

Techno-economic assessment of Ni removal from industrial wastewater by electrocoagulation using rectangular aluminium electrodes

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Received 17 December 2021; Accepted 1 June 2022

ABSTRACT

The present research focuses on the removal of nickel Ni(II) from synthetic and industrial wastewater using rectangular aluminium electrodes. The main effect of electrocoagulation (EC) parameters to remove heavy metals in a batch electrolytic reactor was evaluated and the characteristics of the EC sludge were investigated to understand the behaviour of nickel during EC. The electrocoagulation process was applied to assess the effect of electrochemical parameters such as: initial pH (pH_i), current density (j), electrolyte concentration [NaCl], electrolysis time t_{EC} and connection mode on removal efficiency of Ni(II), energy consumption, flow structure and treatment cost. The results indicated that maximum nickel removal was obtained with a bipolar connection, initial pH = 5.0, current density $j = 1.388 \text{ mA cm}^{-2}$, electrolysis time $t_{EC} = 30 \text{ min}$ and [NaCl] = 1.5 g L^{-1} . At optimal conditions, nickel removal reached over 95.51% with an energy consumption of barely 0.195 kWh m^{-3} . Once electrocoagulation performance was determined, economic treatment cost of the process was evaluated. In this way, a useful economic feasibility indicator is obtained, and it has been possible to show the effectiveness of this process in the treatment of industrial waste water with a total removal of Ni(II) and a low treatment cost. In the light of these results, this method promises interesting industrial applications.

Keywords: Electrocoagulation; Nickel removal; Electrocoagulation parameters; Wastewater; Economic cost

1. Introduction

Nickel is a trace element with a beautiful white and stainless appearance which was discovered in the eighteenth century (in 1751) [1], its first applications appear in the 1820s [2]. In 1875, five European countries share the world production of 300 tons of nickel, which are Saxony, Hungary, Northern Italy, Sweden and Norway. The New Caledonian Mining Industry in 1876 produced 400 tonnes of nickel in the European Market, accounting for 40% of world production. In 1884, nickel development boosted in the Sudbury area (Ontario, Canada) [3]. In 1875, the use of nickel in various fields was increased which explains the multiplication of

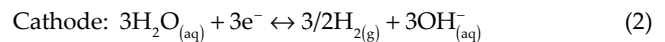
its production from 1875 to 1913 (from 500 to 32,700 tons). Thanks to these properties, the world production of nickel or “green gold” is becoming more and more important. It is in the order of 1.93 million tonnes in 2014 [4]. Nickel is one of the hardest, malleable, ductile metals and is a good electrical and thermal conductor [5]. It favours different non-ferrous alloys that are used for making coins, kitchen, household utensils, and jewellery, etc. [6]. Nickel is also widely used to make stainless steel because it improves their mechanical and heat properties [7]. In chemistry, it is known as a catalyst [8], which increases the speed of hydrogenation reactions, petroleum product desulfurization, reduction of nitrogen oxides, etc. Nickel oxide (NiO) is used for

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manufacture of nickel salts and ferrites and is also used as glass dye and porcelain paint [9]. Nickel is a heavy metal that is non-biodegradable so it can accumulate in the living organism and results in an increase in its concentration and it causes distressing problems that threaten the existence of mankind and other forms of life on Earth [10]. It is one of the necessary metals for living but it becomes toxic and sometimes fatal in high concentrations. Exposure to excessive amounts of nickel can have serious health consequences such as increased risk of developing lung cancer, kidney disease, respiratory failure, asthma and chronic bronchitis, allergic reactions and heart problems (cardiovascular) [11]. The limit value of nickel for drinking water is 0.02 mg L⁻¹ and the limit value for loading of evacuated wastewater into natural receptors with Ni is equal to 1 mg L⁻¹ [12].

Several techniques that have been used for abduction pollutant water, including coagulation and flocculation, ion exchange, activated carbon, filtration, membrane filtration techniques and advanced oxidation processes [13,14] but electrochemical methods are becoming more and more efficient among the other techniques proposed [15]. So it is needed to have more powerful yet economically viable treatment process: the electrocoagulation (EC) process is one of these techniques.

For the EC the chemical coagulants was generated by anodic dissolution with simultaneous reduction of H₂O giving the hydroxyl ion formation using an electrical current. When aluminum is used as a sacrificial anode, they dissolve and produce Al³⁺ ions into solution and the metal hydroxides, Al(OH)₃, are produced as below in water. The metal hydroxides will then agglomerate to give rise to colloids. These colloids can then interact with the pollutants in solution and aggregate to form flocs. The agglomeration and flotation flocs are favored by the hydrogen gas thus produced at the electrode Fig. 1. Abdulhadi et al. [10] summarized the EC mechanism as follows:



Aluminum hydroxides are produced:



EC is a process that bids simplicity, efficiency, environmental compatibility, safety and selectivity with a low cost [16]. To improve the efficiency of the EC process, several research works have coupled EC with other processes like adsorption onto granular activated carbon or proposed new reactor design [17,18]. The determination of optimal EC parameters (pH, treatment time, current density, etc.) is necessary in order to have maximum removal efficiency at a lower cost, because it has an effective effect on the energy consumption and the properties of flocs [19,20]. However, flocs' characteristics such as size, structure and morphology had a direct influence on the efficiency and treatment cost [21].

In this work, the effects of pH, current density and electrolyte concentration have been investigated to minimize energy consumption, maximize elimination rate and avoid excessive anodic dissolution. For this purpose, Ni removal, faradic yields and flocs characterization were investigated. To conclude feasibility of small-scale application, a techno-economic analysis was conducted for electroplating industrial wastewater.

