

Optimization of the electrocoagulation process for the removal of copper, lead and cadmium in natural waters and simulated wastewater

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Abstract

Chemical, electrochemical and flow variables were optimized to examine the effectiveness of the electrocoagulation process for the removal of copper, lead and cadmium. The electrochemical process, which uses electrodes of commercial laminate steel, was applied to simulated wastewater containing 12 mg dm^{-3} of copper, 4 mg dm^{-3} of lead and 4 mg dm^{-3} of cadmium. The optimum conditions for the process were identified as $\text{pH} = 7$, flow rate = $6.3 \text{ cm}^3 \text{ min}^{-1}$ and a current density between 31 and 54 A m^{-2} . When the electrode geometric area and time of electrolysis reached critical values, the copper removal reached a maximum value of 80%. A linear relationship was identified between the current density and the mass of generated sludge. In addition, a linear relationship was found between specific energy consumption and current density. The results of this investigation provide important data for the development of an industrial-scale electrolytic reactor.

Keywords: Electrocoagulation; Copper; Lead and cadmium removal; Optimization conditions for electrocoagulation

1. Introduction

Historical effluent discharges from a variety of anthropogenic activities have resulted in contamination of rivers, lakes and other water-bodies. The explosive population growth and expansion of urban areas has exacerbated the adverse impacts on water resources. Since growing populations result in significant increases in wastewater volume, there is an urgent need to develop innovative, effective and inexpensive technologies to treat wastewater. To address this problem, technologies such as ion exchange, ultrafiltration, reverse osmosis and chemical precipitation have been developed. Each treatment method has advantages and disadvantages. Ion exchange, for example, while highly effective in removal of certain charged contaminants, requires resin regeneration or replacement at a high cost. Ultrafiltration and reverse

osmosis are clean processes, but can be prohibitively expensive. While chemical precipitation is a simple process, it does generate a high volume of sludge.

An effective technology that meets the requirements of process cleanliness, ease of manipulation, and low operational and investment costs is electrocoagulation. This technology was first employed in the 19th century to treat wastewater on ships, and has recently been utilized as an alternative to more conventional treatment processes. The electrocoagulation technologies are essentially electrolytic processes that involve the destabilization of suspended, emulsified or dissolved pollutants in an aqueous medium, by the application of an electric current. In electrocoagulation (a process similar to chemical coagulation), there is a reduction of the net surface charge to a point where the colloidal particles can approach closely enough for Van der Waal's forces to hold them together and allow aggregation to take place. The surface charge reduction is a consequence of the decrease of the repulsive potential of the electrical double layer by the presence of an electrolyte

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having an opposite charge. This mechanism corresponds to the destabilization of colloidal particles (Hiemenz and Rajagopalan, 1997).

During electrocoagulation, the coagulant is generated in situ by electrolytic oxidation of an anode of appropriate material. Charged ionic species are removed from wastewater by allowing ions to react with oppositely charged ions, or with flocs of metallic hydroxides generated within the effluent (Mollah et al., 2001).

Optimization of color removal in wastewater (Ibáñez et al., 1998), treatment of wastewater with oils (Ibáñez et al., 1995) and destruction of organic residuals has been accomplished using electrocoagulation (Ibáñez et al., 1997). Vik et al. (1984) studied the efficacy of electrocoagulation in removal of humic acid from potable water. This technology has also been investigated for the removal of suspended solids, oil and fat in restaurant wastewater (Chen et al., 2000), oils and fat in residuals from petroleum refineries (Monte Alegre and Martínez, 1993a, b), oil in industrial wastewater (Oblinger et al., 1984), and in the treatment of textile wastewater (Lin and Chen, 1997).

Because electrocoagulation is being satisfactorily used to treat wastewater, the need for additional physical chemistry studies is indicated (Mollah et al., 2001). Many studies have been designed to evaluate only the efficiency of the process as a function of fluctuations in critical variables. In this study, optimization of the chemical and electrochemical variables (of electrocoagulation) was carried out in natural waters and simulated wastewater to improve copper, lead and cadmium removal efficiency. This work includes the approach described by Levenspiel (1999) to apply the methodology to industrial needs.

