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Removal of zinc ions from synthetic and industrial Tunisian wastewater by electrocoagulation using aluminum electrodes

Khaled Brahmi[a,*], Wided Bouguerra[a], Béchir Hamrouni[a], Mouna Loungou[b]

[a]*Faculté des Sciences de Tunis, Département de Chimie, U. R Traitement et Dessalement des Eaux, 2092 Manar II, Tunisia, Tel./Fax: +21671871282; email: khaled.brahmii@gmail.com (K. Brahmi)*
[b]*Groupe Chimique Tunisien, Usine de M'Dhilla Gafsa, km. 14 Route, 2100 M'Dhilla, Gafsa, Tunisia, Tel. +216 76211515*

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ABSTRACT

Electrocoagulation (EC) is an efficient technique for cleaning waste water containing heavy metals before discharge in the environment. The performance of electro coagulation for zinc ions removal using aluminum electrodes was investigated in this paper. Several electrochemical parameters such as pH, current density, electrolyte doses, energy consumption, initial concentration, EC time, the state of the aluminum plates, and heavy metal ions concentration were studied in an attempt to achieve high zinc removal efficiency. Optimum conditions for zinc removal were found at a pH value of 7, a current density of 7.35 mA cm^{-2}, an inter-electrode potential of 5 V, a conductivity of 5.3 mS cm^{-1}, and an EC time of 30 min. These operating conditions can simultaneously achieve a good mix, good flotation, high flocs stability, and thus efficient removal in a relatively short reaction time and low cost with a removal percentage up to 98.96. The testing of zinc removal from industrial waste water showed that the removal by EC using aluminum electrodes was effective and the removal efficiency of zinc reached 100% in the first 5 min of treatment with a very low power consumption of 1.02 kW h m^{-3} for an initial pH over 5. In the light of these results, this method promises interesting industrial applications.

Keywords: Industrial wastewater treatment; Electrochemistry; Electrocoagulation; Zinc removal

1. Introduction

Industrial effluents of phosphate fabrication contain high amounts of heavy metal ions, such as mercury, cadmium, and zinc. These heavy metals, known as powerful toxic agents, are not only teratogenic but also carcinogenic and pose potential hazard to plant, animal, and human life. Zinc is one of the most frequent elements in the earth's crust. This heavy metal hardly decreases in potency after it is released into the environment. Over time, zinc tend to accumulate in the environment, be absorbed or ingested by plants and animals, accumulate in the tissues of animal and plant then pass through the food chain and cause long-term human health and ecological problems [1].

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*Corresponding author.

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Zinc is an essential element in human's life, but a large amount of zinc is harmful and can also damage human health. Eating food containing so much of zinc in a short time can cause stomach cramps, nausea, and vomiting [2].

The Chemical Tunisian Group wastewaters may contain up to 100 mg L^{-1} toxic heavy metals which present an acceptable level, according to environmental regulations worldwide, before it is discharged and released in the environment. For this reason and from the standpoint of environmental protection and resource saving, effective recycling and reusing of the heavy metal wastewater have come to be urgent. Closed-recycle system or so-called effluent-free technology should be developed.

The most well-known methods that have been conventionally used in extensive studies seeking to remove heavy metals from industrial wastewaters are ion exchange [3], precipitation [4], adsorption [5], ions exchange [6], coagulation–flocculation [7], electro dialysis [8], and electrocoagulation (EC) treatment [9].

EC does not involve using chemical coagulating agents generated during the electrolysis process by electro-dissolution of a sacrificial anode made of aluminum. EC has been successfully performed for many types of industrial wastewaters treatment such as decolorization of textile wastewaters [10], the defloration of water [11], the treatment of water flowing from tobacco factory [12], treatment of oil wastes [13], diary effluents [14], diesel and bio-diesel wastewaters [15], and the treatment of wastewaters charged with heavy metals [16].

This paper reports the optimization of the electrochemical variables of EC using aluminum electrodes to enhance zinc removal efficiency. In this work, this method is implemented to meet industrial needs in the most cost-effective way possibly. Besides, this study presents a detailed account of the effects of different parameters such as initial pH, applied current density, state of the aluminum plates, conductivity, Faradic efficiency, and energy consumption on Zn(II) removal.

