obtained at the
316 applied electric charges in this work (j: 5 A m⁻²; Q_{max}: 0.267 kAh m⁻³; j: 10 A m⁻²; Q_{max}:
317 0.533 kAh m⁻³; j: 50 A m⁻²; Q_{max}: 2.6 kAh m⁻³; j: 100 A m⁻²; Q_{max}: 5.267 kAh m⁻³), it is
318 possible to completely remove the concentration of uric acid at 100 A m⁻² (Figure 4c).
319 Nonetheless, the trend observed for the other current densities suggests that a complete
320 removal of this organic would be attained. Likewise, the same behavior can be observed
321 in the evolution of creatinine for all the current densities studied (Figure 4b). Finally, the
322 urea concentration seems to require higher electric charges to attain a noteworthy
323 decrease at these current densities (5-100 A m⁻²) due to its higher concentration in
324 synthetic urine. Specifically, the maximum removal rate was 20.2, 26.2, 21.8 and 44.40
325 % for 5, 10, 50 and 100 A m⁻², respectively (Figure 4a).

326 The organics present in synthetic urine contains nitrogen atoms in their structure which
327 can be released during the electrolysis. In the literature, it has been described that nitrogen
328 from organics is initially oxidized to nitrite [Eq. (10)] [37, 38]. Then, this species is
329 rapidly transformed into nitrate [Eqs. (11) and (12)] and, finally, this last one can be
330 electrochemically reduced over the cathode surface, favoring the production of
331 ammonium [Eqs. (13) and (14)] [39]. To confirm that this applies to urine electrolysis,

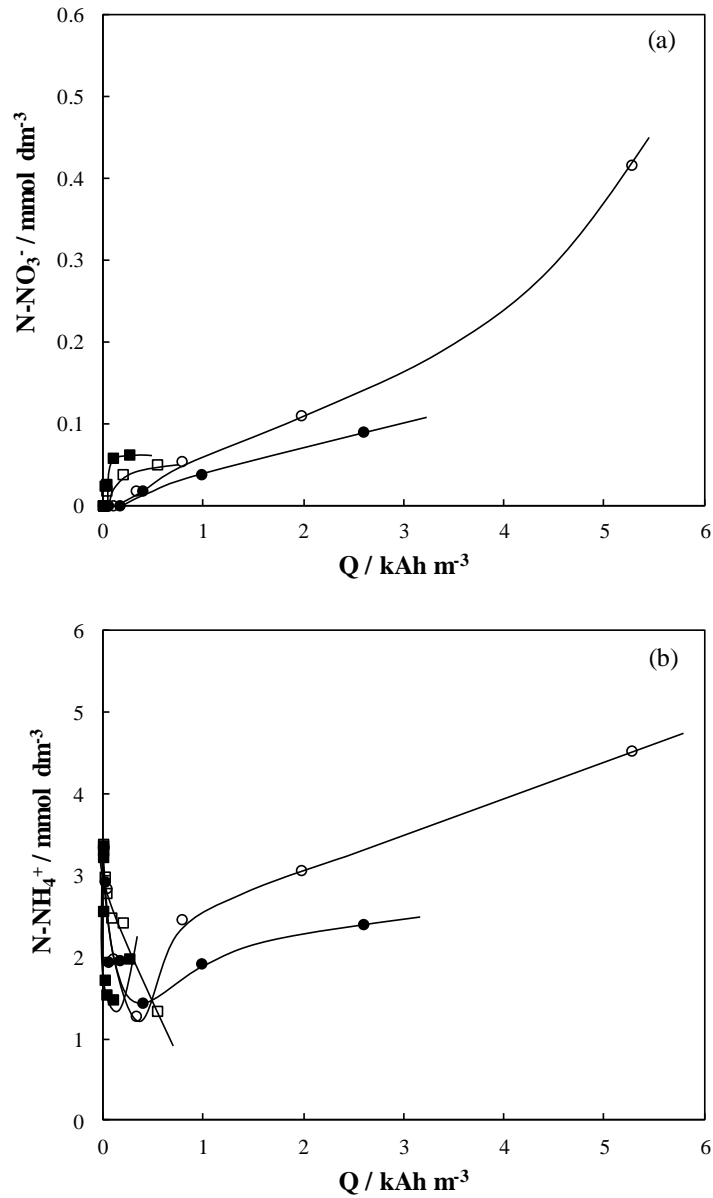
332 the evolution of nitrate and ammonium was monitored during the electrochemical
333 disinfection. Nitrites were not detected during the whole process, probably because of its
334 fast reaction to nitrates and, therefore, they are not shown.