2. Experimental

2.1. Apparatus and analytical measurements

Analytical determination of the metals was carried out using anodic stripping voltammetry. A voltammetric analyzer BAS (Bioanalytical Systems Lafayette, IN, USA), model CV-50 W, was used with a mercury film electrode on vitreous carbon as a work electrode, silver electrode/silver chloride as reference and a platinum electrode as auxiliary.

The experiments in batch were carried out on a BAS CV-27 voltammograph as a potentiostat with continuous current. For the experiments in continuous mode, a Phywe power source (220 V and 50 Hz with variable current flow) was used. An Ismatec MS-Reglo peristaltic pump, a Goldstar ammeter in series, and a Goldstar voltmeter in parallel to the circuit were also used.

2.2. Reagents and solutions

Solutions were prepared with distilled–demineralized water from a NANO pure, ultra-pure Barnstead Water System. In all experiments, a simulated solution control

Table 1

Cationic and anionic constituents of the simulated solution control

Cationic and anionic species	K ⁺	Ca ²⁺	Mg ²⁺	Na ⁺	SO ₄ ²⁻	HCO ₃ ⁻	Cl ⁻
Concentration (mg dm ⁻³)	2	102	48	94	192	250	182

Table 2

Cationic and anionic constituents of the synthetic wastewater

Cationic/anionic species	Concentration (mg dm ⁻³)
Al ³⁺	0.1
As _{total}	0.05
Ba ²⁺	0.05
Ca ²⁺	730
Cr _{total}	0.008
Cl ⁻	20
Mg ²⁺	5.5
Mn ²⁺	0.01
Na ⁺	79
SO ₄ ²⁻	1000
CN ⁻	0.01
F ⁻	0.2
Fe ²⁺	0.02
Ni ²⁺	0.01
Pb ²⁺	0.3
Cd ²⁺	0.8
Cu ²⁺	2.7

was used. The constituents of this solution are shown in Table 1.

Titrisol Merck[®] Standard Solutions of 1000 mg dm⁻³ of copper, lead and cadmium were used, and solutions of different concentrations were obtained by adequate dilutions. For pH adjustment, Merck[®] Solutions of 18.3 g dm⁻³ of HCl and 20.0 g dm⁻³ of NaOH were used. For the study of the influence of humic acid, a sodium salt derived from humic acid with a >300 °C melting point (Aldrich[®]) was used.

A synthetic wastewater was prepared to further evaluate the efficacy of the electrocoagulation process. The synthetic wastewater was CaSO₄-dominated with an ionic composition similar to what might be encountered in real-world effluent (Table 2).

2.3. Procedure in batch mode

A 600 cm³ beaker was used as a reactor, or electrocoagulation cell. Two sheets of rectangular laminate steel (degree SAE 1020 >99% iron) with an electrode geometric area of 54 cm² and 0.8 mm thickness were used as electrodes, and placed vertically in the bottom of the reactor.

A current density of 36 A m⁻² was applied for 10 min to 400 cm³ of control solution in the presence of 12 mg dm⁻³ of copper, 4 mg dm⁻³ of cadmium and 4 mg dm⁻³ of lead. The mixture was then heated at 35 °C, gently agitated for

2.5 min, left to sit undisturbed for 8 min and then vacuum filtered. A 1 cm^3 aliquot of filtrate sample was taken and diluted with 15 cm^3 of base electrolyte. All experiments were performed at room temperature (20°C).

2.4. Procedure for copper electrodeposition

The electrolysis and analytical measurements were completed using a batch mode. The retained fraction was obtained by dissolving the coagulated product with HCl 18.25 g dm^{-3} to produce 50 cm^3 ; from this volume, an aliquot was withdrawn and analyzed. The fraction in solution was determined in the filtrate and the electrodeposition fraction was determined by mass balance of the copper retained in the coagulated product and the copper in solution.

2.5. Procedure in continuous mode

The electrocoagulation cell and one-channel manifold used in the experiments in continuous mode are shown in Fig. 1. Two sheets of rectangular laminate steel (degree SAE 1020 > 99% iron) with an electrode geometric area of 14 cm^2 and 0.8 mm thickness were used as electrodes. The samples containing 36 cm^3 of control solution, with 12 mg dm^{-3} of copper and 4 mg dm^{-3} of cadmium and lead, were electrolyzed. The samples were collected in the cell exit, centrifuged for 10 min and then analyzed. In the study to evaluate the influence of pH, the pH was maintained between 4 and 9, flow rate was between 6.3

and $17\text{ cm}^3\text{ min}^{-1}$, and current densities ranged between 11 and 108 A m^{-2} . All the experiments were carried out at room temperature (20°C).