2. Materials and methods

2.1. Cell construction and procedure

A schematic diagram of electrochemical cell is shown in Fig. 1. The electrolytic cell consists of a 1 L glass beaker. The electrodes (anode and cathode) used in this work were formed by two parallel rectangular aluminum plates (250 mm × 80 mm × 2 mm). Both sides of active electrode surface area were (85 mm × 80 mm × 2 mm) corresponding to active electrode surface $S_a = 136\ \text{cm}^2$. The anode–cathode distance (ACD) was varied from 5 to 20 mm. In order to avoid a passivation film, these electrodes were cleaned before use by treating them with NaCl and HCl aqueous solutions. A gentle agitation was made using a magnetic mixer. The applied current density was maintained at the ranges of 0–3 A and 0–30 V using a regulated direct current (DC) AFX 2930 SB DC power supply, and the voltage cell was continuously recorded. The conductivity and pH of the solution were measured during the experiments using a conductivity meter Jenway 4510 (Ω Metrohm) and a pH meter pH Cyber Scan 510 (WDW, Germany), respectively. If required, the pH of the electrolyte was adjusted with HCl or NaOH solution of 0.1 M concentration before the electrolysis started. Sodium chloride dose was added in the solution to adjust conductivity. The current intensity between the electrodes and the resulting voltage was controlled using the generator. In each EC test, 1,000 mL of 100 mg L^{-1} zinc solution was treated. As the EC time progresses, every five minutes a sample was extracted from the solution and analyzed after filtration. The experimental error was around 5%. Zinc removal efficiency is calculated by Eq. (1).

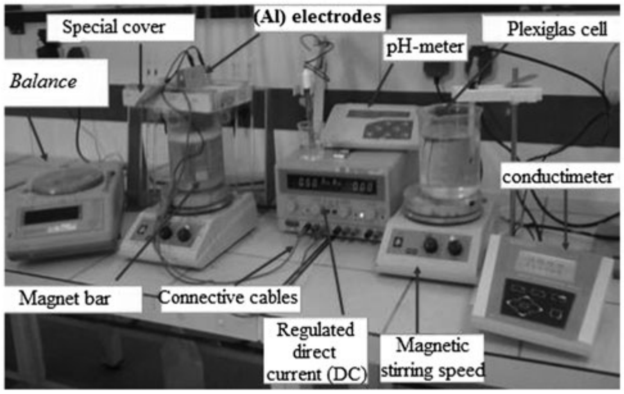

Fig. 1. Laboratory scale cell assembly.

$$\text{Zinc removal efficiency } (\%) = \frac{C_i - C_0}{C_0} \times 100 \tag{1}$$

where C_i and C_0 are the initial and residual concentration (mg L^{-1}) of the zinc in the solution, respectively.

2.2. Analytical techniques

Zinc concentration was determined by atomic absorption spectroscopy with flame (AASF) method using back ground correction. In the context of this study, this method was the most feasible one and could be adequately adapted to the measurement of higher concentration of zinc, with detection limits consistent with the objectives of the analysis of natural water. For this reason, atomic absorption spectroscopy with flame Analytic Jena Nova 400 was used while conducting the analyses of zinc concentration.

2.3. Validation of the analytical techniques

In order to perform the experiments and to assure the reliability and validity of the atomic absorption method that was used to determine residual zinc(II) concentration, several tests were done to calculate the linearity, specificity, fidelity (reproducibility and repeatability) as well as limits of both instrumental method detection and quantification. The result of the experimental validation of the atomic absorption analytical method is shown in Table 1.

Based on the values presented in Table 1, the method for Zn(II) determination by AASF without background correction is an efficient method with a detection limit of 0.01078442 mg L^{-1} and quantification of 0.03594806 mg L^{-1}in a linearity range of 0.1–1 mg L^{-1}.

3. Results and discussion

3.1. Study of the influence of the initial solution pH

3.1.1. Optimization of the initial pH

Previous studies [17] have proved that pH is an important parameter influencing the performance of the EC process. Hence, pH optimization was done by studying the initial pH effect as a function of the removal efficiency. The initial pH effect was determined over a pH range of 1.3–10, a current density (J) of 3.68 mA cm^{-2}, an electrolysis time (t_{EC}) of 60 min, and a sodium chloride concentration of 2.5 g L^{-1} corresponding to a conductivity of 5.19 mS cm^{-1}. The initial pH effect on the removal of Zn(II) by EC is shown in Fig. 2.

