Study of the performance of a cylindrical flow-through electro-Fenton reactor using different arrangements of carbon felt electrodes: effect of key operating parameters

Josué Daniel García-Espinoza1 · Irma Robles2 · Alfonso Durán-Moreno3 · Luis A. Godínez1

Received: 3 June 2021 / Accepted: 10 December 2021 / Published online: 25 January 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract

In this work, a cylindrical flow-through electro-Fenton reactor containing graphite felt electrodes and an Fe(II) loaded resin was evaluated for the production of the Fenton reaction mixture and for the degradation of amoxicillin (AMX) and fecal coliforms containing aqueous solutions. First, the influence of several factors such as treatment time, current intensity, flow rate, and electrode position was investigated for the electrogeneration of H2O2 and the energetic consumption by means of a factorial design methodology using a 2⁴ factorial matrix. Electric current and treatment time were found to be the pivotal parameters influencing the H2O2 production with contributions of 40.2 and 26.9%, respectively. The flow rate had low influence on the responses; however, 500 mL min⁻¹ (with an average residence time of 1.09 min obtained in the residence time distribution analysis) allowed to obtain a better performance due to the high mass transport to and from the electrodes. As expected, polarization was also found to play an important role, since for the cathode-to-anode flow direction, lower H2O2 concentrations were observed when compared with the anode-to-cathode flow arrangement, indicating that part of the H2O2 produced in the cathode was destroyed at the anode. A fluorescence study of hydroxyl radical production, on the other hand, showed that higher yields were obtained using an anode-to-cathode flow direction (up to 3.88 µM), when compared with experiments carried out using a cathode-to-anode flow path (3.11 µM). The removal of a commercial formulation of the antibiotic AMX was evaluated in terms of total organic carbon, achieving up to 57.9% and 38.63% of pollutant mineralization using synthetic and real sanitary wastewater spiked, respectively. Finally, the efficiency of the process on the inactivation of fecal coliforms in sanitary wastewater samples was assessed, reducing 90% of the bacteria after 5 min of electrolysis.

Keywords Electro-Fenton · Carbon felt electrodes · Electrochemical disinfection · Amoxicillin · Fecal coliforms

Introduction

Electrochemical advanced oxidation processes (EAOPs) constitute an attractive approach to treat wastewater effluents contaminated with persistent pollutants. These processes are characterized by the use of hydroxyl radicals (•OH) which are strong oxidant species capable of attacking a wide variety of organic contaminants (E° = 2.8 V vs. standard hydrogen electrode, SHE) (Comninellis 1994; Brillas et al. 2009; Brillas 2020). Among the different EAOPs, the so-called electro-Fenton processes are quite promising since they are based on the in situ electro-generation of H2O2 by means of the 2e⁻ reduction of dissolved oxygen at a suitable cathode material under acid or alkaline conditions (see Eqs. (1)–(2)).
and in the presence of an iron promoter as shown in Eq. (3) (Salmerón et al. 2021).

\[
\begin{align*}
O_2 + 2H^+ + 2e^- & \rightarrow H_2O_2 \quad (1) \\
2H_2O + O_2 + 2e^- & \rightarrow H_2O_2 + 2OH^- \quad (2) \\
H_2O_2 + Fe^{2+} & \rightarrow Fe^{2+} + OH^- + OH^- \quad (3)
\end{align*}
\]

Since the electro-Fenton process involves electrochemical reactions, its performance is limited by the mass transport of oxygen and the pollutant species to the electrode surface and therefore it is closely related to the reactor design (García-Segura et al. 2020). Over the last years, the design of most of the continuous-flow electro-Fenton reactors has focused on the flow-by configuration, where the pollutant containing effluent flows parallel to the anode and cathode surfaces (Zhou et al. 2017). In these systems, convection becomes negligible near the electrode-solution interface and therefore, in order to reduce the mass transport limitations of the conventional flow-by reactors, it is important to incorporate fluid mixer promoters such as mechanical agitators or pumps.

In this way, flow-through electro-Fenton reactors stand out as an attractive option to overcome these weaknesses since the solution flows through porous anode and cathode electrodes, increasing mass transport events that result in improved electrochemical conversion, current efficiency, and reduced energy consumption (Zhou et al. 2017). In flow-through electro-Fenton reactors, 3D porous electrodes have shown good yields in the abetment of several pollutants (Jiao et al. 2020; Yu et al. 2020) and among the electrodes employed, carbonaceous materials, such as graphite felt, stand out as desirable electrodes because of their stability, electric conductivity, high surface area, chemical resistance, efficient cathodic regeneration of Fe(II) as well as its inherent filtration characteristics (Brillas et al. 2009; Panizza and Oturan 2011; Zhou et al. 2012, 2014, 2017; Petrucci et al. 2016).

Due to these features, the performance of flow-through electro-Fenton reactors has been extensively reported. For instance, Ren et al. (2016) studied the degradation of tartrazine in a vertical-flow electro-Fenton reactor, made up 10 cell compartments using a PbO\(_2\) anode and a modified graphite felt mesh cathode. Those authors reported the complete abatement of the pollutant and 61% of total organic carbon (TOC) removal at pH 3, using a voltage of 4.0 V, a flow rate of 40 mL min\(^{-1}\), and a concentration of 0.4 mM Fe(II) (Ren et al. 2016). In a subsequent study, Ren et al. (2020) also reported the treatment of real domestic sewage using a stacked flow-through electro-Fenton reactor equipped with modified graphite felt cathodes and dimensionally stable anode (DSA) mesh anodes. Applying 2.5 V and using 0.4 mM Fe(II), these authors obtained a bacterium inactivation value of log 3.34–3.46 and efficient removals of COD, N-NH\(_3\), and total phosphorus (Ren et al. 2020). Also, Chai et al. (2021) evaluated a coupled system of flow-through electro-Fenton and electrosorption processes for the treatment of high-salinity organic wastewater using iron, Ti, and activated carbon felt electrodes. In this work, the authors achieved removal values of chemical oxygen demand (COD), total nitrogen, and salinity of 96.5, 98.2, and 46.2%, respectively (Chai et al. 2021). The modification of activated carbon fibers coupled to a DSA anode in a flow-through electro-Fenton process for orange II dye abetment has also been reported by Jiao et al. (2020) (Jiao et al. 2020).