2. Materials and methods

2.1. EC Reactor

The EC tests are conducted using an electrolytic cell formed by a 1 L glass beaker and tow aluminum (Al) parallel plates as electrodes. (Al) plates (anode and cathode) were obtained from a commercial grade aluminum sheet of 2 mm thickness. The effective area of each electrode used was 72 cm² (9 cm × 8 cm) and during the optimization of the EC parameters the inter-electrode distance is fixed at 1 cm

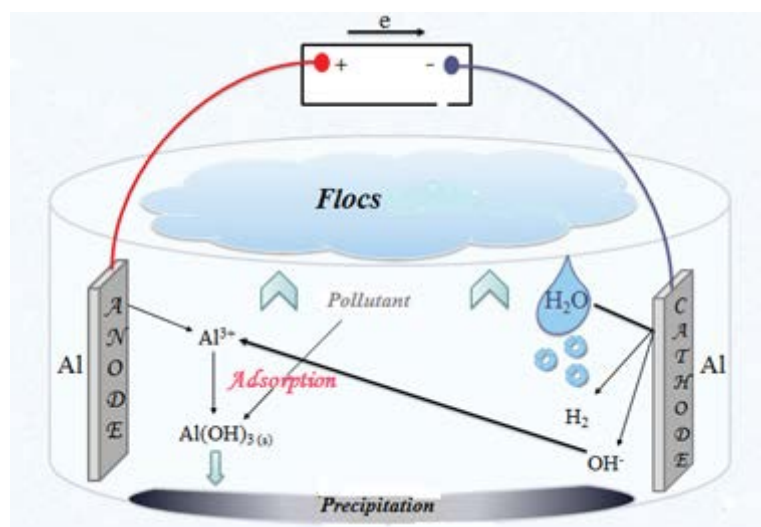


Fig. 1. Electrocoagulation mechanism.

while it is variable for the die optimization section. The current intensity and the voltage were respectively maintained at the ranges of 0 to 3 A and 0 to 30 V, applying a direct current (DC) AFX 2930 SB DC power supply, and the voltage was continuously followed and recorded. The treated water was stirred with a magnetic stirrer during treatment with an appropriate stirring speed. To guarantee the surface reproducibility and avoid passive film, the electrodes were first mechanically rubbed with abrasive paper, rinsed with bi-distilled water, degreased with NaOH and HCl, rinsed with bi-distilled water and dried prior to any EC test.

2.2. Experimental procedure

A solution of 1 g L⁻¹ was prepared from N₂NiO·6H₂O that was taken from Sigma-Aldrich. The solution was diluted to 70 mg L⁻¹ for experiments.

The Ni solution (70 mg L⁻¹) was put into the EC reactor and was agitated with a magnetic stirrer during EC process. The pH of the solution was varied with a solution of HCl or NaOH at a concentration of 0.1 M before the beginning of electrolysis and was recorded using a pH meter (Cyber Scan 510, WDW, Germany). The conductivity of the solution was spied up and adjusted to various values by adding NaCl. To pursue the progress of the treatment, samples of 10 mL were periodically taken from the EC cell then filtrated to eliminate sludge formed during electrolysis. The residual concentrations of Ni were determined by atomic absorption spectroscopy with flame (Analytic Jena Nova 400). The percentage of Ni removal is calculated by Eq. (4).

$$\text{Ni removal efficiency } \%Ni = \frac{C_0 - C_f}{C_0} \times 100 \quad (4)$$

where C_0 is the initial concentration (mg L⁻¹) of Ni in solution; C_f is the final concentration (mg L⁻¹) of Ni in solution.

Flocs structure and morphology was explored by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) by electronic microscopy (Philips EM120).

2.3. Economic study

Industrial efficiency of such water treatment process is directly related to the pollutant removal efficiency and the cost of treatment. Once EC performance was determined, the economic cost of the treatment process can be calculated as follows [22]:

$$TC = aW + bm_{\text{electrode}} + D \quad (5)$$

where a : energy cost; $a = 0.073846$ USD kWh⁻¹; b : (Al) cost; $b = 1.033844$ USD kg⁻¹; W : energy consumption (kWh m⁻³).

$$W(\text{kWh/m}^3) = \frac{U \cdot I \cdot t}{V} \quad (6)$$

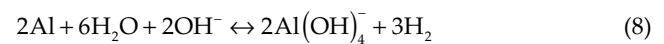
where U is the cell voltage (V), I is the current (A), t is the electrolysis time (h) and V is the volume of treated solution (m³).

$-m_{\text{electrode}}$ (kg Al m⁻³): The consumption quantities (Al):

$$m_{\text{electrode}} = \frac{I \times t \times M}{n \times F \times V} \quad (7)$$

where I is the current (A), t is the time of electrolysis (s), M is the molecular mass of (Al) ($M = 26.98$ g mol⁻¹), n is the number of transferred electrons ($n = 3$), F is Faraday's constant ($F = 96,487$ C mol⁻¹) and V is the volume (m³); D : cost of the chemicals used; $D = \text{cost of salt} + \text{cost acid} = 0.036923$ USD m⁻³.

The electrodes can undergo corrosion according to the following equations [22]:



3. Results and discussion

3.1. Optimization of initial pH

3.1.1. Effect of initial pH_i on Ni removal efficiency

The initial pH (pH_i) has a significant effect on the performance of EC process [16–19], the anodic dissolution, the chemical reactions and the chemical form of Al in solution. Hence, to optimize the pH, the percentage of Ni removal and the final pH fluctuation as a function of the initial pH were studied, over a pH range of 4–8, a current density (J) of 1.388 mA cm⁻², with an electrolysis time (t_{EC}) of 60 min and a sodium chloride concentration of 1 g L⁻¹.