When the initial pH was highly acidic, the zinc removal efficiency decreased. This decrease was attributed to an amphoteric behavior of the coagulant Al $(OH)_3$ which led to soluble Al^{3+}, $Al(OH)^{2+}$ and $Al(OH)_2^+$ cations at acidic medium and monomeric anions $Al(OH)_4^-$ at an alkaline medium. These species are not useful for water treatment. At an initial alkaline pH higher than 8, OH^- ions can also partially combine with Zn^{2+} to form insoluble zinc hydroxide precipitation $Zn(OH)_2$ and zinc removal efficiency increased. The removal percentage increased up to 79.21% for an initial pH value of 7. This could be explained by the increase in the quantity of the coagulant $AlOH_3$ formed in the solution which led to a maximum zinc adsorption by EC (Fig. 3). As shown in Fig. 4, a gelatinous film formation on the surface of the anode was displayed at the anode surface and increased in more alkaline medium. Additionally, when the pH was higher than 8, having been formed, the film reduced the active surface of the anode and prevented the anodic dissolution of the aluminum plate. This confirms that zinc removal at alkaline medium is attributed to zinc hydroxide precipitation.

The optimal initial pH for the removal of zinc by EC was found in the vicinity of pH 7 with a percentage of removal up to 79.21%.

3.1.2. Study of the pH evolution

As has been pointed out in several previous papers [18,19], the use of soluble anodes causes a change in the pH of the solution during EC. In each EC test, we measured the pH of the treated solutions as a function of time; all results are shown in Fig. 5.

The final pH of the solution depends not only on the metal ions concentration but also on the initial pH and the buffer capacity $AlOH_3/Al(OH)_4^-$ of the treated water. As shown in Fig. 5, no change occurred in the final pH for an initial strong acidic pH of 1.3. In contrast, for an initial pH in the range 3–7, there was a

Table 1
Experimental validation of the analytical method

Test	Experiment value	Critical value	Conclusion
Linearity	$F_l = 13234.972$	$V_{Cl} = 8.1$	Linear linearity
	$F_{nl} = 4.549$	$V_{Cnl} = 4.94$	No curvature approved
Specificity	$T_{obs} = 1.973$	$t_{(8;0.995)} = 3.355$	Slope equal to 1 Origin specific
	$T'_{obs} = 1.578$		
Cochran	$C_{xobs} = 0.498$	$C_{Cochran,\alpha=5\%} = 0.629$	Point group is considered no aberrant
		$C_{Cochran,\alpha=1\%} = 0.721$	Point group is considered no suspect
Fidelity	$CV_r = 1.500; 1.303; 1.013; 1.189$	$CV_r < 5\%$	Repeatable faithful
	$CV_R = 1.465$	$CV_R < 5\%$	Reproductible

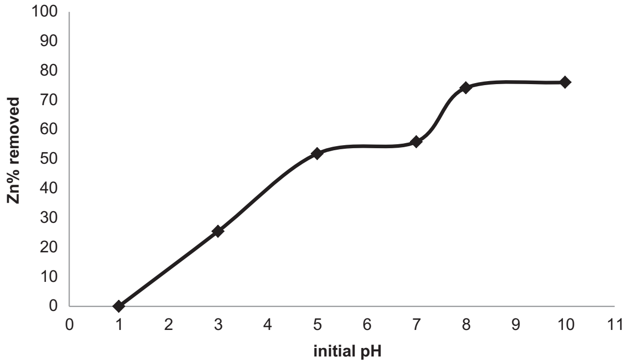

Fig. 2. Initial pH effect on the Zn(II) removal by EC.

large variation in the final pH. The study of zinc elimination from water by EC showed that pH would increase at initial pH lower then 7.

This increase was attributed to the evolution of hydrogen at cathodes. The liberation of CO_2 from wastewater was disturbed by H_2 gas bubble [19]. In fact, at low pH, CO_2 was more saturated in wastewater and could release for the period of H_2 evolution, causing an increase in the solution pH. It is important to note that for a strong initial basic pH higher then 10, the final pH was lower than the initial pH.

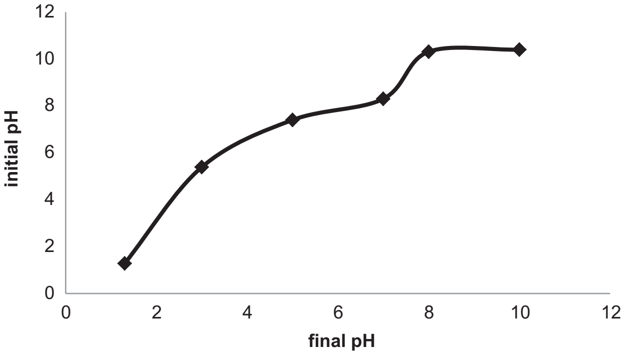

Fig. 5. Evolution of final pH versus initial pH.