As it can be seen, from these and other reports, good yields on pollutant removal are obtained using flow-through electro-Fenton configurations. However, the use of anodes such as iron, PbO\(_2\), or DSA and the need to add Fe(II) as the Fenton mixture promoter limit the use of these reactors in large-scale applications, and in this context, flow-through electro-Fenton reactors equipped with electrodes made of affordable carbonaceous materials and where the Fe(II) is provided and retained by an ion exchange resin have also been reported by our research group (García-Espinoza et al. 2019, 2021; Robles et al. 2020).

In spite of the interest in 3D and flow-through reactors, there is still a severe lack on the understanding of reactor configuration effects since most electrochemical publications focus on novel electrode materials rather than on recognizing the significant influences of mass transport on pollutant degradation (García-Segura et al. 2020). In this way, the flow direction of the solution is an important operational variable in flow-through reactors because it can control the overall performance of the process. This is the case of the electrochemical elimination of N-NH\(_2\), in which by arranging an anode-to-cathode flow is possible to achieve its removal and obtain safe N\(_2\), since in the anode, the oxidation of N-NH\(_2\) to NO\(_2^-\) and NO\(_3^-\) is achieved, prior to its subsequent reduction to N\(_2\) in the cathode. This sequence of reactions is not obtained in the cathode-to-anode flow configuration (Heck et al. 2019; García-Segura et al. 2020; Ren et al. 2020).

The performance of the electro-Fenton process has also been tested for the degradation of biorecalcitrant pollutants (Komitchou et al. 2015; García-Espinoza et al. 2019; Castillo-Monroy et al. 2020; Droguett et al. 2020; Puga et al. 2021). Among them, the elimination from aquatic media of antibiotic compounds such as amoxicillin (AMX) is relevant since this is a pharmaceutical compound that is widely used in human and veterinary medicine (aus der Beek et al. 2016). In water, AMX is rapidly degraded by biotic and abiotic factors, yielding different intermediate products which are suspected to be more resistant to degradation, and potentially more toxic, than the parent compound (Elizalde-Velázquez et al. 2016; Loos et al. 2018). Furthermore, AMX
may bioaccumulate in fish muscle tissues, which results in the potential presence of this pharmaceutical compound in food, leading to a passive consumption of the antibiotic that may result in undesirable effects on consumer health such as immunoallergenic responses. However, the main problem related with the presence of the AMX in fish tissues is the possibility of inducing bacterial resistance genes (Elizalde-Velázquez et al. 2016). Furthermore, since 60 to 80% of the substance is excreted without alteration (Sodhi et al. 2021) and the hydrolysis half-life of the AMX in water at pH 7 has been reported to be 19.7 d (Braschi et al. 2013), AMX has been detected in water bodies with concentrations of up to 0.218 µg L⁻¹ (Gros et al. 2013) which is higher than the predicted no-effect concentration (PNEC) of 0.078 µg L⁻¹ (Loos et al. 2018).

Due to its physicochemical proprieties such as low LogKow value, low volatility, high stability, high polarity, and complex chemical structure (Table 1), AMX is a persistent compound which may result in eco-toxicological effects and human health affectations (Jones et al. 2002) and therefore, is one compound in the watch list of substances being monitored by the European Union (Commission Implementing Decision (EU) 2015).

In the context of the interest to develop efficient EAOPs for the degradation of commercial formulations of biocalcitran compounds (Murillo-Sierra et al. 2018; de Matos et al. 2020; Carrera-Cevallos et al. 2021), the aim of this work was to evaluate the performance on the degradation of AMX of a flow-through electro-Fenton reactor equipped with carbon felt electrodes. First, residence time distribution was investigated. Later, the capability of the electrochemical reactor to generate H₂O₂ was evaluated at different current intensities, recirculation flow, treatment time and position of the electrodes, also considering the energetic consumption. Afterwards, the process effectivity for the mineralization of AMX containing solutions was evaluated under different experimental conditions. Finally, the process was also tested for the inactivation of fecal coliforms using real sanitary wastewater.

**Materials and methods**

**Chemicals and solutions**

While coumarin and cerium sulfate (IV) were purchased from Sigma-Aldrich, reagent grade H₂SO₄, NaCl, and Na₂SO₄ were supplied by J.T. Baker. A commercial formulation of the antibiotic AMX (AMSA, Mexico) in capsule presentation of 500 mg was employed. For the determination of H₂O₂, solutions were prepared using demineralized water dissolving 0.05 M of Na₂SO₄ as supporting electrolyte. Using this electrolyte, solutions of coumarin (0.4 mM) and AMX (0.27 mM) were used. Samples of real sanitary wastewater pretreated by biological processes were also used (chemical oxygen demand, COD: 45.6 ± 16, pH 7.7 ± 0.2, conductivity: 0.9 ± 0.04 mS cm⁻¹). While the pH of all solutions was 7.0 ± 0.5, the electric conductivity of the Na₂SO₄ electrolyte and the sanitary wastewater were 8.8 ± 0.4 and 0.8 ± 0.2 mS cm⁻¹, respectively.

**Electro-Fenton reactor**

The treatment was carried out using a three-compartment cylindrical reactor made of nylon in which the central section of the reactor (141 cm³) was coupled on each side to one identical compartment using stainless steel screws (see Fig. 1a). The experimental setup consisted of the reactor equipped with a power source, a peristaltic pump, a recirculation tank, and an oxygen concentrator (Fig. 1b).

| Table 1 Physicochemical properties of the amoxicillin |
|------------------------------------------------------|
| Pharmaceutical group                                 |
| Aminopenicillin antibiotic                           |
| Molecular formula                                    | C₁₆H₁₉N₃O₅S                                       |
| CAS                                                  | 26787-78-0                                       |
| Chemical structure                                   | ![Chemical structure](image)                     |
| Molecular mass (g mol⁻¹)                             | 365.4                                            |
| Water solubility (mg L⁻¹)                            | 3.43x10³                                         |
| pKa                                                  | 3.2, 11.7                                        |
| LogKow                                              | 0.87                                             |
| Henry’s law constant (atm m³mol⁻¹)                   | 2.49X10⁻²¹                                       |

pKa acid dissociation constant, logKow octanol–water partition coefficient
Carbon cloth circular pieces (28 cm² effective area, 0.6 mm thickness, 0.5 Ω in² electrical resistivity) served as electrical contacts for cylindrical carbon felt electrodes (6 cm diameter, 2.35 cm length), positioned between the compartments (Fig. 1c and d). For the electro-Fenton assays, while in the compartment next to the cathode, a cation exchange resin containing Fe(II) was placed, the same amount of a Na⁺-activated cation exchange resin was located in the compartment next to the anode (Fig. 1e). As can be seen in Fig. 1a, the reactor was fed in such a way that the pollutant solution passed through the three sections of the reactor; that is, across the resin compartments and the polarized cloth and carbon felt electrodes, flowing towards a receiving tank where the effluent solution was mixed with the influent solution and from where the solution was pumped by means of a peristaltic pump. (7) recirculation pipe; e—electrodes placed in the center arrangement, d—electrodes placed in the extremes arrangement, e—configuration where resin is placed in C1 and C3 compartments