Fig. 2 shows that Ni removal efficiency increased from 55.12% to 100% when the initial pH increases from 4.0 to 8.0. On the other hand, the treatment progression is also accompanied by an increase in the pH of solution that depends on the pH_i (Fig. 3), because initial pH influenced the production and the consumption of OH⁻ [23]. From (Fig. 3), in acidic conditions final pH undergoes a slight increase, due to the fast anodic dissolution of Al to Al₃ [24], thus favouring the formation of a high quantity of Al(OH)₃ with raised adsorption capacity [25,26].

Besides, for pH superiors to 5, the totality of Ni was eliminated, but it's not only due to the effect of EC process but of the precipitation of Ni²⁺ to Ni(OH)₂, since OH⁻ ions can also partially combine with Ni²⁺ to form insoluble nickel hydroxide precipitation Ni(OH)₂. The final pH_f of the solution increases but does not exceed 6.4. At this value, the most predominant species is aluminium hydroxide (Al(OH)₃) with a maximum of 95% at a pH of 6.5. Thus this process not only leads to an acceptable removal yield but also guarantees the quasi absence of ionic forms of Al in waters treated by EC for pH_i of 5 [26].

So, to ensure a best elimination of nickel by EC process, initial pH will be fixed at 5.

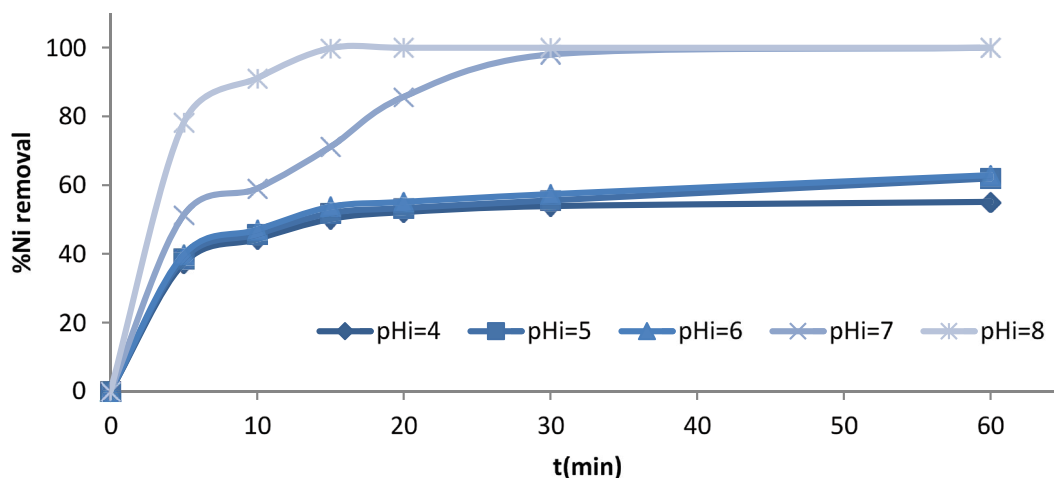


Fig. 2. Effect of pH on Ni removal ($[\text{Ni}]$: 70 mg L^{-1} ; current density: 1.338 mA cm^{-2} ; $[\text{NaCl}]$: 1 g L^{-1} ; d_{e} : 1 cm ; stirring speed = 300 rpm).

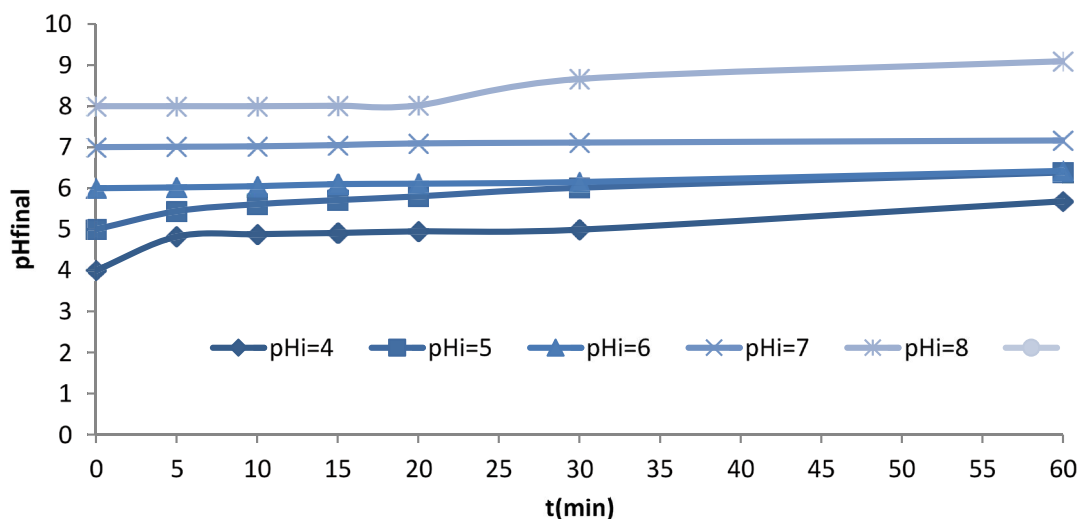


Fig. 3. Evolution of final pH for different initial pH ($[\text{Ni}^{2+}]$: 70 mg L^{-1} ; current density: 1.338 mA cm^{-2} ; $[\text{NaCl}]$: 1 g L^{-1}).

3.1.2. Effect of initial pH in flocs' characterization

To look into the surface morphology features and the flocs constitution three kinds of flocs, (floc at pH 5), were characterized by SEM and EDS.

We can notice from Fig. 4 that the flocs have a crystalline structure. For pH_i of 5, porous structure of the flocs was observed whose pores are clear and sharp [20] leading to an enhancement of Ni(II) removal. A similar observation has been reported by Wang et al. [27]. Table 1 depicts that Al weight percentage increase from 32.4% to 40.44% for pH 4 and 5 respectively. Therefore, based on all these results, pH 5 should be chosen as optimal pH for Ni removal.