340 Figure 5 shows the concentration of inorganic nitrogen compounds with the applied
341 electric charge during the electrochemical disinfection of synthetic urine at different
342 current densities. As it can be observed, the concentration of nitrates increases for all the
343 current densities (Figure 5a). However, the values obtained are not very high and, it is
344 necessary to apply 100 A m^{-2} to attain concentrations higher than $0.1 \text{ mmol N dm}^{-3}$. These
345 results agree the previous obtained in the evolution of urine organic compounds (Figure
346 4) where the maximum current density led to the higher removal of urea, creatinine and
347 uric acid and, hence, the maximum release of inorganic nitrogen.

348 On the other hand, the low nitrate concentration can also be related to its evolution to
349 ammonium on the cathode surface (electro-reduction). Thus, the concentration of this
350 species is shown in Part b of Figure 5. It is important to highlight that the initial
351 concentration of ammonium is not zero because it is a component of the raw synthetic
352 urine as $(\text{NH}_4)_2\text{HPO}_4$ (C_0 : 83.34 mg dm^{-3}). Ammonium ions decrease at the beginning of
353 the treatment until reach electric charges around 0.5 kAh m^{-3} from which their
354 concentration starts to increase, regardless the current density applied. This behavior
355 suggests that this species could initially react with others present in urine since the direct

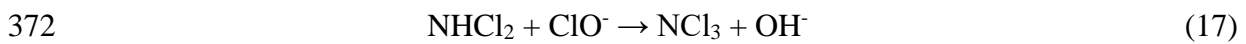
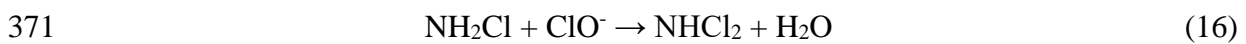
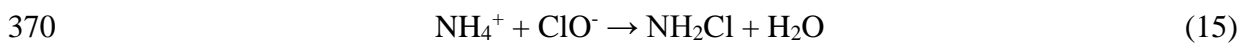
356 oxidation of ammonium with BDD electrolysis is known to be not favored [40]. In this
 357 context, the presence of chlorine compounds in high oxidation state (Figure 3) during the
 358 process can play a key role in the evolution of ammonium, specifically, hypochlorite.



359

360 **Figure 5.** Nitrogen speciation as function of applied electric charge during the
 361 electrochemical disinfection of synthetic urine with diamond anodes. (a) NO₃⁻; (b) NH₄⁺;
 362 (■) 5 A m⁻²; (□) 10 A m⁻²; (●) 50 A m⁻²; (○) 100 A m⁻²

363 Hypochlorite is well known to react with ammonium, favoring the production of
364 combined chlorine commonly called chloramines [Eqs. (15)-(17)]. These species also
365 contribute to the disinfection processes but they are less aggressive than hypochlorite
366 [12]. For this reason, the concentration of chloramines was measured for all the tests
367 carried out, finding zero values of these species in the effluents. This means that they
368 have reacted with microorganisms and other organics present in wastewater, favoring
369 their degradation.