**Experimental set-up and methods**

Residence time distribution (RTD) was obtained from a tracer test which was conducted using the pulse injection method. In this experiment, a concentrated solution of NaCl was instantly introduced to the inlet line of the reactor and total dissolved solids (TDS) were measured every 5 s at the outlet of the reactor. The normalized residence time distribution function (\(E(t)\)) and the average residence time (\(\mu\)) after the pulse tracer input were obtained using Eqs. (4) and (5), respectively (Martin-Dominguez et al. 2005):

\[
E(t) = \frac{C(t)}{\int_0^\infty C(t)dt}
\]

\[
\mu = \frac{\int_0^\infty tC(t)dt}{\int_0^\infty C(t)dt}
\]

In these equations, \(C(t)\) corresponds to the tracer concentration evolution at the reactor exit and \(t\) is time. Later, a full 2⁴ factorial design (FD) was used to investigate the effect of the factors and their interactions on
the electrogeneration of H₂O₂ and on the energetic consumption of the process. From the FD, an empirical linear model is obtained (see Eq. (6)):

\[ Y_j = \beta_0 + \sum \beta_i X_i \]  

(6)

Here, \( Y_j \) is the response variable, \( X_i \) is the independent variable, and \( \beta_0 \) and \( \beta_i \) correspond to the constant and the linear model coefficients, respectively (Aquino et al. 2013). Four independent factors were studied as follows: electrolysis time (\( X_1 \)), current intensity (\( X_2 \)), recirculation flow (\( X_3 \)), and the position of the electrodes (\( X_4 \)). Three of these variables were quantitative factors (\( X_1, X_2, \) and \( X_3 \)) and one corresponded to a categorical factor (\( X_4 \)). Sixteen assays were required for the FD. Experimental data was analyzed using the Design Expert® program software (Design Expert 7, Stat-Ease Inc., Minneapolis). The FD was developed within the range of the independent variables according to Table 2. Once the conditions that maximize the H₂O₂ electrogeneration were determined, the percentage of current efficiency (\( \phi \)) for the production of H₂O₂ was computed using Eq. (7), where \( n \) is the number of transferred electrons (2) to produce H₂O₂ via oxygen reduction, \( F \) is the Faraday constant (96 485 C mol⁻¹), \( C_{\text{H}_2\text{O}_2} \) is the H₂O₂ concentration (g L⁻¹), \( V \) is the volume of the solution (L), \( M_{\text{H}_2\text{O}_2} \) is the molecular weight of H₂O₂ (34.01 g mol⁻¹), \( I \) is the applied current (A), and \( t \) is the treatment time (s) (Ma et al. 2019).

\[ \phi = \frac{nF C_{\text{H}_2\text{O}_2} V}{M_{\text{H}_2\text{O}_2} It} \times 100 \]  

(7)

The energetic consumption per cubic meter of treated water (EC) was calculated using Eq. (8) (Brillas and Martínez-Huitlje 2015).

\[ \text{EC} \left( \frac{kWh}{m^3} \right) = \frac{VIt}{Vol1000} \]  

(8)

where \( V \), \( A \), \( t \), and \( Vol \) correspond to the voltage (V), current (A), time (h), and the volume of treated water (m³), respectively. It is important to note that the EC values obtained only take into account the electricity used in the electrolysis assays, disregarding the energy required to pump the solutions and that consumed in the oxygen concentrator.

### Analytical methods

Cerium sulfate (IV) dissolved in an acid solution (H₂SO₄) with phenanthroline as indicator was prepared and used along with a calibration curve previously constructed, to quantitatively determine the concentration of H₂O₂ using a volumetric redox titration method (Daghrir et al. 2013; Komtchou et al. 2015). Assessment of ⋅OH radical production was carried out by measuring the generation of the fluorescent 7-hydroxicoumarin (7-HC) that results from the selective hydroxylolation reaction of coumarin with the ⋅OH electrogenerated species. The wavelengths of excitation (\( \lambda_{\text{ex}} \)) and emission (\( \lambda_{\text{em}} \)) corresponded to 340 and 456 nm, respectively. Both excitation and emission slits were fixed at 5 nm. The concentration of ⋅OH (\( C_{\text{●OH}} \) in μM) was determined by means of Eq. (9) which considers that 29% of all ⋅OH radicals are trapped by coumarin to produce 7-HC (Toku-mura et al. 2011). This equation also considers that 2 mol of ⋅OH radicals react with 1 mol of coumarin to produce 1 mol 7-HC. Since the slope of the calibration curve, \( C_{7-\text{HC}} \), corresponds to the concentration of 7-HC, then \( C_{\text{●OH}} \) can be obtained from the fluorescence intensity at 456 nm, \( FI_{456} \).

\[ C_{\text{●OH}} = \left( \frac{2}{0.29} \right) C_{7-\text{HC}} = 23.45 \times 10^{-3} FI_{456} \]  

(9)

The removal of AMX, on the other hand, was determined from the TOC assessment. While spectrophotometric tests were carried out using a DR600 HACH apparatus and the TOC measurements utilizing a Shimadzu TOC LCSN equipment, fluorescence measurements were performed using a Cary Eclipse Agilent spectrophotometer. pH, TDS, and dissolved oxygen concentration were measured employing a Thermo Scientific potentiometer model Orion Versa Star Pro. COD and nitrate ion (NO₃⁻) concentrations were determined employing HACH reagents.

### Results

#### Hydraulic characterization

As it was previously pointed out, RTD measurements were used to investigate the hydraulic characteristics of

### Table 2 Range and codification of independent variables (\( X_i \))

| \( X_i \)                | Variable                             | Experimental range         |
|--------------------------|--------------------------------------|-----------------------------|
| \( X_1 \)                | Electrolysis time (min)              | 15                          |
| \( X_2 \)                | Current intensity (mA)               | 150                         |
| \( X_3 \)                | Recycling flow rate (mL min⁻¹)        | 375                         |
| \( X_4 \)                | Electrode position                   | Center, C2 sister, C1, C3   |
the flow-through electro-Fenton reactor under study. In a pulse, an amount of tracer is suddenly injected in one shot into the feed-stream entering the reactor. The outlet concentration is then measured as a function of time. Figure 2 shows the obtained RTD curves at two different flow rates and using the reactor with the electrodes placed in the center (see Fig. 1c) and in the absence of applied current.