3.2. Optimization of electrolysis time t_{EC}

Electrolysis time is a major EC parameter, it has a real effect on the EC efficiency and the treatment cost such as the electrical energy and electrode consumption [Eqs. (6) and

(7)]. Hence, optimization of electrolysis time for Ni removal was done by varying the initial t_{EC} value from 0 to 60 min and controlled the EC efficiency, charge loading (Eq.) and energy consumptions. The results are shown in Figs. 3 and 5.

Fig. 3 shows that Ni removal efficiency is notably reduced over the first 30 min of electrolysis (55.57% for pH = 5). Subsequently, Ni removal manifested only a trifling increase (62% for pH of 5 during 60 min). Hence, in accordance with Eqs. (6) and (7), there is a reaction between the t_{EC} , the charge loading [28] and the energy consumption [22]. Fig. 5 summarizes the effect of the t_{EC} on charge loading and energy consumption. It appears that charge loading increases significantly with electrolysis time from 0 to 0.062 Fm^{-3} for 0 to 60 min. Hence, the charge loading is a parameter that guarantees a specific estimation of the effectiveness of the EC reactor [28]. It is shown in Fig. 5 that an increase of the charge loading from 0 to 0.03 Fm^{-3} results in a sudden increase of the removal efficiency with an accepted energy consumption W .

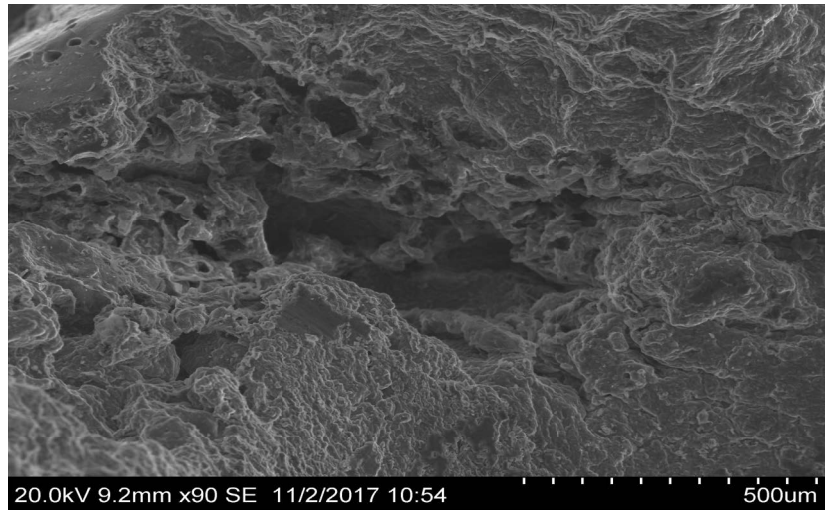


Fig. 4. SEM images of flocs generated in EC process pH_i = 5; j = 1.338 mA cm⁻²; [NaCl]: 1 g L⁻¹; [Ni] = 0 mg L⁻¹.

Table 1
Floc composition (EDAX TEAM EDS)

Element	pH =4, [Ni] = 0 mg L ⁻¹			pH = 5, [Ni] = 0 mg L ⁻¹			pH = 5, [Ni] = 70 mg L ⁻¹		
	Weight %	Atomic %	Net int. error	Weight %	Atomic %	Net int. error	Weight %	Atomic %	Net int. error
CK	5.22	7.98	0.05	7.02	11.14	0.13	4.91	9.76	0.09
OK	59.16	67.83	0.00	49.09	58.44	0.01	34.54	51.56	0.01
NaK	1.61	1.29	0.04	–	–	–	–	–	–
AlK	32.40	22.03	0.00	40.44	28.54	0.01	24.65	21.82	0.01
SiK	0.22	0.14	0.10	–	–	–	–	–	–
S K	0.36	0.20	0.13	0.54	0.32	0.26	0.59	0.44	0.12
ClK	1.04	0.54	0.05	2.91	1.56	0.09	7.72	5.20	0.02
NiK	–	–	–	–	–	–	27.6	11.23	0.02

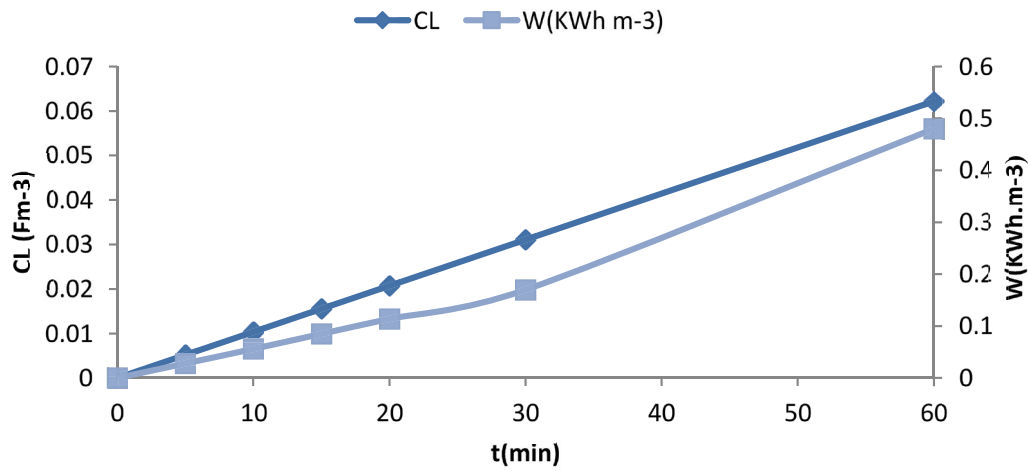


Fig. 5. Effect of time on the charge loading and the energy consumption for ([Ni²⁺]: 70 mg L⁻¹; pH: 5; current density: 1.338 mA cm⁻²; [NaCl]: 1 g L⁻¹).