2.6. Procedure for the sludge-generation study

The general continuous mode procedure (described earlier) was used, but without previous centrifugation. The samples were collected in the electrocoagulation cell exit in $25 \times 2.5\text{ cm}$ tubes. Coagulated product was allowed to form for 1 h, then the formed sludge was vacuum filtered through a $0.45\text{ }\mu\text{m}$ filter (mixed cellulose ester) and weighed. The mass of the sludge was determined by weighing after the sludge was dried at 105°C for 24 h.

2.7. Procedure for the electrode lifetime study

The general (continuous mode) procedure (described earlier) was used. A flow rate of $6.3\text{ cm}^3\text{ min}^{-1}$ and a current density of 54 A m^{-2} were utilized. The initial pH was neutral (approximately 7.0). After electrolysis, the mass lost by the anode was determined by comparing the initial and final weights.

2.8. Copper, lead and cadmium analysis

Copper, lead and cadmium concentrations were determined by anodic stripping voltammetry. A base electrolyte solution of 7.45 g dm^{-3} of KCl in the presence of 80.2 mg dm^{-3} of Hg^{2+} was used.

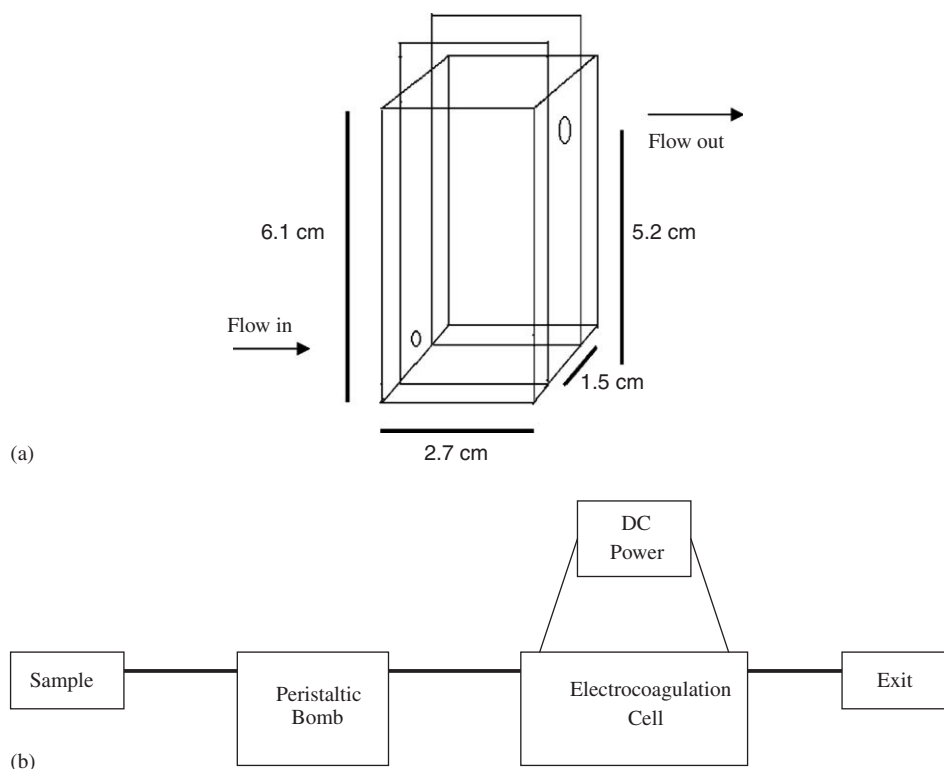


Fig. 1. Procedure in continuous mode: (a) electrocoagulation cell and (b) one-channel manifold.

The calibration curves and the samples were recorded at -1100 mV, during an active period of 180 s, followed by a 20 s resting period. Scanning was carried out between -1100 and 300 mV, with a scan rate of 35 mV s $^{-1}$, sensitivity of 1 mA V $^{-1}$, and instrumental recording interval of 1 mV. At lower concentrations, the calibration curves and the samples were recorded at -1100 mV, during an active period of 720 s with a 30 s resting period. Scanning at lower concentrations was completed between -1100 and 300 mV, with a scan rate of 50 mV s $^{-1}$, sensitivity of 1 mA V $^{-1}$, and instrumental recording interval of 1 mV.