3.1.3. Optimization of the EC time

To highlight the effect of the electrolysis time on zinc removal, a set of EC tests were performed by tracking the concentration of zinc for different electrolysis time spans for different initial pH of the solution to determine the optimal time required for the removal under various conditions of EC process. The evolution of the percentage of zinc removal was studied over a pH range of 1.3–10 for an initial conductivity (σ) of $5.19\,\mathrm{mS\,cm^{-1}}$, a current density ($J$) of $3.68\,\mathrm{mA\,cm^{-2}}$, and a salt concentration of $2.5\,\mathrm{g\,L^{-1}}$.


pH= 1.3 pH= 7 pH= 10

Fig. 3. Influence of initial pH on hydroxide flocs quantity formation.

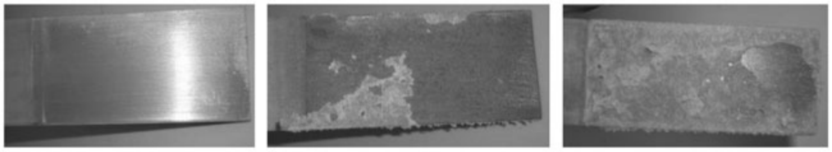
pH= 1.3 pH= 8 pH= 10

Fig. 4. Influence of initial pH on the state of the anode.

Fig. 6 shows the variation of the residual concentration of zinc by EC with time for different initial pH of the solution.

Based on Fig. 6, it is readily noticeable that the residual zinc concentration decreased significantly during the first stage of electrolysis. For an initial pH higher than 5, zinc concentration decreased significantly within a span of 30 min. An electrolysis time of 30 min would be sufficient to obtain a maximum zinc removal by EC.

3.1.4. Effect of the current density

It is well-known that electrical current determines the coagulant dosage rate, the bubble production rate and size, and the flocs growth [20]. The optimization of the electrical current is so important to reduce as much as possible, energy wastage. For this purpose, the effect of current density on the zinc removal was investigated, a series of tests was carried out where the parameters are an electrolysis time of 60 min, a salt concentration of 0.4 g L^{-1}, an initial conductivity $\sigma_i = 0.87$ mS cm^{-1}, and a current density ranging between 2.21 and 7.35 mA cm^{-2}. Fig. 7 shows the removal of Zn(II) as a function of time for different current densities.

It can be noticed from Fig. 6 that a significant increase in Zn(II) removal occurred just at the beginning of the process for all the applied current densities and became slower thereafter. The percentage of zinc removal reached 30% in 15 min, for all the studies applied current densities.

Lower current density had lesser effect on the final total Zn(II) removal and the time required to attain good efficiencies increased. The removal of zinc increased significantly with the increase in current density. The highest electrical potential between the two electrodes produced the quickest treatment; more than 76.84% reduction occurred after the first 30 min. This could be explained by the fact that at higher voltage the quantity of aluminum oxidized increased resulting in a higher quantity of coagulant and a better zinc removal.

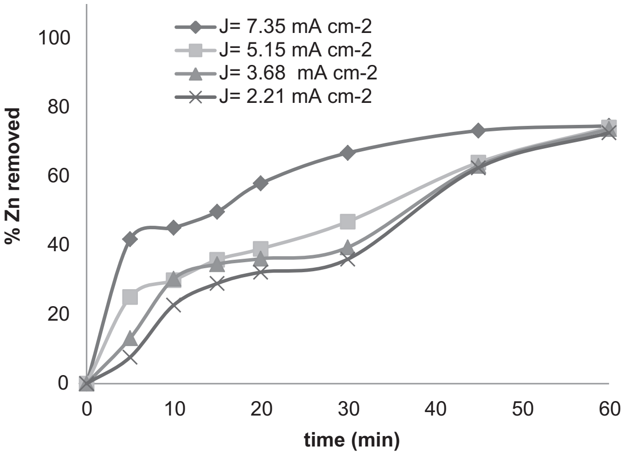

Fig. 7. Variation of zinc removal percentage as a function of EC time for different current densities.

For low current densities of 2.21 mA cm^{-2}, white deposits with a gelatinous appearance on the anode were formed. This passivation film, which reduced the active surface of the anode preventing its dissolution, could explain the decrease in removal efficiency of zinc. At high current density ranging from 5.15 to 7.35 mA cm^{-2}, a darkening on the cathode surface due to chemical corrosion appeared. Therefore, we can note that the surface deposit disappeared with increasing the current density.