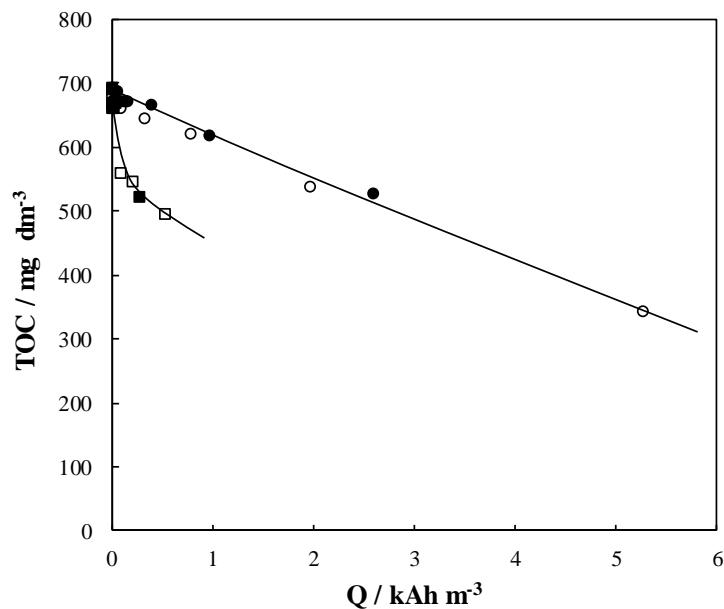


373 At higher electric charges, the concentration of ammonium significantly increases,
374 reaching final values higher than the initial concentration present in synthetic urine. For
375 example, at 100 A m⁻² the initial and final values were 60.5 mg dm⁻³ 81.3 mg dm⁻³,
376 respectively. This fact can be explained in terms of the higher release of nitrogen from
377 the organics at these charges, which allows not only the formation of chloramines but also
378 the production of a remaining effluent with high levels of free ammonium.

379 The electrolysis of urea, creatinine and uric acid can lead to the formation of other
380 intermediates that can be even more hazardous. Some of the most harmful organic
381 intermediate compounds which can be formed during the electrochemical disinfection in
382 presence of free chlorine are THMs. These are generated by the reaction between
383 hypochlorite and the organic matter contained in wastewater. The main THMs established
384 by WHO are CH₃Cl, CHBrCl₂, CHBr₂Cl and CH₃Br. Therefore, the concentration of
385 these compounds was monitored during the process and results show that only chloroform
386 (CH₃Cl) was generated, finding a maximum concentration of 0.036 μg dm⁻³ of this

387 compound at 5 A m^{-2} . This value is much lower than that established by WHO for
388 drinking water (0.3 mg dm^{-3}) [41]. Nonetheless, the final concentration reached of CH_3Cl
389 was null for this current density. This suggests that THMs are not persistent during the
390 disinfection of synthetic urine with diamond electrodes at low current densities. Likewise,
391 the concentration of this compound was also null for the current densities within the range
392 $10\text{-}100 \text{ A m}^{-2}$.

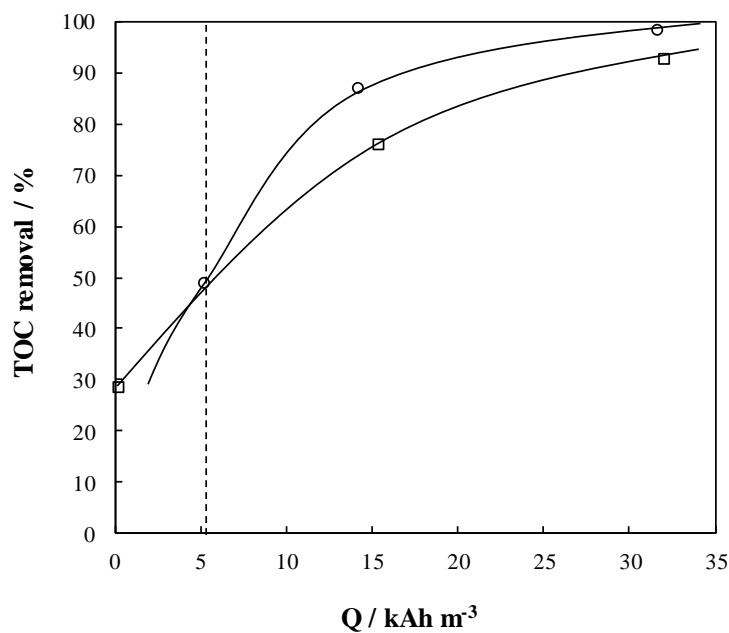
393 Furthermore, it is necessary to control all the organic matter present in the system. For
394 that, the total organic carbon (TOC) was also measured during the process. This parameter
395 informs about the complete mineralization of the organic matter contained in the effluent.
396 Figure 6 shows changes in TOC concentration with the applied electric charge during the
397 electrochemical disinfection at different current densities. As it can be observed, TOC
398 decreases with the applied electric charge for all the tests carried out. The efficiency is
399 higher when working at current densities lower than 10 A m^{-2} . These results agree the
400 previous obtained on the removal of microorganism (Figure 1) and organics (Figure 4).