2.9. Iron analysis

Iron was measured using the thiocyanate spectrophotometric method. After electrolysis, the samples were centrifuged and filtered through a 0.45 μ m filter (mixed cellulose ester). A 1 cm 3 aliquot of the filtrate was diluted to 10 cm 3 , with 4 cm 3 of 1 mol dm $^{-3}$ NaSCN and 5 cm 3 of 6 mol dm $^{-3}$ H $_2$ SO $_4$ solutions. The analytical wavelength was 450 nm, using 10 mm optical path cells.

3. Results and discussion

Standard solutions were used to develop the calibration graphs for copper, lead and cadmium. The anodic stripping voltammetry method was validated using certified river sediment of high-purity standard. The recovery ($n = 11$) was between 98% and 102% with a relative standard deviation of 1.9%. These data indicate the method was both accurate and repeatable.

3.1. Electrocoagulation results in batch mode

A logistical relationship between electrode geometric area (A_G) and copper removal efficiency ($r = 0.9909$; $\chi^2 = 3.71$) was found (Fig. 2). As expected, the increase in copper removal was related to an increase in A_G ,

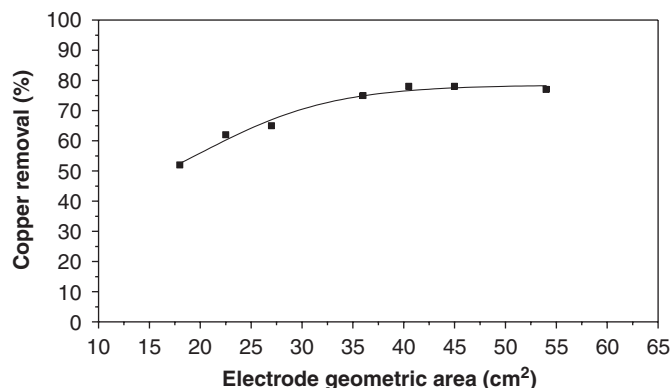


Fig. 2. Effect of geometric area of electrodes on copper removal: copper = 12 mg dm $^{-3}$. pH = 7.4, electrolysis time = 10 min, distance between electrodes = 1 cm, conductivity = 900 mS cm $^{-1}$.

reaching an optimal value of 35 cm 2 , with an asymptotic value near 80%.

The concentration of iron also increased since the number of loci suitable for electrogeneration also increased. While substantial copper removal was expected, a point was reached where the amount of coagulated iron was sufficiently high to counterbalance the transport process, and maximum coagulation and removal were therefore achieved.

In this context, the electrochemical system can behave as a capacitor, and the capacitive current could become more important than the faradic current. On the other hand, under the pH conditions observed in these studies, the copper partially precipitates as a hydroxylated form, and the remaining copper fraction is removed by electrolysis.

Increasing the spatial separation of electrodes reduces metal removal due to a decrease in current flow and coagulant generation (Fig. 3). An optimal distance of 2.0 cm for removal of lead and 2.5 cm for removal of cadmium and copper was identified. For later experiments, the electrode separation value of 2.5 cm was used.

This procedure promotes competition for the metallic cations between the generated coagulant agent and the cathode. Varying the intensity of the electric field causes opposite effects. If electric field intensity is increased, electrostatic attraction also increases and metal removal diminishes. Conversely, when field intensity is reduced, cathode attraction decays, thus increasing metal removal.

The study of the effect of electrolysis time on the copper removal shows a gradual increase along time, with a maximum copper removal of 80% occurring in 6 min.

Therefore, all the experiments in batch mode used an electrolysis time of 10 min, ensuring maximum removal. A similar trend was observed during the electrode geometric area study. The pH of the test solution must be considered, since at pH between 0 and 5, the hydroxylated species do not significantly affect metal removal. Other cations were found to behave in a similar manner.