Thus, an electrolysis time of 30 min would be sufficient to obtain a maximum nickel removal by EC.

3.3. Effect of electrolyte concentration

A conductive electrolyte is intended for the suitable operating of EC processes with Al electrodes [22]. In this work, NaCl is used; forgoing studies have proved, in a comparison of Na_2SO_4 and NaCl, that NaCl furnishes the best effective electrolyte support for EC [22]. The option of NaCl is founded on the event that chloride ions permit an important reduction of the negative effects of other ions (e.g., HCO_3^- and SO_4^{2-}) that are attractive to form an insulating film at the electrode area, that findings in an augmentation in the EC cell resistance [29].

Establishing the effect of conductivity requires the optimization of the NaCl dose. Toward this object, various EC tests were carried out and the NaCl dose was ranged from 0.3 to 1.5 g L⁻¹. Since it can be plainly seen in Fig. 6, Ni removal over taken 50% after 30 min of EC for NaCl dose superior to 0.5 g L⁻¹.

Growing the solution conductivity (σ) showed in an increase in the percentage of Ni removal, for the better chemical dissolution. Increasing the conductivity from 0.87 to 5.86 mS cm⁻¹ coupled with enhanced removal efficiency from 46.9 to 70.28%. On the other hand, increasing the sodium chloride dose from 0.3 to 1.5 g L⁻¹ resulted in a decrease of the energy consumption from 0.17 to 0.065 kWh m⁻³, so the electrical energy consumption decreased with increasing wastewater conductivity [22–26]. The chloride ions inhibit the passivation on the electrodes surface, but at high NaCl dose, there is an overconsumption of the Al electrodes owing to a corrosion of the Al anode. Middle NaCl concentration of 1 g L⁻¹ was thus fixed to be the optimal electrolyte dose, gifted that this concentration enabled 55.57% Ni removal. The chosen NaCl concentration was also set up to be optimal with fulfilment to energy consumption, to the prejudice of the rapid dissolution of the electrodes, as well as to the inhibition of ode corrosion.

3.4. Effect of current density on Ni removal

Previous studies [26–30] have proved that current density has been known to be an important factor that influenced the performance of the EC process, especially on the kinetics of metal removal. The effect of current density was investigated in the range 0.277–1.388 mA cm⁻² at pH of 5.0 and a conductivity of 1.77 mS cm⁻¹ an electrolysis time of 30 min. Fig. 7 shows that Ni removal increased significantly from 25.62% to 55.57% when the current density was increased from 0.277 to 1.388 mA cm⁻².

This is ascribed to the fact that the extent of anodic dissolution of aluminum increases at high current density so the quantity of aluminum oxidized and the kinetics of coagulant formation was increased. On the other hand, electrical current determines the bubble production (rate and size), and the flocs growth. These effects would be beneficial for high pollutant removal by H₂ flotation [27]. Nevertheless, the increase of the anodic dissolution increased the electrode consumption [Eqs. (1) and (2)].

On the other hand, Energy and electrodes consumption was directly related with the current density. The energy and electrode consumption changed linearly when the current density increased. The EC electric power consumption W (kW hm⁻³) and Faraday Act were calculated by Eqs. (6) and (10). Figs. 8 and 9 show that the increase in the current density from 0.555 to 1.66 mA cm⁻² resulted in an increase in energy consumption from 0.01 to 0.07 kWh m⁻³ and electrode consumption from 0.0119 to 0.063 kg m⁻³. Table 3 depicts that the experimental mass varies proportionally with J , but remains slightly higher than the theoretical mass for values of J at or below 0.833 Am cm⁻².

The verification of Faraday's law was carried out via several EC tests at different current densities with an electrolysis time of 30 min. The theoretical calculation of the amount of Al oxide was based on Faraday's law as follows:

$$\text{Faraday act: } R_{\text{Faradique}} = \frac{m_{\text{exp}}}{m_{\text{théo}}} \times 100 \quad (11)$$

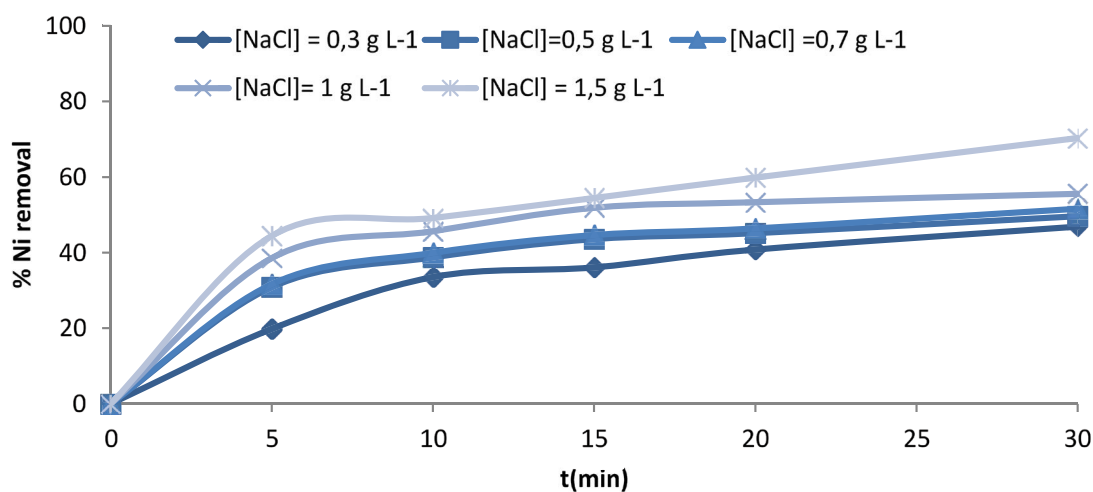


Fig. 6. Effect of NaCl concentration on Ni removal ($[\text{Ni}^{2+}]$: 70 mg L⁻¹; current density: 1.338 mA cm⁻²; pH_i: 5).