The calculated average residence time under both experimental conditions corresponded to 1.37 and 1.09 min at 375 and 500 mL min⁻¹, respectively (see dotted lines in Fig. 2), which are shorter than the theoretical retention times (1.6 and 1.2 min for 375 and 500 mL min⁻¹ flow rates, respectively). This reflects that the porous carbon felt electrodes occupy part of the effective volume of the reactor, thus shortening the time needed for the solution to reach the outlet. Furthermore, the parabolic shape of the curves means that there is no by-pass effects in the reactor (Monteil et al. 2021); however, the asymmetric shape of the tails also reflects the presence of stagnant zones (Haoran et al. 2013). At the highest flow rate, a higher and thinner peak can be observed when compared with the one obtained at the lower flow rate. This observation suggests that by increasing the flow rate, it is possible to obtain a plug flow behavior and that by reducing the flow rate, the system behaves as a continuous-stirred tank reactor (Monteil et al. 2021). To further evaluate the effect of the flow rate on the generation of H₂O₂ for the proposed flow-through reactor, a FD study was carried out.

**Effect of operational parameters**

The factorial design matrix, experimental and predicted data for the H₂O₂ generated in anode-to-cathode flow direction, and the calculated energy consumption are presented in Table 3. The empirical relationship between the responses and variables are expressed by the polynomial Eqs. (10)–(11).

\[ Y_{H_2O_2} = 10.54 + 1.40X_1 + 1.71X_2 + 0.68X_3 - 1.03X_4 + 8.5 \times 10^{-3}X_1X_2 
+ 0.25X_1X_3 + 0.46X_1X_4 + 0.37X_2X_3 - 0.66X_2X_4 + 0.20X_3X_4 \]  
(10)

\[ Y_{EC} = 2.26 + 0.76X_1 + 1.15X_2 - 0.22X_3 + 0.23X_4 
+ 0.39X_1X_2 - 0.080X_1X_3 
+ 0.090X_1X_4 - 0.18X_2X_3 + 0.11X_2X_4 
+ 0.11X_3X_4 \]  
(11)

The coefficient \( R^2 \), defined as the ratio of the explained to the total variation, reflects a measure of the degree of fitting. For a good fit, \( R^2 \) should be at least 0.80 (Fu et al. 2007). The obtained \( R^2 \) (0.9871 for H₂O₂ generation and 0.9891 for energetic consumption) can be seen to be high for both responses, reflecting that the model describes reasonably well the process performance. This was also confirmed by the determination of adjusted coefficients (adj-\( R^2 \)) characterized by the values of 0.9614 and 0.9674 for H₂O₂ production and energetic consumption, respectively. Analysis of variance (ANOVA) of the results was also performed to evaluate the significance of the models (Tables 1-S and 2-S).

Fig. 2 RTD curves at flow rates of **a** 375 and **b** 500 mL min⁻¹. Dotted lines represent the average residence time.
Table 3 Experimental factorial matrix and experimental results

| Exp | $X_1$ | $X_2$ | $X_3$ | $X_4$ | Electrolysis time (min) | Current intensity (mA) | Recycling flow rate (mL min$^{-1}$) | Electrode position | $\text{H}_2\text{O}_2$ (mg L$^{-1}$) | Actual value | Predicted value | EC (kWh m$^{-3}$) | Actual value | Predicted value |
|-----|-------|-------|-------|-------|--------------------------|------------------------|-------------------------------|-------------------|-------------------------------|-------------|----------------|----------------|-------------|----------------|
| 1   | −1    | −1    | −1    | −1    | 15                       | 150                    | 375                           | Center            | 8.30                          | 8.41        | 0.68           | 1.37           | 0.77        |
| 2   | −1    | 1     | −1    | −1    | 30                       | 150                    | 375                           | Center            | 9.40                          | 9.77        | 1.49           | 1.49           | 2.43        |
| 3   | −1    | −1    | 1     | −1    | 15                       | 300                    | 375                           | Center            | 12.75                         | 12.39       | 2.42           | 2.43           | 4.95        |
| 4   | −1    | 1     | 1     | −1    | 30                       | 300                    | 375                           | Center            | 13.92                         | 13.79       | 4.71           | 4.71           | 4.71        |
| 5   | 1     | −1    | −1    | −1    | 15                       | 150                    | 500                           | Center            | 8.50                          | 8.12        | 0.64           | 0.63           | 0.63        |
| 6   | 1     | 1     | −1    | −1    | 30                       | 150                    | 500                           | Center            | 10.60                         | 10.48       | 1.25           | 1.03           | 1.03        |
| 7   | 1     | −1    | 1     | −1    | 15                       | 300                    | 500                           | Center            | 13.00                         | 13.59       | 1.68           | 1.58           | 1.58        |
| 8   | 1     | 1     | 1     | −1    | 30                       | 300                    | 500                           | Center            | 16.10                         | 15.99       | 3.21           | 3.54           | 3.54        |
| 9   | −1    | −1    | −1    | 1     | 15                       | 150                    | 375                           | Extremes          | 6.30                          | 6.34        | 0.86           | 0.63           | 0.63        |
| 10  | −1    | 1     | −1    | 1     | 30                       | 150                    | 375                           | Extremes          | 10.10                         | 9.54        | 1.71           | 1.72           | 1.72        |
| 11  | −1    | −1    | 1     | 1     | 15                       | 300                    | 375                           | Extremes          | 7.50                          | 7.69        | 2.60           | 2.71           | 2.71        |
| 12  | −1    | 1     | 1     | 1     | 30                       | 300                    | 375                           | Extremes          | 10.60                         | 10.94       | 5.25           | 5.35           | 5.35        |
| 13  | 1     | −1    | −1    | 1     | 15                       | 150                    | 500                           | Extremes          | 6.70                          | 6.84        | 0.77           | 0.92           | 0.92        |
| 14  | 1     | 1     | −1    | 1     | 30                       | 150                    | 500                           | Extremes          | 10.70                         | 11.05       | 1.61           | 1.68           | 1.68        |
| 15  | 1     | −1    | 1     | 1     | 15                       | 300                    | 500                           | Extremes          | 10.10                         | 9.68        | 2.33           | 2.29           | 2.29        |
| 16  | 1     | 1     | 1     | 1     | 30                       | 300                    | 500                           | Extremes          | 14.04                         | 13.93       | 4.80           | 4.61           | 4.61        |
Comparison of the actual and predicted values for H₂O₂ electrogeneration and energetic consumption indicates that as expected, the highest yields of H₂O₂ production and energetic consumption are reached when applying the maximum current and treatment time (Fig. 1-S).