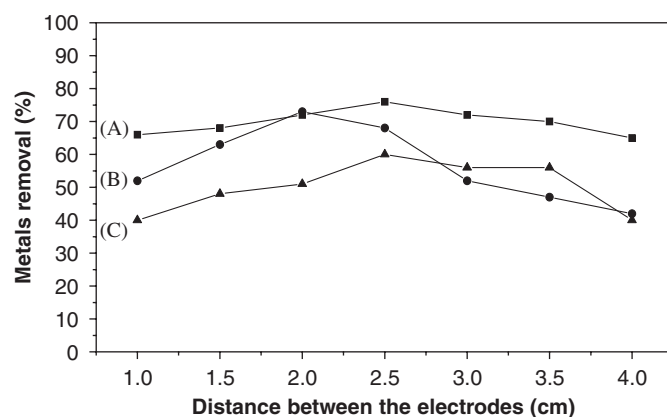


Fig. 3. Effect of distance between the electrodes on lead, copper and cadmium removal efficiency: (A) copper, 12 mg dm $^{-3}$, (B) lead, 4 mg dm $^{-3}$ and (C) cadmium, 4 mg dm $^{-3}$. Current density = 36 A m $^{-2}$, electrolysis time = 10 min, conductivity = 900 mS cm $^{-1}$.

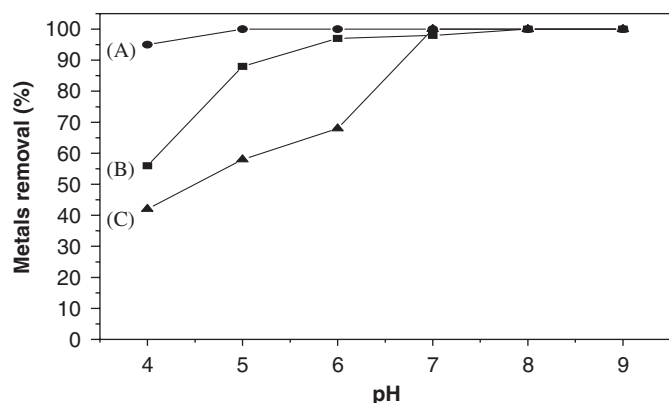


Fig. 4. Effect of pH on lead, copper and cadmium removal: (A) lead, 4 mg dm^{-3} , (B) copper, 4 mg dm^{-3} and (C) cadmium, 12 mg dm^{-3} . Current density = 36 A m^{-2} , electrolysis time = 10 min, distance between electrodes = 2.5 cm, conductivity = 1100 mS cm^{-1} .

The removal efficiency of copper and cadmium peaked at pH of 5 and 7, respectively (Fig. 4). The removal efficiency of lead did not appear to change substantially with pH. At a neutral pH of 7, all the metals demonstrated an optimal and consistent removal efficiency. When solution pH becomes acidic, the oxidation of ferrous iron (Fe II) to ferric iron (Fe III) diminishes, and therefore metal removal decreases. Alkaline pH, however, tend to favor Fe (II) to Fe (III) oxidation as well as complex polymerization. Finally, hydroxylated colloidal polymers and an insoluble precipitate of hydrated ferric oxide (Hiemenz and Rajagopalan, 1997) were formed and the removal efficiency was increased. At an alkaline pH, metal removal efficiency increased considerably, reaching nearly 100% removal, due to the precipitation of the target analytes.

Humic acid was found to have an initial positive impact on metal removal efficiency. In all cases, removal efficiency was higher in the first 5 min of agitation, probably due to the formation of insoluble compounds with the cationic metals in the presence of humic acid (Sauve et al., 1997, 1998). Over a longer period, however, the removal efficiency for all three metals was constant because the concentration of metals and humic acid did not vary.

Higher copper concentrations were measured in the coagulated product during the study to evaluate the impacts of electrode geometric area (Fig. 5). Electrodeposited copper increased along with the electrode geometric area, reaching a maximum at 35 cm^2 , and decreasing for bigger surfaces. On smaller surfaces, a significant migration allows copper to reach the cathode and be reduced on small surfaces. On larger surfaces, the migration becomes less significant and copper cannot reach the cathode. For this reason the copper percentage retained in the coagulated product increases starting from 35 cm^2 (Fig. 5A).