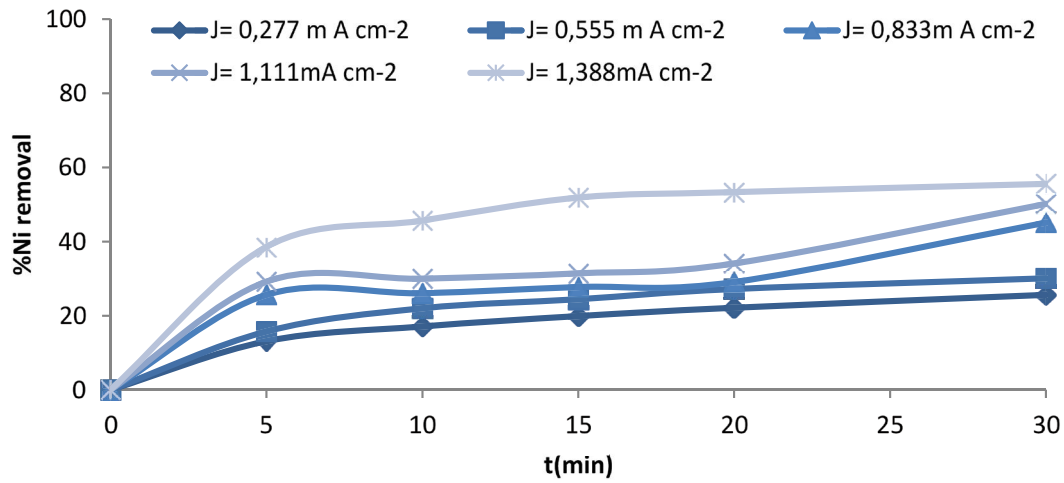


Fig. 7. Effect of current density on Ni removal ($[Ni^{2+}] = 70 \text{ mg L}^{-1}$; $[NaCl] = 1 \text{ g L}^{-1}$; $pH_i = 5$).

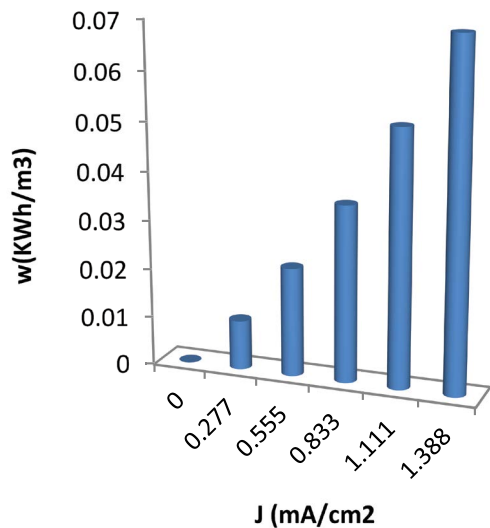


Fig. 8. Evolution of energy consumption.

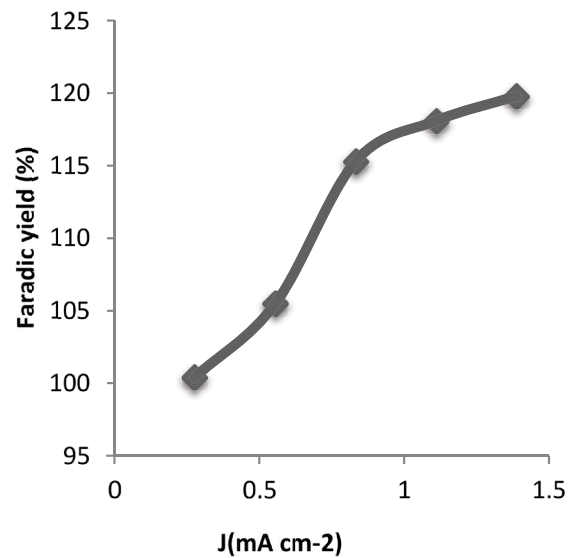


Fig. 9. Evolution of faradic yield.

Table 2
Effect of electrolyte concentration on electrical energy consumption

[NaCl] g L ⁻¹	0.3	0.5	0.7	1.0	1.5
σ (mS cm ⁻¹)	0.87	2.03	3.22	4.61	5.86
I (Å)	0.1	0.1	0.1	0.1	0.1
U (V)	3.4	2.3	1.8	1.4	1.3
W (kWh m ⁻³)	0.17	0.115	0.09	0.07	0.065
% Ni removal	46.9	49.65	51.62	55.57	70.28

$$\text{with: } m_{\text{théo}} = \frac{M \cdot I \cdot t}{n \cdot F} \quad (12)$$

$$m_{\text{exp}} = m_{\text{before EC}} - m_{\text{after EC}} \quad (13)$$

Table 3
Effect of current density on electrode and electrical energy consumption

J (mA cm ⁻²)	0.277	0.555	0.833	1.111	1.388
% Ni removal	25.62	30.1	45.17	50.21	55.57
U (V)	1.1	1.1	1.2	1.3	1.4
W (kWh m ⁻³)	0.01	0.022	0.036	0.052	0.07
$m_{\text{theoretical}}$	0.01185	0.02370	0.03556	0.04742	0.05927
$m_{\text{experimental}}$	0.01190	0.02500	0.04100	0.05600	0.07100
Faradic yield (%)	100.421	105.485	115.298	118.09	119.79

The experimental results are summarized in Table 3. The consequence of current density on the total quantity consumed of both electrodes, as well as the mass casualties theoretically forecasted granted to Faraday's law, are shown

in Fig. 9. Thus, the variation of the theoretical mass is proportional to the current density. Similarly for the experimental mass of Al consumed, but the latter was slightly higher than the theoretical mass; resulting in Faraday efficiency above 100. The acceptable faradic efficacy was set at 119%; this result was due to the anodic oxidation of the Al that simultaneously produced Al^{3+} and Al^+ [31,32].