It was also found that the increase in current density was accompanied by an increase in the difference

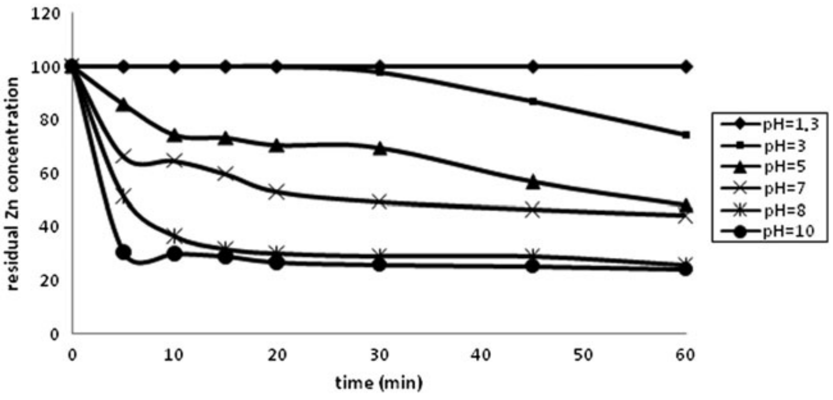

Fig. 6. Evolution of zinc concentration as a function of EC time at different initial pH of the solution.

of potential between the two electrodes, which led to an increase in energy consumption. During all the EC tests, the difference in potential between the electrodes was measured over time for different current densities studied. The obtained results are summarized in Table 2.

3.1.5. Energy consumption

Different parameters such as current density, the potential difference between the electrodes and dissolved amount of salt present in the solution affect the current efficiency and the energy consumption. The difference in potential between the electrodes was measured over time for the different current densities studied. The EC electric power consumption W (kW h m^{-3}) was calculated by Eq. (2). Fig. 8 shows the variation in energy consumption as a function of time for different current densities studied.

$$W = \frac{U \cdot I \cdot t}{v} \tag{2}$$

where U is the voltage cell (V), I is the current (A), t is the time of electrolysis (h), and v is the volume (m^3) of the solution.

The energy consumption varied linearly as the EC time progressed. The increase in the current density resulted in a fairly rapid increase in energy consumption. Thus, to choose the current density and the optimum EC time, a compromise between economically suitable energy and removal efficiency should be found. Table 3 summarizes the removal efficiencies of zinc and energy consumption as a function of time for the applied current densities.

The highest current densities produced the quickest treatment, more than 66.84% reduction occurred after the first 30 min for a current density of 7.35 mA cm^{-2}. This could be explained by the fact that at higher voltage the quantity of aluminum oxidized increased resulting in a higher quantity of coagulant and a better zinc removal. But this increase in removal efficiencies is accompanied by high energy consumption with a disadvantage, the use of high current densities.

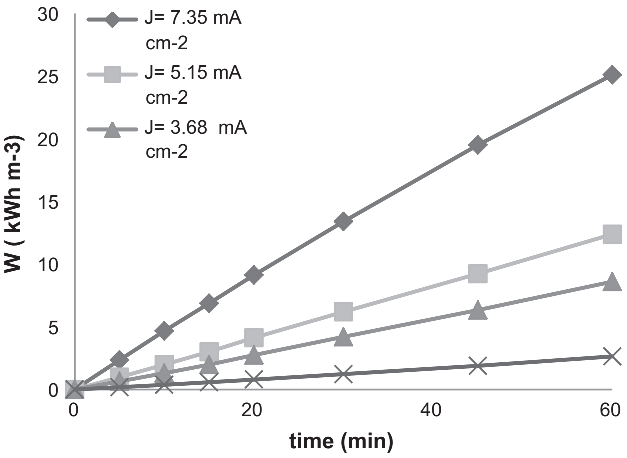

Fig. 8. Variation of energy consumption as a function of EC time for different current densities.

3.1.6. Effect of conductivity and electrolyte (sodium chloride) dose

The addition of electrolyte promotes the electrical transport ensuring better chemical dissolution of aluminum. In the absence of electrolyte, the current density and the solution conductivity would be lower. Generally, sodium chloride is considered as a conductive electrolyte essential for the functioning of the EC process with aluminum electrodes [21,22]. In order to highlight the effect of conductivity by the addition of electrolyte NaCl on the effectiveness of water treatment, five tests were performed by varying the conductivity of the solution from 0.87 to 5.86 mS cm^{-1} by adding a different dose of sodium chloride. The results are summarized in Table 4.

Fig. 9 illustrates the variation of zinc removal overtime for different added doses of sodium chloride.