3.2. Electrocoagulation results in continuous mode

In the study to evaluate the effect of pH on the removal efficiency of copper, lead and cadmium, removal increased

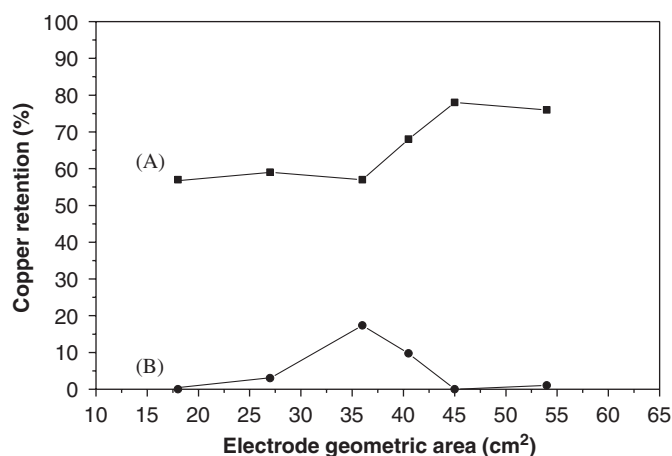


Fig. 5. Effect of geometric area of electrodes on: copper retention in coagulated product (A), copper electrodeposition (B). Copper, 12 mg dm^{-3} , pH = 7.5, electrolysis time = 10 min, distance between electrodes = 2.5 cm, conductivity = 900 mS cm^{-1} .

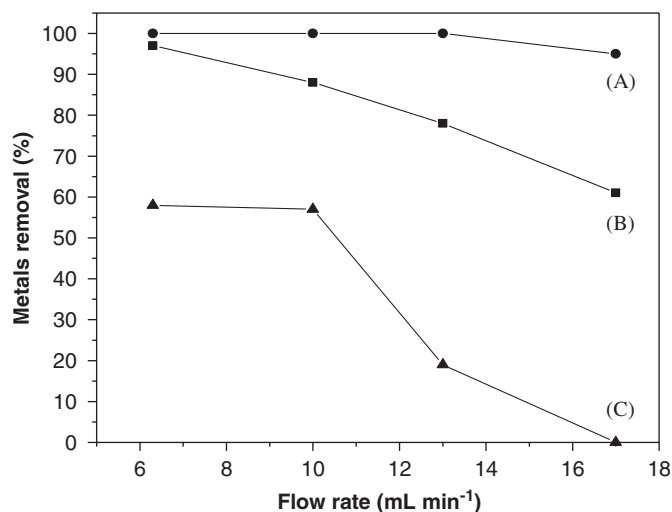


Fig. 6. Effect of flow rate on copper, lead and cadmium removal efficiency: (A) lead, 4 mg dm^{-3} , (B) copper, 4 mg dm^{-3} and (C) cadmium 4 mg dm^{-3} . pH = 6, current density = 40 A m^{-2} , distance between electrodes = 1.5 cm, conductivity = 1100 mS cm^{-1} .

gradually when pH increased. Consequently, results from the batch and continuous mode studies are similar. When the pH was greater than 7, flow rate was $6.3 \text{ cm}^3 \text{ min}^{-1}$, and electrode distance was between 31 and 54 A m^{-2} , a continuous removal rate of close to 100% was observed.

Copper, lead and cadmium removal efficiency decreased when the flow rate increased (Fig. 6). This reduction is likely due to a reduced residence time in the electrocoagulation cell. Removal of lead and copper remained consistently higher than cadmium, regardless of the flow rate. Lead removal was the least affected by increases in flow, never dropping below approximately 95%, even at the highest flow rates measured. Cadmium removal, on the other hand, decreased to near 0 at the highest flow rate. This substantial difference for cadmium is not unexpected

since, under the pH conditions in the study, only a small fraction of cadmium hydroxide and cadmium hydroxylated species are present.

Changes in metal removal under different flow rates (Fig. 6) occurred at a pH of 6. When the pH of the solution was increased to 7, cadmium removal continued to decrease when flow rate increased, again because of reduced contact time with the coagulant. Lead and copper removal at pH 7, however, proved to be more independent of the flow rate, possibly due to an increase in the overall process productivity at higher pH.

Removal efficiency of all three metals increased when current density increased, due to the generation of more coagulant as a higher current flow passed through the electrodes. Under these conditions, lead was completely removed from solution, and it was not possible to make quantitative observations regarding lead removal and current density. Removal efficiency was independent of current density when tests were run at a pH of 7, possibly because the process is generally favored at higher pH. Similarly, iron precipitation was found to increase as the pH rose, while at more acidic pH, electrogenerated iron is more readily dissolved.