Figure 3a, on the other hand, shows the values of the effects of the independent factors obtained from the polynomial Eqs. (10)–(11). As can be observed from inspection of this figure, for H₂O₂ electrogeneration, the independent variables, treatment time, current intensity, and recycling flow show all positive effects (see Table 2). This means that the highest yield of H₂O₂ production is reached when the values of these three independent variables correspond to their high levels. The other independent variable, which corresponds to electrode position, shows a negative effect (b₄H₂O₂ = -1.03). This means that the high level of this variable (electrodes placed at the far-end-positions of the reactor) results in lower H₂O₂ concentrations when compared to the ones obtained when the electrodes are positioned in the central compartment (see Table 2).

For energetic consumption (the other dependent variable), the data in Fig. 3a shows that treatment time, current intensity and position of the electrodes show all positive effects (b₁EC = 0.76, b₂EC = 1.15, b₄EC = 0.23). This reflects that when the high level of these variables is used, high energy is required (see Table 2). The recirculation flow, on the other hand, is characterized by a negative effect on the response (b₃EC = -0.22), which means that high energetic consumptions are expected when the low level of this variable is utilized (see Table 2). This means that at high flow rates, the energetic consumption is reduced because mass transfer to the electrodes is favored; a fact that also decreases the potential difference. In order to get further insight from the experimental data, the percentage effect of each factor and their interactions on the responses were calculated using Eq. (12):

\[ P_i = \left( \frac{b_i^2}{\sum_{i=1}^{k} b_i^2} \right) 100 \text{(i \neq 0)} \] (12)

where \( P_i \) is the percentage contribution of each independent factor \( i \), and where \( b_i \) represents the estimation of the main effect of factor \( i \).

As depicted in Fig. 3b, the contribution of the primary effects on H₂O₂ generation corresponds to 26.9%, 40.2%, 6.24%, and 14.6% for electrolysis time, current, recycling flow rate, and electrode position, respectively. For energetic consumption on the other hand, the contribution of the same variables corresponds to 26.1%, 59.3%, 2.2%, and 2.5%. As shown in Fig. 3b, the applied current is the factor with the highest contribution for both responses, followed by treatment time. The preponderant significance of current and treatment time lies in the fact that both parameters are strongly related with the amount of electric charge entering the reactor, that is, a higher number of 2e⁻ oxygen reduction events that result in the electrogeneration of H₂O₂. Similar
results have been reported for the performance of EAOPs (Zaviska et al. 2011, 2012; Daghrir et al. 2014; García-Espi-noza et al. 2016, 2018).

Assuming that the maximum concentration of H$_2$O$_2$ corresponds to the optimal reactor’s performance, the best operating conditions are as follows: 30 min of electrolysis at 300 mA, 500 mL min$^{-1}$ as recycling flow rate and arranging the electrodes in the central compartment of the reactor. Under these optimized conditions, the predicted electrogenerated H$_2$O$_2$ concentration proposed by the model corresponds to 15.99 mg L$^{-1}$, a value which is quite close to the experimentally obtained one (16.10 mg L$^{-1}$).

Figure 4a shows the concentration of H$_2$O$_2$ on time in the anode-to-cathode flow direction under oxygen and air saturation conditions. As expected, an oxygen concentration increase allows to obtain higher yields (2.72 times more) when compared to the values achieved using air (the corresponding concentration of oxygen in the solution is 30 mgO$_2$ L$^{-1}$ under oxygen saturation vs. 7.5 mgO$_2$ L$^{-1}$ at air saturation). It is interesting to note that in the cathode-to-anode flow direction arrangement under oxygen saturation conditions, lower H$_2$O$_2$ concentrations were obtained when compared to the anode-to-cathode set-up (16.1 and 6.1 mg L$^{-1}$, respectively). This observation suggests that 62% of H$_2$O$_2$ produced in the cathode is consumed at the anode when this arrangement is employed as indicated by Eq. (13):

$$H_2O_2 + OH^- \rightarrow HO_2^+ + H_2O + e^-$$

Similar H$_2$O$_2$ concentration values were obtained by (Zhang et al. 2021), who achieved up to 17.68 mg L$^{-1}$ at pH 3 after 120 min of electrolysis using a reticular stainless-steel cathode and a DSA anode.

Current efficiencies for H$_2$O$_2$ generation were also determined and the resulting data is shown in Fig. 4b. Inspection of the experimental curves reveals that as expected, the current efficiency values are higher in the cathode-to-anode flow direction and in the presence of pure oxygen.

On the other hand, it is well documented that the optimal pH value for *OH production from Fenton reaction mixtures corresponds to 3 (Sirés and Brillas 2021). Taking into account the economic viability of electro-Fenton processes at neutral pH values however, (Estrada-Arriaga et al. 2016; Olvera-Vargas et al. 2021), all the assays reported in this work were carried out under pH conditions close to those found in real wastewater (pH~7).

**Assessment of •OH production**

Once the experimental conditions that promote the best H$_2$O$_2$ generation were obtained, the production of •OH was evaluated. Figure 5 shows the fluorescence intensity and the obtained •OH concentration. Inspection of the experimental data reveals that in the cathode-to-anode flow direction arrangement, the electro-Fenton process allows to obtain up to 3.11 μM of •OH at 5 min of electrolysis, which represents...
a lower production of the radical when compared with the one obtained in the anode-to-cathode flow direction set-up (3.88 µM of *OH). The higher yields of the anode-to-cathode configuration can be related with the fact that the washed Fe(II) from the resin in C1 interacts with the electrogenerated H₂O₂ in the cathode positioned after the anode, near to the outlet of the reactor. Therefore, the residual H₂O₂ in Fig. 4a promotes the production of *OH directly at the sample point. On the other hand, the *OH concentration obtained in the cathode-to-anode flow direction configuration is slightly lower when compared with the aforementioned configuration. In this way, higher *OH concentration is expected within the reactor since Fe(II) ions react directly with the electrogenerated H₂O₂ in the electrode placed at the reactor’s inlet. In the absence of Fe(II) (see Fig. 5c and d), the *OH concentration is considerably smaller. The electrochemical oxidation process with the addition of air in the cathode-to-anode flow direction, on the other hand, allowed to obtain up to 0.42 µM of *OH and as expected, this value increases with the addition of pure oxygen (0.49 µM of *OH). In both cases, *OH generation can be related to the monoelectronic reduction of H₂O₂ according the Eq. (14):