Table 2
Variation of the difference in potential between electrodes as a function of time for different current densities

		Time (min)						
J (mA cm^{-2})	I (A)	0	5	10	15	30	45	60
7.35	1	28.2	28.20	28.00	27.50	27.40	26.8	26.00
5.15	0.7	16.80	16.80	17.00	17.20	17.70	17.7	17.60
3.68	0.5	13.60	15.40	15.60	15.90	16.50	16.8	16.90
2.21	0.3	7.10	7.30	7.50	7.50	8.00	8.10	8.40

Table 3
Variation of energy consumption as a function of current density

J (mA cm^{-2})	3.68				5.15				7.35			
Time (min)	15	30	45	60	15	30	45	60	15	30	45	60
%Zn removed	34.59	39.47	63.08	73.76	35.87	46.92	64.05	74.19	49.80	66.84	73.29	74.68
W (kW h m^{-3})	1.98	4.20	6.33	8.60	3.01	6.19	9.24	12.39	6.87	13.40	19.50	25.10

The experimental results proved that this addition increased the removal efficiency. The percentage of zinc removal exceeded 80% after only 15 min for 2 and 3 g L^{-1} of sodium chloride doses. Increasing the sodium chloride dose from 0.3 to 3 g L^{-1} resulted in an increase in the removal efficiency from 54.01 to 83.48%. Table 5 shows the variation of the electric power consumption caused by the increase in the conductivity of the solution for an electrolysis time span of 30 min.

The results show that the addition of salt could be beneficial in terms of energy consumption, but, on the other hand, we noticed that there was an overconsumption of aluminum electrodes by corrosion if the NaCl concentration exceeded 2 g L^{-1} corresponding to a conductivity of 4.28 mS cm^{-1}. This addition allowed to overcome the problem of the high energy consumption caused by the anode–cathode resistance.

3.1.7. Effect of initial concentration

To demonstrate the effect of the initial zinc concentration on the removal efficiency as a function of time, solution with different concentrations of 10, 100, 200, 300, and 500 mg L^{-1} were prepared. This study was realized by keeping constant current density at 3.68 mA cm^{-2}, initial pH at 7, conductivity at 5.86 mS cm^{-1}, and distance between electrodes at 2 cm. The pH, the temperature, the difference in potential between the two electrodes, and the final zinc concentration was measured for each sample. Energy consumption and treatment cost were calculated for each sample. The results are presented in Table 6.

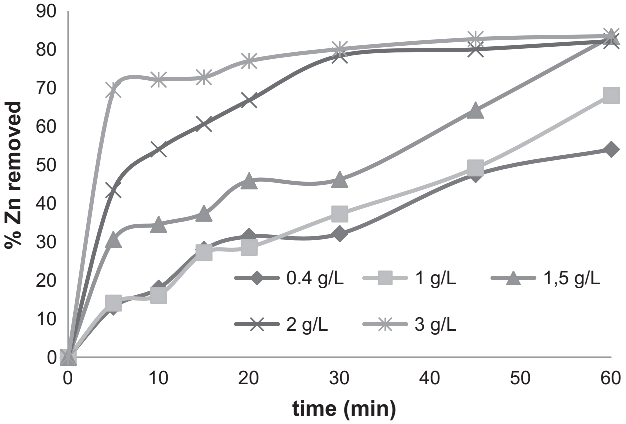

Fig. 9. Variation of zinc concentration as a function of EC time for different conductivities.

Table 5
Variation of energy consumption as a function of conductivity

Conductivity (mS cm^{-1})	0.87	2.12	3.32	4.28	5.86
[NaCl] (g L^{-1})	0.4	1	1.5	2	3
I (A)	0.5	0.5	0.5	0.5	0.5
U (V)	15.5	7.7	6.5	4.7	3.6
W (kW h m^{-3})	3.775	1.85	1.65	1.175	0.9
%Zn removed	32.07	37.24	46.23	78.37	80.07

Table 4
Variation of zinc concentration as a function of EC time for different doses of added NaCl

		Time (min)							
Conductivity (mS cm^{-1})	m NaCl (g L^{-1})	0	5	10	15	20	30	45	60
0.87	0.4	100	86.95	82.09	72.03	68.59	67.93	52.54	45.99
2.12	1	100	85.91	83.9	72.85	71.41	62.76	50.78	31.95
3.32	1.5	100	69.4	65.48	62.58	54.15	53.77	35.78	16.66
4.28	2	100	56.59	45.97	39.39	33.2	21.63	19.98	17.83
5.86	3	100	30.53	27.89	27.23	23.01	19.93	17.31	16.52

Table 6
pH temperature, difference in potential between the two electrodes, and residual zinc concentration as a function of time for different initial Zn(II) concentrations