401

402 **Figure 6.** TOC depletion as function of the applied electric charge during the
403 electrochemical disinfection of synthetic urine with diamond anodes. (■) 5 A m⁻²; (□) 10
404 A m⁻²; (●) 50 A m⁻², (○) 100 A m⁻².

405 The maximum TOC concentration removed was around 25 % for current densities lower
406 than 50 A m⁻² whereas 50 % removal was attained when applying 100 A m⁻². Therefore,
407 it is not possible to achieve a complete mineralization of the organic matter contained in
408 the effluent with the electrolysis charges applied. The trend observed in TOC is similar
409 to the shown for urea concentration (Figure 4a) and this is easily explained taking into
410 account that urea is the primary organic in urine and hence it is the main species that
411 contributes to the TOC concentration. Finally, TOC data suggest that an increase in the
412 applied electric charge at these current densities could lead to a complete removal of the
413 organic matter. To check this, the electrochemical disinfection of a synthetic urine was
414 carried out at the two different current densities previously used: 10 and 100 A m⁻². After
415 30 kAh m⁻³ of electric charge passed, the removal of microorganisms (data not shown)
416 attained was similar to than observed in Figure 1. Regarding organics, Figure 7 shows the
417 maximum removal of TOC with the applied electric charge. As it can be observed, more
418 than 90 % of mineralization can be attained when the electrolysis is run during long time
419 (electric charge passed over 30 kA m⁻³). The carbon mass balance taking into account the
420 carbon from organics (urea, creatinine and uric acid) and TOC values reveals that the
421 formation of intermediate organic compounds are more favored when working at low
422 current densities (10 A m⁻²). This is an expected behavior because of the soft oxidation
423 conditions at this value in comparison with the strong conditions at 100 A m⁻² where the
424 organics are completely mineralized. These results reveal that electrolysis with diamond
425 anodes is a suitable technology not only for the disinfection of urine but also for the
426 removal of the organic matter present in wastewater using low current densities.



427

428 **Figure 7.** Final TOC concentration as function of the applied electric charge during the
 429 electrochemical disinfection of synthetic urine with diamond anodes. (□) 10 A m⁻²; (○)
 430 100 A m⁻².

431

432 **4. Conclusions.**

433 From this work, the following conclusions can be drawn:

- 434 - Electrolysis with diamond anodes allow to completely disinfect urine at applied
 435 electric charges lower than 2 kWh m⁻³ and current densities within the range 5-100
 436 A m⁻². During the process, large amounts of oxidants are produced from the
 437 electrooxidation of the ions present in synthetic urine which are the main
 438 responsible of the removal of microorganisms.
- 439 - Urea, creatinine and uric acid are also degraded by the attack of electrogenerated
 440 oxidants during the electrochemical disinfection. The oxidation of these organics
 441 leads to the release of nitrogen from their chemical structure which is transformed

442 into nitrite, nitrate and, finally, ammonium. This last one reacts with free chlorine
443 present in the effluent, favoring the production of chloramines.

444 - The process efficiency is clearly influenced by the current density for both
445 microorganisms and organics removal. In this context, low current densities (5-
446 10 A m^{-2}) lead to a more efficient disinfection and degradation of urea, creatinine
447 and uric acid from wastewater. Nonetheless, it is necessary to applied higher
448 electric charges to attain a complete removal of organics for all the current
449 densities studied.

450 - A mineralization of the organic matter higher than 90 % is achieved after passing
451 electric charges around 30 kAh m^{-3} (j : $10\text{-}100 \text{ A m}^{-2}$). Under these conditions, it
452 is possible to completely remove not only the concentration of microorganisms
453 but also the urea, creatinine and uric acid concentrations by electrolysis with
454 diamond anodes.

455

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462

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