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

(14)

Degradation of AMX containing solutions

The effectiveness of the electro-Fenton process was also evaluated in terms of the mineralization of AMX containing solutions. To clarify the role of the processes that take place within the system, different experimental conditions were evaluated, namely, adsorption (without current intensity), electro-oxidation (same reactor without using the Fe(II) loaded resin), and electro-Fenton using cathode-to-anode flow and anode-to-cathode flow directions. As shown in Fig. 6 TOC removal for AMX degradation assays using a synthetic solution: black ■ electro-Fenton process, cathode-to-anode flow configuration with oxygen saturation, red dot: electro-Fenton process, anode-to-cathode flow arrangement with oxygen saturation, blue triangle electrochemical oxidation process, cathode-to-anode flow setup with oxygen saturation, green down pointing triangle: adsorption (without current). Using real sanitary wastewater: empty black ■ electro-Fenton process, cathode-to-anode flow arrangement with oxygen saturation. 300 mA, pH 7 and 500 mL min⁻¹ recirculation flow rate.
Fig. 6a, while the TOC values reflect negligible removal by adsorption, the electrochemical oxidation process results in a value of 28.92%. As expected, TOC decrease was largely improved (after 30 min of electrolysis) by the electro-Fenton process using either the anode-to-cathode set-up (45.5%), or the cathode-to-anode arrangement (57.9%). This observation confirms not only that the •OH radical species is generated by Eq. (3), playing the most important role in the mineralization of the solution, but also that the cathode-to-anode configuration allows to obtain the higher yields. For AMX mineralization, the cathode-to-anode configuration allows to obtain higher yields when compared with the anode-to-cathode flow arrangement. This observation confirms not only that the •OH radical species is generated by Eq. (3), playing the most important role in the mineralization of the solution, but also that the cathode-to-anode configuration allows to obtain the higher yields. AMX mineralization, the cathode-to-anode configuration allows to obtain higher yields when compared with the anode-to-cathode flow arrangement. This observation confirms not only that the •OH radical species is generated by Eq. (3), playing the most important role in the mineralization of the solution, but also that the cathode-to-anode configuration allows to obtain the higher yields. This observation can be related to the electrogeneration of •OH (see Eq. (3)) as follows: the contaminated solution passes through the C1 compartment washing Fe(II) ions from the resin and taking them into the central section of the reactor where dissolved O2 is reduced to produce H2O2 at the cathode. This gives rise to the Fenton mixture which in turn is responsible for the observed AMX abatement. Under these conditions, residual H2O2 may be oxidized at the anode.

The empty black squares in Fig. 6, on the other hand, show the mineralization efficiency of the cathode-to-anode configured electro-Fenton process for real sanitary wastewater, which was previously contaminated with AMX as described in the experimental section. Using this complex effluent matrix, a 38.6% of mineralization was achieved after 30 min of reaction. The lower effectiveness of the process using this solution is probably related to the presence of soluble organic matter that not only inhibits the electro-generation of H2O2 but also promotes competitive reactions. As it can be noted from the experimental data, the quasi-steady state was reached after 5 mean hydraulic residence times.

It is interesting to compare the AMX mineralization data obtained in this study with other reports using electro-Fenton process. In this way, Kadji et al. (2021) obtained 74% of AMX mineralization after 180 min of electrolysis, with an initial AMX concentration of 0.082 mM. This value was reduced to 39% using a higher AMX concentration (0.164 mM) due to a competitive consumption of oxidizing •OH radicals between AMX and the by-products formed during the experiments (Kadji et al. 2021). On the other hand, Garza-Campos et al. (2018) obtained 55% of AMX mineralization after 240 min of treatment using a BDD anode and an air diffusion mesoporous carbon cathode (Garza-Campos et al. 2018). In this contribution, 57.95% AMX mineralization efficiency was obtained after 30 min of treatment which is not only a competitive value when compared with those in the literature, but also cost-attractive due to the use of affordable carbonaceous materials in the electrodes. Furthermore, since in the electro-Fenton process, the •OH radical is the dominant oxidant agent, the acute toxicity of the aqueous solution after the treatment was reduced in 50% using Daphnia magna as a biological indicator (Zhang et al. 2021). This observation suggests that the degradation of AMX by electro-Fenton reactions allows to obtain by-products with lower acute toxicity when compared with the parent compound.

Fig. 7 a NO3− from AMX degradation and b fecal coliforms concentration vs time in real wastewater. Black ■: electro-Fenton process in cathode-to-anode configuration, red dots: adsorption process.
The concentration of NO$_3^-$ was also determined as evidence of the degradation of the antibiotic by means of the electro-Fenton process arranged in the cathode-to-anode configuration. Figure 7a shows the NO$_3^-$ concentration on time, and it can be noted that the ion concentration increases with increasing treatment time up to a concentration of 3.6 mg L$^{-1}$. The presence of NO$_3^-$ is explained by the mineralization reaction of AMX (Eq. 15), which produces NH$_4^+$ that in turn, when interacting with $^\cdot$OH radicals, generates NO$_2^-$ (Eq. 16) and eventually NO$_3^-$ (Eq. 17). The presence of nitrate ions in the electrolytic solution, confirms the mineralization of AMX.

$$
\text{C}_{16}\text{H}_{19}\text{N}_3\text{O}_5\text{S} + 3\text{H}_2\text{O} \rightarrow 16\text{CO}_2 + 3\text{NH}_4^+ + \text{SO}_4^{2-} + 69\text{H}^+ + 70e^- \\
(15)
$$

$$
2\text{OH} + \text{NH}_4^+ \rightarrow \text{NO}_2^- + 6\text{H}^+ + 6e^- \\
(16)
$$

$$
2\text{OH} + \text{NO}_2^- \rightarrow \text{NO}_3^- + \text{H}_2\text{O} + e^- \\
(17)
$$

Figure 8 depicts a diagram of the pathways that are suggested to take place within the flow-through electro-Fenton reactor under study. In this way, the reduction of dissolved oxygen at the carbon felt cathode to promote H$_2$O$_2$ needs to occur along with the concomitant production of $^\cdot$OH by the presence of the Fe(II) washed from the iron-loaded resin in the C1 compartment of the reactor so that finally, it is possible to obtain CO$_2$, H$_2$O, and inorganic ions.