$[\mathrm{Zn}]_{\mathrm{initial}}$ (mg L^{-1})	*t* (EC)	*T* (°c)	*U* (V)	pH	Conductivity (mS cm^{-1})	Intensity of current (A)	*W* (kW h m^{-3})
10	5	15.9	4.7	7.92	4.28	0.5	11.75
	10	16.1	4.7	8.07	4.28	0.5	23.50
	15	16.3	4.5	8.60	4.28	0.5	33.75
	20	16.6	4.5	8.70	4.28	0.5	45.00
	30	16.9	4.5	8.83	4.28	0.5	67.50
	45	17.5	4.4	9.05	4.28	0.5	99.00
	60	18.1	4.4	10.18	4.28	0.5	132.00
100	5	15.5	3.5	6.40	4.28	0.5	8.75
	10	16.2	3.5	5.68	4.28	0.5	17.50
	15	16.6	3.5	5.71	4.28	0.5	26.25
	20	16.8	3.5	7.23	4.28	0.5	35.00
	30	17.2	3.5	7.31	4.28	0.5	52.50
	45	17.6	3.5	7.90	4.28	0.5	78.75
	60	18.3	3.5	8.30	4.28	0.5	105.00
200	5	15.8	3.6	7.40	4.28	0.5	9.00
	10	16.1	3.6	6.64	4.28	0.5	18.00
	15	16.2	3.6	7.09	4.28	0.5	27.00
	20	16.4	3.6	7.73	4.28	0.5	36.00
	30	17	3.6	8.08	4.28	0.5	54.00
	45	17.9	3.6	8.93	4.28	0.5	81.00
	60	18.1	3.6	9.05	4.28	0.5	108.00
300	5	15.9	3.7	6.13	4.28	0.5	9.25
	10	16	3.6	5.82	4.28	0.5	18.00
	15	16.3	3.6	6.83	4.28	0.5	27.00
	20	16.4	3.6	7.18	4.28	0.5	36.00
	30	16.6	3.6	7.69	4.28	0.5	54.00
	45	17.6	3.7	8.36	4.28	0.5	83.25
	60	18.3	3.7	9.23	4.28	0.5	111.00
500	5	16.1	2.1	6.68	4.28	0.5	5.25
	10	16.4	2.1	6.66	4.28	0.5	10.50
	15	16.7	2.3	6.60	4.28	0.5	17.25
	20	17.1	2.3	7.03	4.28	0.5	23.00
	30	17.7	2.2	7.62	4.28	0.5	33.00
	45	18.6	2.2	7.70	4.28	0.5	49.50
	60	19.7	2.2	8.33	4.28	0.5	66.00

The experimental results presented in Fig. 10 show that the zinc removal efficiency is higher for low concentration of 10 mg L^{-1} and reached 100% of removal in only 5 min. For high concentrations ranging from 100 to 300 mg L^{-1}, to achieve good final removal, a high EC time was required. Above the concentration of 100 mg L^{-1}, the adsorption capacity of flocs was exhausted and the generation of intermediate products increased, which competed with zinc in the solution and the zinc removal rate fell down. Certainly, for higher concentrations longer time for removal is needed. For an initial zinc concentration of 500 mg L^{-1}, 32% of zinc was removed after only 10 min. The removal of this large amount could be explained by the increase in the probability of contact between flocculants and Zn(II) ions at high concentration. Therefore, we can conclude that the EC process is more effective at the first step of the reaction when the concentration is higher.

4. Treatment of the case-study wastewater

In order to validate the applicability and to examine the performance of the EC process, EC tests were applied on the treatment of an industrial effluent sample without any pretreatment. The industrial effluent was collected from a Tunisian phosphate fabrication

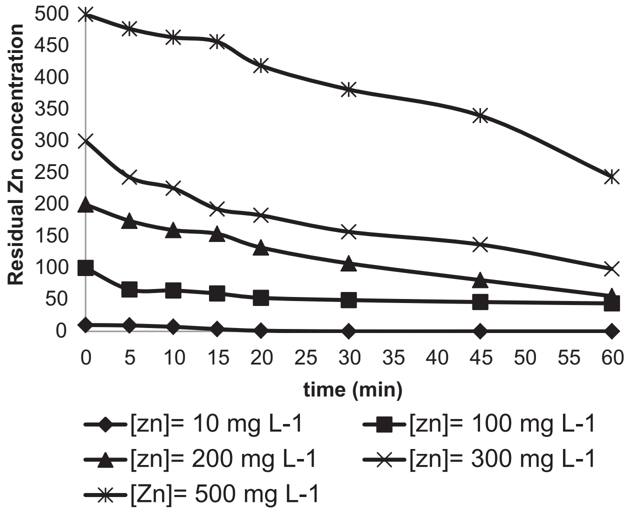

Fig. 10. Variation of residual zinc concentration as a function of EC time for different initial zinc concentrations.