Chemical reactions in the treated water result in the formation of gases, which alter metal speciation and affect water quality parameters. Water undergoes anodic oxidation to form O_2 (g), or cathodic reduction to form $H_{2(g)}$ (Levine, 1995). In this electrochemical system, the main anodic reaction is the oxidation of the Fe^0 to form Fe^{+2} , and, therefore, the reduction of the water is more significant than oxidation. The evolved gas in the experiments was H_2 (g), and the reduction of water also produced OH^- ions. While some hydroxyl ions are consumed in the formation of iron and metal hydroxides, the OH^- ions remaining solution explain the increase in solution pH during the reaction.

To identify an approach for application of the electrocoagulation process at an industrial level, it was necessary to establish a predictable relationship between current density and specific energy consumption. A linear relationship (when pH = 7) was found ($r = 0.9964$, $F = 272$, $p = 0.004$) (Fig. 7). The resulting equation (pH 7; flow rate = $6.3 \text{ cm}^3 \text{ min}^{-1}$) was

$$\begin{aligned} \text{Specific energy consumption (kW h m}^{-3}\text{)} \\ = 0.049 \times j - 1.05, \end{aligned} \quad (1)$$

where j is the current density, $A \text{ m}^{-2}$.

Specific energy consumption depends on cell voltage, and in this case, energy consumption depends on the equilibrium potential, the over-potentials at the cathode and the anode and the ohmic voltage losses in the cell (Scott, 1995). An increase in the current density causes a proportional increase of the ohmic voltage losses in the cell and of the specific energy consumption. This explains the behavior observed in Fig. 7.

In the electrode lifetime study, a lost anode mass rate of 2.2 g d^{-1} was found. Considering this result and the

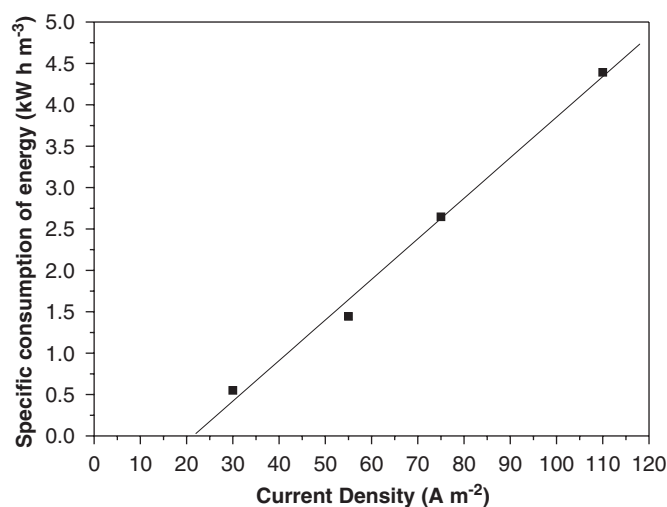


Fig. 7. Effect of current density on the specific consumption of energy. Flow rate = $6.3 \text{ cm}^3 \text{ min}^{-1}$, pH = 7, distance between electrodes = 1.5 cm, conductivity = 1000 mS cm^{-1} .

Table 3
Copper, lead and cadmium removal

Analyte	Initial conc. (mg dm^{-3})	Final conc. (mg dm^{-3})	Removal (%)
Copper	3.0	0.27	91
	1.0	0.27	73
Lead	1	0.01	99
	0.5	0.015	97
Cadmium	1	0.03	97
	0.5	0.04	92

Current density = 31 A m^{-2} , flow rate = $6.3 \text{ cm}^3 \text{ min}^{-1}$, pH = 7, distance between electrodes = 1.5 cm, conductivity = 1100 mS cm^{-1} .

dimensions and purity of the anode, an electrode lifetime of 4 d operating continuously was estimated. However, further studies that consider the passivity and scale-up of the electrodes are necessary for determination of a more accurate estimate of electrode lifetime.