Although these results provide information on the mineralization of AMX using the flow-through electro-Fenton reactor under study, it is clear that, in order to follow the degradation path of the pollutant and to identify by-products, a specific analytic technique such as HPLC should be used.

**Disinfection assays**

In order to test the efficiency of the process in the inactivation of fecal coliforms, real sanitary wastewater treated by an anaerobic biodigester and anoxic-aerobic bioreactor was used. Under the optimal conditions of the electro-Fenton reactor, Fig. 7b shows that after 5 min of electrolysis, it was possible to reduce the concentration of the fecal coliform from 24 000 MPN 100 mL$^{-1}$ to 2400 MPN 100 mL$^{-1}$ and this value was maintained after 30 min of treatment, which means an efficiency of inactivation of microorganisms of 90%. On the other hand, when the water passed through the system in the absence of current, there was no decrease in fecal coliforms after 5 min and after 30 min, a value of 11 000 MPN 100 mL$^{-1}$ was obtained; indicating that under these conditions, around 50% of fecal coliforms can be retained in the reaction system.

**Conclusions**

The performance of a cylindrical flow-through electro-Fenton reactor using carbon felt electrodes was evaluated. An experimental design methodology was applied to evaluate the effects of four independent variables and to determine the best experimental conditions. Among the studied factors current and treatment time were the most meaningful parameters. The best operational parameters were found to be: current of 300 mA during 30 min, 500 mL min$^{-1}$ of recirculation flow rate, with the electrodes placed in the middle of the reactor and at cathode-to-anode flow direction achieving a H$_2$O$_2$ concentration of 16.1 mg L$^{-1}$ and an energy consumption of 3.21 kWh m$^{-3}$. Under these conditions, the system allows to obtain an $^\cdot$OH concentration of 3.11 µM, an AMX mineralization efficiency of 57.9%, and a fecal coliforms inactivation of 90%. The proposed reactor is a promising modular technology that can be used as tertiary treatment to remove contaminants of emerging concern and for the disinfection of wastewaters.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s11356-021-18118-6.

**Author contribution** Josué Daniel García-Espinoza: investigation, validation, formal analysis. Irma Robles: investigation, methodology, formal analysis. Alfonso Durán-Moreno: investigation, formal analysis.
supervision. Luis A. Godínez: conceptualization, writing—reviewing and editing, project administration, funding acquisition.

Funding This work is funded by the Mexican Council for Science and Technology: CONACYT (Grant No. PENTA2019-1–303758 and CB–2016–01-285309), the Ministry for Education, Science, Technology and Innovation of CDMX (SECTE/259/2019), and the Bill and Melinda Gates Foundation (Grant No. OPP1156657).

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Aquino JM, Rocha-Filho RC, Rodrigo MA et al (2013) Electrochemical degradation of the Reactive Red 141 dye using a boron-doped diamond anode. Water Air Soil Pollut 224:1–10. https://doi.org/10.1007/s11270-012-1397-9

aus der Beck T, Weber FA, Bergmann A et al (2016) Pharmaceuticals in the environment—global occurrences and perspectives. Environ Toxicol Chem 35:823–835. https://doi.org/10.1002/etc.3339

Braschi I, Biasiol S, Fellet C et al (2013) Persistence and degradation of new β-lactam antibiotics in the soil and water environment. Chemosphere 93:152–159. https://doi.org/10.1016/j.chemosphere.2013.05.016

Brillas E (2020) A review on the photoelectro-Fenton process as efficient electrochemical advanced oxidation for wastewater remediation. Treatment with UV light, sunlight, and coupling with conventional and other photo-assisted advanced technologies. Chemosphere 250:126198. https://doi.org/10.1016/j.chemosphere.2020.126198

Brillas E, Martínez-Huitte CA (2015) Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods. An updated review. Appl Catal B: Environ 166–167:603–643. https://doi.org/10.1016/j.apcata.2014.11.016

Brillas E, Sirés I, Oturan MA (2009) Electro-fenton process and related electrochemical technologies based on fenton’s reaction chemistry. Chem Rev 109:6570–6631. https://doi.org/10.1021/cr900130g

Carrera-Cevallos JV, Prato-Garcia D, Espinoza-Montero PJ, Vasquez-Medrano R (2021) Electro-oxidation of a commercial formulation of glyphosate on boron-doped diamond electrodes in a prepilot-scale single-compartment cell. Water Air Soil Pollut 232:69. https://doi.org/10.1007/s11270-020-04941-z

Castillo-Monroy J, Godínez LA, Robles I, Estrada-Vargas A (2020) Study of a coupled adsorption/electro-oxidation process as a tertiary treatment for tequila industry wastewater. Environ Sci Pollut Res https://doi.org/10.1007/s11356-020-11031-4

Chai Y, Qin P, Wu Z et al (2021) A coupled system of flow-through electro-Fenton and electroosorption processes for the efficient treatment of high-salinity organic wastewater. Sep Purif Technol 267:118683. https://doi.org/10.1016/j.seppur.2021.118683

Commission Implementing Decision (EU) 2015/495 of 20 (2015) Watch list of substances for Union-wide monitoring in the field of water policy pursuant to Directive 2008/105/EC of the European Parliament and of the Council

Commìnillles C (1994) Electrocataylsis in the electrochemical conversion/combustion of organic pollutants for waste water treatment. Electrochim Acta 39:1857–1862. https://doi.org/10.1016/0013-4686(94)85175-1

Dagheri R, Drogui P, El Khakani MA (2013) Photoelectrocatalytic oxidative chlorotetracycline using Ti/TiO2 photo-anode with simultaneous H2O2 production. Electrochim Acta 87:18–31. https://doi.org/10.1016/j.electacta.2012.09.020

Dagheri R, Drogui P, Tshibangu J et al (2014) Electrochemical treatment of domestic wastewater using boron-doped diamond and nanostructured amorphous carbon electrodes. Environ Sci Pollut Res 21:6578–6589. https://doi.org/10.1007/s11356-014-2558-8

de Matos DB, Barbosa MPR, Leite OM et al (2020) Characterization of a tubular electrochemical reactor for the degradation of the commercial diuron herbicide. Environ Technol (United Kingdom) 41:1307–1321. https://doi.org/10.1080/09593330.2018.1531941

Droguett C, Salazar R, Brillas E et al (2020) Treatment of antibiotic cephalxin by heterogeneous electrochemical Fenton-based processes using chalcopyrite as sustainable catalyst. Sci Total Environ 740:140154. https://doi.org/10.1016/j.scitotenv.2020.140154