From reported results in previous studies for the Al configuration, 80% of the total amount of the dissolved electrode was due to electrochemical dissolution and 20% was due to chemical dissolution [33,34]. The calculation of the dissolved theoretical mass was directly assumed by the difference in valence. This consumption was deducted to be due also to the chemical hydrolysis of the cathode, as illustrated by Eq. (4). It can also be explained by the phenomenon of corrosion and oxidation of the electrode surface. The electrodes corrosion mechanism suggested involved chloride ions [Eqs. (8) and (9)]. For this reason, the optimal current density is considered to be 1.388 mA cm^{-2} .

3.5. Arrangement of electrodes

The increase in anodic dissolution kinetics and the formation of a great quantity of the $\text{Al}(\text{OH})_3$ flocs give rise to

a right efficacy of the EC in a short time; This is directly related to the increase of the active surface of the electrodes which is strengthened by an increase in the number of plates thus forming the electrodes [26].

However, it is necessary to note that the increase in the number of plates can cause a significant increase of the ohmic cell, therefore an increase of the energy consumption. This can be avoided by the good choice of the configuration and the number of electrodes.

In general, we have two types of electrode configuration. The first one is monopolar connection where the anodes and cathodes are connected and the current is split between all the electrodes to the resistance of individual cells. The second mode is bipolar connection only the first electrode is connected to the anode and the last electrode to the cathode [26].

Fig. 10 and Table 4 show that for bipolar electrode connections, 95.5% of nickel removal was obtained for an energy consumption of $W = 0.275 \text{ kWh m}^{-3}$. Monopolar electrodes in parallel connections result in a removal of 89.99% with an energy consumption of $W = 0.065 \text{ kWh m}^{-3}$. It is clear that a bipolar electrode connection is more efficient, but this mode consumed higher energy. In view of that, the choice of monopolar configuration would more reasonable.

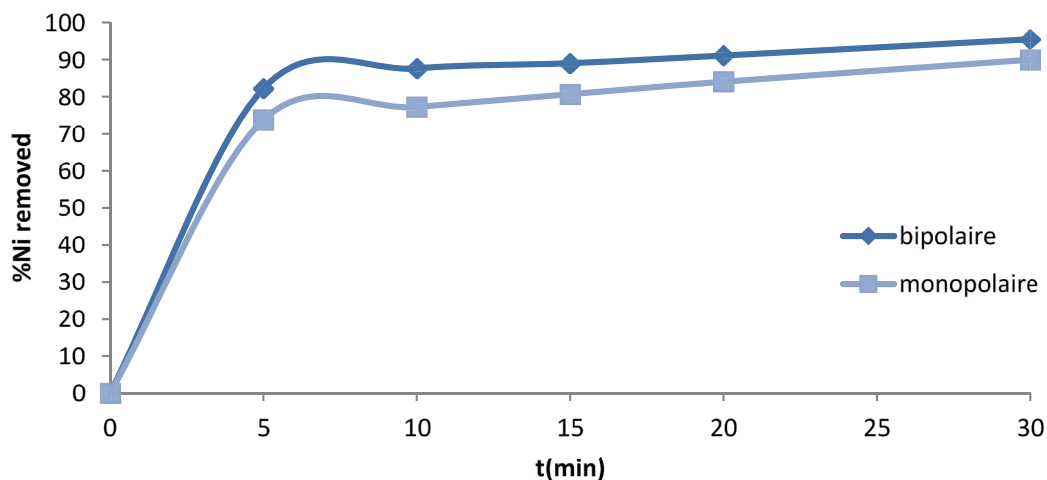


Fig. 10. Effect of the connection mode on Ni removal ($[\text{NaCl}] = 1 \text{ g L}^{-1}$; $[\text{Ni}] = 70 \text{ mg L}^{-1}$; stirring speed = 300 rpm; $d_{\text{ic}} : 1 \text{ cm}$; pH: 5.0).

Table 4
Variation of energy consumption as a function of electrode configuration

t (min)	Bipolar configuration			Monopolar configuration		
	U (V)	W (kWh m^{-3})	% Ni removal	U (V)	W (kWh m^{-3})	% Ni removal
0	6.2	0.000	0.00	2.0	0.000	0.00
5	6.0	0.0499	82.22	1.9	0.0158	73.75
10	5.9	0.098	87.65	1.8	0.0130	77.23
15	5.8	0.1450	89.05	1.6	0.0400	80.68
20	5.7	0.1899	91.11	1.4	0.0566	84.04
30	5.5	0.195	95.51	1.3	0.095	89.99

4. Investigation of the feasibility of the electrocoagulation process on the removal of Ni from electroplating industrial wastewater

4.1. EC performance for Ni removal

In order to examine the effect of all the optimum EC parameters together on the removal of Ni from industrial wastewater, we treated an effluent from electroplating industry contained a Ni concentration of 44.3 mg L⁻¹, a conductivity of 12.49 mS cm⁻¹, and a pH of 8.89, with bipolar connection, pH of 5, *t*_{EC} of 30 min. The evolutions of Ni removal percentage and the effluent properties before and after the treatment are summarized in Table 5 and Fig. 11.