There was a positive linear relationship between current density and the mass of dry sludge generated at a pH of 7 ($r = 0.998$, $F = 360$, $p = 3.19 \times 10^{-4}$). At a current density of 31 A m^{-2} , copper and cadmium removal rates decrease when the initial concentration of these metals decreases in the electrocoagulation cell (Table 3). For example, while 91% of the copper was removed when the initial concentration was 3.0 mg dm^{-3} , removal dropped to 73% when the initial concentration was 1.0 mg dm^{-3} . The final concentration in both cases was 0.27 mg dm^{-3} . This drop in percent removal occurs because the interaction probability with the coagulant decreases when cationic ions are present at lower concentrations. Because of its high mobility, the removal of lead is not as greatly affected when initial concentration is decreased. When the current density was 54 A m^{-2} , percent removal of lead and cadmium was not

Table 4
Copper, lead and cadmium removal

Analyte	Initial conc. (mg dm ⁻³)	Final conc. (mg dm ⁻³)	Removal (%)
Copper	3.0	0.21	93
	1.0	0.23	77
Lead	1	0.02	98
	0.5	0.005	99
Cadmium	1	0.01	99
	0.5	0.005	99

Current density = 54 A m⁻², flow rate = 6.3 cm³ min⁻¹, pH = 7, distance between electrodes = 1.5 cm, conductivity = 1100 mS cm⁻¹.

Table 5
Copper, lead and cadmium removal in a synthetic wastewater

Analyte	Initial conc. (mg dm ⁻³)	Final conc. (mg dm ⁻³)	Removal (%)
Copper	2.73	0.235	91
Lead	0.288	0.00288	99
Cadmium	0.818	0.00818	99

Flow rate = 6.3 cm³ min⁻¹, pH = 7, current density = 54 A m⁻², distance between electrodes = 1.5 cm, conductivity = 1100 mS cm⁻¹.

affected by the decrease in initial metal concentrations (Table 4). The reduction in copper removal at 54 A m⁻² was very similar to the reduction observed at the lower current density.

3.3. Application of electrocoagulation

Application of electrocoagulation to a synthetic wastewater at a pH of 7 was investigated. The copper concentration was reduced by approximately one order of magnitude, while both lead and cadmium were reduced by two orders of magnitude (Table 5). These data demonstrate that the electrocoagulation process is an efficient means of reducing cationic metals in wastewater.

3.4. Theoretical industrial application of the electrocoagulation process

In this application, previously identified optimized variables were used. At a pH of 7, copper and lead removal is nearly 100%, while the removal of cadmium depends on current density and flow rate.

The study was conducted to evaluate the impacts of flow rate on metal removal efficiency, taking into account the kinetics for cadmium. A linear relationship of the log-transformed cadmium concentration through time ($r = 0.9936$; $F = 155$; $p = 0.0064$) was identified. The results indicated a first-order kinetic reaction at a rate constant of 1.053 min⁻¹, for 31 A m⁻². First-order kinetics

were also indicated at 11 A m⁻², although the removal efficiency was better at 31 A m⁻².

Using the previously determined rate constant and a cadmium removal efficiency of 99.8%, and the piston flow equation (Levenspiel, 1999), the residence time (τ) was 5.9 min.

With a flow rate of 100 m³ h⁻¹, the volume of the reactor corresponds to 9.83 m³. The current density used was 31 A m⁻², resulting in a specific consumption of 0.47 kW h m⁻³ of energy according to the Eq. (1). The obtained results are a first step toward an industrial application of the process.

4. Conclusions

This study generated important information on the optimal conditions of several variables that influence electrocoagulation. It was found that copper removal was achieved primarily by adsorption in the coagulated product. Electrodeposition of the metal did not play a major role in metal removal, except at a short electrode distance. At a critical electrode geometric area of 35 cm² and electrolysis time of 6 min, a maximum copper removal rate of 80% was observed. Optimum electrode distances of 2 cm for lead and 2.5 cm for cadmium and copper were found. For both systems, the analyte removal efficiency increased considerably with the pH, reaching 100% removal when the pH exceeded 7.

In continuous mode, optimal performance was achieved when the pH was 7 (which resulted in a slightly alkaline output), flow rate was 6.3 cm³ min⁻¹ and current density ranged between 31 and 54 A m⁻². Also, an increase in the copper and cadmium removal efficiency at higher concentrations was observed. Removal appeared to follow first order kinetics, with a rate constant of 1.053 min⁻¹ for cadmium removal at a pH of 7. Using these results, it was possible to determine the residence time and volume of an industrial-scale reactor, in a first attempt to upwardly scale the electrocoagulation process. Additional studies are necessary to verify these results and further refine parameters for industrial application.

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