Elizalde-Velázquez A, Gómez-Oliván LM, Galar-Martínez M et al (2016) Amoxicillin in the aquatic environment, its fate and environmental risk. In: Environmental Health Risk - Hazardous Factors to Living Species

Estrada-Arriaga EB, Cortés-Muñoz JE, González-Herrera A et al (2016) Assessment of full-scale biological nutrient removal systems upgraded with physico-chemical processes for the removal of emerging pollutants present in wastewaters from Mexico. Sci Total Environ 571:1172–1182. https://doi.org/10.1016/j.scitotenv.2016.07.118

Fu J, Zhao Y, Wu Q (2007) Optimising photoelectrocatalytic oxidation of fulvic acid using response surface methodology. J Hazard Mater 144:499–505. https://doi.org/10.1016/j.jhazmat.2006.10.071

García-Espinoza JD, Gortárez-Moroyqui P, Orta-Ledesma MT et al (2016) Electrochemical removal of carbamazepine in water with Ti/PbO2 cylindrical mesh anode. Water Sci Technol 73:1155–1165. https://doi.org/10.2166/wst.2015.591

García-Espinoza JD, Mijaylova-Nacheva P, Avilés-Flores M (2018) Electrochemical carbamazepine degradation: effect of the generated active chlorine, transformation pathways and toxicity. Chemosphere 192:142–151. https://doi.org/10.1016/j.chemosphere.2017.10.147

García-Espinoza JD, Robles I, Gil V et al (2019) Electrochemical degradation of triclosan in aqueous solution. A study of the performance of an electro-Fenton reactor. J Environ Chem Eng 7:103228. https://doi.org/10.1016/j.jece.2019.103228

García-Espinoza JD, Robles I, Durán-Moreno A, Godínez LA (2021) Study of simultaneous electro-Fenton and adsorption processes in a reactor containing porous carbon electrodes and particulate activated carbon. J Electroanal Chem 895:115476. https://doi.org/10.1016/j.jelechem.2021.115476

García-Segura S, Qu X, Alvarez PJJ et al (2020) Opportunities for nanotechnology to enhance electrochemical treatment of pollutants in potable water and industrial wastewater—a perspective. Environ Sci Nano 7:2178–2194. https://doi.org/10.1039/d0en0194e

Garza-Campos B, Morales-Acosta D, Hernández-Ramírez A et al (2018) Air diffusion electrodes based on synthesized mesoporous carbon for application in amoxicillin degradation by electro-Fenton and solar photo-electro-Fenton. Electrochim Acta 269:232–240. https://doi.org/10.1016/j.electacta.2018.02.139

Gros M, Rodríguez-Mozaz S, Barceló D (2013) Rapid analysis of multi-class antibiotic residues and some of their metabolites in hospital, urban wastewater and river water by ultra-high-performance liquid chromatography coupled to quadrupole-linear ion trap tandem mass spectrometry. J Chromatogr A 1292:173–188. https://doi.org/10.1016/j.chroma.2012.12.072
Ren G, Zhou M, Liu M et al (2016) A novel vertical-flow electro-Fenton reactor for organic wastewater treatment. Chem Eng J 298:55–67. https://doi.org/10.1016/j.cej.2016.04.011
Ren G, Zhou M, Zhang Q et al (2020) A novel stacked flow-through electro-Fenton reactor as decentralized system for the simultaneous removal of pollutants (COD, NH3-N and TP) and disinfection from domestic sewage containing chloride ions. Chem Eng J 387:124037. https://doi.org/10.1016/j.cej.2020.124037
Robles I, Becerra E, Barrios JA et al (2020) Inactivation of helmhinth eggs in an electro-Fenton reactor: towards full electrochemical disinfection of human waste using activated carbon. Chemosphere 250:126260. https://doi.org/10.1016/j.chemosphere.2020.126260
Salmerón I, Oller I, Plakas KY, Malato S (2021) Carbon-based cathodes degradation during electro-Fenton treatment at pilot scale: changes in H2O2 electrogeneration. Chemosphere 275:129962. https://doi.org/10.1016/j.chemosphere.2021.129962
Sirés I, Brillas E (2021) Upgrading and expanding the electro-Fenton and related processes. Curr Opin Electrochem 27:100686
Sodhi KK, Kumar M, Singh DK (2021) Insight into the amoxicillin resistance, ecotoxicity, and remediation strategies. J Water Process Eng 39:101858. https://doi.org/10.1016/j.jwpe.2020.101858
Tokumura M, Morito R, Hatayama R, Kawase Y (2011) Iron redox cycling in hydroxyl radical generation during the photo-Fenton oxidative degradation: dynamic change of hydroxyl radical concentration. Appl Catal B Environ 106:565–576. https://doi.org/10.1016/j.apcatb.2011.06.017
Yu F, Chen Y, Pan Y et al (2020) A cost-effective production of hydrogen peroxide via improved mass transfer of oxygen for electro-Fenton process using the vertical flow reactor. Sep Purif Technol 241:116695. https://doi.org/10.1016/j.seppur.2020.116695
Zaviska F, Drogui P, Blais JP et al (2011) Experimental design methodology applied to electrochemical oxidation of the herbicide atrazine using Ti/IrO2 and Ti/SnO2 circular anode electrodes. J Hazard Mater 185:1499–1507. https://doi.org/10.1016/j.jhazmat.2010.10.075
Zaviska F, Drogui P, Pablo G (2012) Statistical optimization of active chlorine production from a synthetic saline effluent by electrolysis. Desalination 296:16–23. https://doi.org/10.1016/j.desal.2012.03.023
Zhang J, Zheng C, Dai Y et al (2021) Efficient degradation of amoxicillin by scaled-up electro-Fenton process: attenuation of toxicity and decomposition mechanism. Electrochim Acta 381:138274. https://doi.org/10.1016/j.electacta.2021.138274
Zhou M, Tan Q, Wang Q et al (2012) Degradation of organics in reverse osmosis concentrate by electro-Fenton process. J Hazard Mater 215–216:287–293. https://doi.org/10.1016/j.jhazmat.2012.02.070
Zhou L, Zhou M, Hu Z et al (2014) Chemically modified graphite felt as an efficient cathode in electro-Fenton for p-nitrophenol degradation. Electrochim Acta 140:376–383. https://doi.org/10.1016/j.electacta.2014.04.090
Zhou M, Ren G, Ma L et al (2017) Cost-effective flow-through reactor in electro-Fenton. In: Handbook of Environmental Chemistry, pp 241–261

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.