Table 7
Characteristics of the industrial wastewater before and after the treatment by EC

Sample characteristics	Before the treatment	After the treatment and after filtration for initial pH 7
pH	2.08	10.94
Conductivity (mS cm^{-1})	1.179	1.126
Density of waste water	1.024	1.009
T (°C)	15.0	18.5
[P_2O_5] (mg L^{-1})	5.017	–
MS	0.256	0.034
[Zn^{2+}] (mg L^{-1})	6.360	0

industry. The characteristics of the sampled effluent before and after the EC treatment are shown in Table 7.

To carry out the treatment of the industrial wastewater, the pH of the solution was adjusted by adding sodium hydroxide salt. In order to obtain pH 3, 5, and 7 without changing the volume of the solution, it was necessary to add different doses of sodium hydroxide. The pH, the temperature, and the difference in potential between the two electrodes was measured for each sample. The results are presented in Table 8.

The testing of zinc removal from industrial wastewater showed that the removal by EC using aluminum electrodes was effective. As shown in Fig. 11, the removal efficiency of zinc reached 100% in 5 min with a low power consumption of 1.02 kW h m^{-3} for an initial pH over 5.

Table 8
pH temperature and the difference in potential between the two electrodes as a function of time for the treatment of the industrial wastewater

Initial pH	Time (min)	U (V)	pH	T (°c)
3	0	2.8	3.00	15.0
	5	2.8	3.14	15.3
	10	2.8	3.17	15.9
	15	2.8	3.19	16.1
	20	2.8	3.2	16.2
	30	2.9	3.16	16.3
	45	2.9	2.93	16.9
	60	2.9	2.98	17.5
5	0	2.5	5.00	15.0
	5	2.2	5.28	15.4
	10	2.0	5.58	15.6
	15	2.0	5.70	15.8
	20	2.0	5.87	15.9
	30	2.0	5.92	16.3
	45	2.0	6.08	16.8
	60	2.0	6.24	17.3
7	0	2.3	7.00	15.0
	5	2.0	7.26	15.9
	10	2.0	7.60	16.2
	15	2.0	7.83	16.3
	20	2.0	7.99	16.6
	30	2.0	9.15	17.1
	45	2.0	10.28	17.9
	60	1.9	10.94	18.5

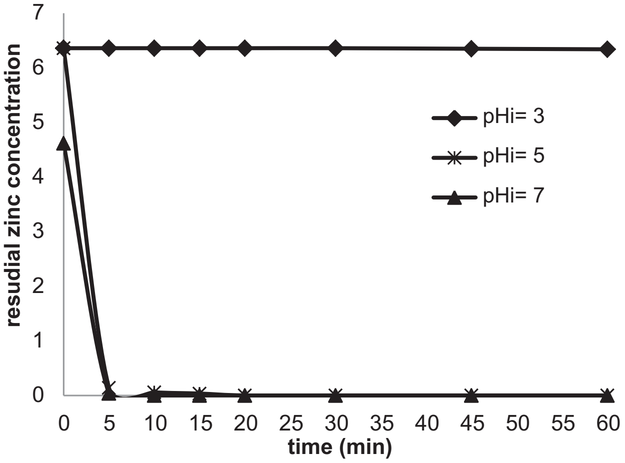

Fig. 11. Variation of residual zinc concentration as a function of EC time for different initial pH.

5. Conclusion

This study aimed at investigating the efficiency of the EC process on the removal of zinc from Tunisian phosphate fabrication industry (Chemical Tunisian Group, M'Dhilla, Gafsa, Tunisia). The main objective of this study was to select the optimal conditions for EC process such as current density, initial pH, conductivity, energy consumption, and operating time. Aluminum material was found to be able to remove Zn(II) ions from synthetic solutions and industrial wastewater. Using tap water, we prepared a synthetic solution of zinc concentration $100\,\mathrm{mg\,L^{-1}}$ which we have systematically treated using aluminum electrodes, and the analyses were conducted by means of atomic absorption spectrophotometer with flame. Best removal capacity for the removal of zinc from water was achieved at pH 7. The removal rate increased with the increase in current density. Also, the optimizations of the sodium chloride dose increased the removal efficiency. The present study ensures that EC presents a clean process providing cost-effective investment and treatment, and a great removal efficiency of zinc from industrial waste water. The investigation of EC on the treatment of the discharged wastewater of Chemical Tunisian Group showed that the removal of zinc from the industrial wastewater was effective and reached 100% in only 5 min of electrolysis with a low power consumption of $1.02\,\mathrm{kW\,h\,m^{-3}}$. In conclusion, we can affirm that EC is an economical method for removing heavy metals from industrial effluents.

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