The experimental results proved that the EC process can be one of the most effective techniques for the removal of Ni from industrial wastewater. The removal rate of Ni reached 100% for only 10 min with a very low energy consumption of 0.042 kWh m⁻³. The technical results are high efficiency and low energy consumption.

4.1. Economic study

Assessing the costs of wastewater treatment is one of the most important and crucial aspects in the feasibility and

sustainability assessment of EC process. In order to show the effectiveness of the EC economically, the evolution of the treatment cost during 30 min was determined. The economic study proved that an increase of the treatment time is accompanied with the increase of treatment cost. Fig. 12 proved that total elimination of Ni is obtained at an electrolysis time of 10 min with a very low treatment cost (0.076 USD). Half of this time (5 min) is sufficient to achieve a removal of over 98% with cost of only (0.063 USD). The obtained results revealed that EC process has high rate removal of Ni(II) from industrial wastewater and useful economic feasibility.

Table 5
Properties of the industrial wastewater before and after the treatment by EC process

	Sample characteristics before the treatment	After the treatment by EC for initial pH 5
pH	8.89	6.65
Conductivity	12.49	12.38
[Ni] (mg L ⁻¹)	44.3	0.00

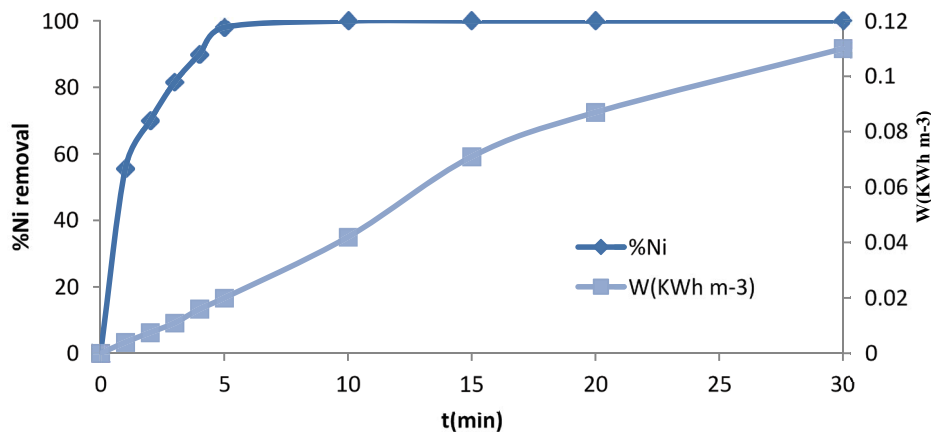


Fig. 11. Evolution of the percentage of Ni removal and energy consumption as a function of treatment time.

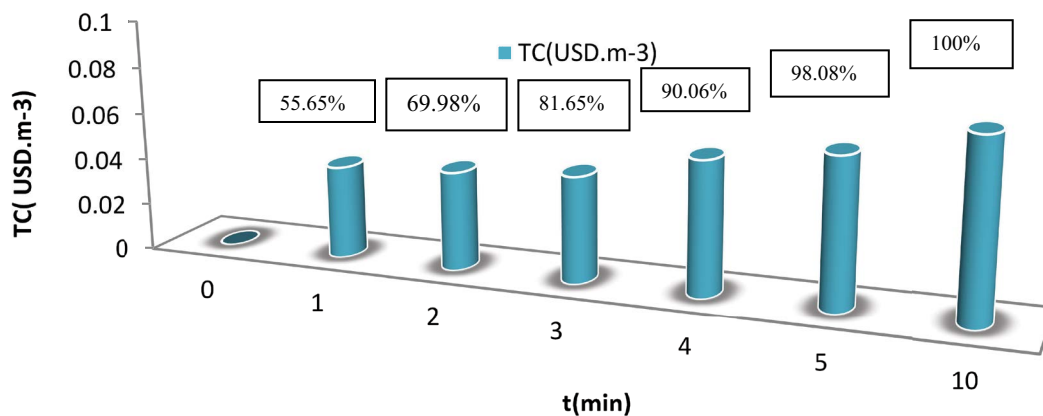


Fig. 12. Evolution of the treatment cost as a function of treatment time.

5. Conclusion

The treatment of synthetic wastewater containing Ni(II) by electrocoagulation process using aluminium electrodes was carried out by the evaluation of the effect of EC parameters, such as initial pH (pH_i), electrolysis time t_{EC} , current density (j), electrolyte concentration and electrodes combinations on EC performance. Energy consumption was evaluated and flocs characterization was carried out. According to the results obtained in the present study, the initial pH has an effect on the EC performance; pH of 5 favoured the removal of 55.57% of Ni by EC process with a porous floc structure. The removal efficiency may such be ameliorated by the increase in current density, electrolysis time and electrolyte concentration. Meanwhile, the consumption of electrical energy and the Al electrode significantly increases with the increase of these last three variables. The effect of the electrode combinations showed that the increase of electrode number given increase of the Ni removal efficiency and that the bipolar connection was recommended for the removal of Ni with 95.51% and a very low energy consumption of 0.195 kWh m^{-3} . The economic study proved that total removal of Ni from real wastewater was obtained for an electrolysis time of 10 min with a very low treatment cost. EC is a high-efficiency process from industrial wastewater treatment with a useful economic feasibility. We have thus succeeded in finding a solution to the problem of the costs of industrial wastewater treatment, which prevents the application of the EC process on industrial scale.

Acknowledgments

We warmly thank the generous support of the research team of the Materials, Environment and Energy Research Unit (ME2) (UR 14 ES26), Department of Chemistry at the Faculty of Sciences of Gafsa, University of Gafsa.

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