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Removal of toxic metal Cr(VI) from aqueous solutions by electrocoagulation using aluminum electrodes

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ABSTRACT

The aim of the present study is to find the effectiveness of electrocoagulation process for removal of chromium (VI) and to evaluate the influence of various operating parameters on the chromium removal process. Initially, the experiments were conducted using synthetic samples of varying chromium (VI) concentrations (5, 50, 200, 300, 500 mg/L). Furthermore, the experiments were conducted using industrial waste obtained from the Domestic Apparatuses Complex, Tizi Ouzou. The operating parameters investigated for the study were current density, salinity, initial pH of the solution, the concentration of the solution, interelectrode distance and number of electrodes. The results obtained show that the Cr(VI) concentration was well within the permissible value and chemical oxygen demand abatement of 80% was achieved. The recovered flocs were visualized using electronics sweeping microscope and analyzed by X-ray diffraction.

Keywords: Aluminum electrode; Chromium removal; Electrocoagulation; Industrial waste

1. Introduction

Chromium is one of the heavy metals which find its use in several activities of the industrial sector, like tanning industry, electroplating, pigment preparation and safeguarding of wood [1]. Small quantities of chromium are also used in the textiles, drilling muds, printer powders, magnetic tapes and catalysts [2]. The main source of contamination by chromium finds its origin in the rejections from electroplating and tanning industry [3]. Increasing contamination of industrial and urban wastewater by chromium threatens the environment. Almost, 60% of the tanneries use about 32% of chromium-like agent for tanning [4,5]. In addition, according to Tiravanti [6], 50% of chromic salts are rejected with wastewater. Thus, the presence of heavy metals such as copper, zinc, cadmium, chromium and lead in the rivers cause several problems owing to their high toxicity [7,8]. In order to meet the water quality standards for most countries, the concentration of heavy metals in wastewater must be regulated.

The chemical and toxicological behaviors of chromium depend on its oxidation state: hexavalent chromium [Cr(VI)] or trivalent chromium [Cr(III)]. Due to its high solubility in water, Cr(VI) has significant mobility in the environment [9]. Cr(III), on the other hand, has low solubility in water and readily precipitates as $Cr(OH)_3$ [10] under alkaline or even slightly acidic conditions. Cr(VI) is toxic to most living organisms [11–13] and a known human carcinogen by the inhalation route of exposure [14–16]. Cr(III) is considered as an essential nutrient for the human body [17], and its toxicity is 500–1,000 times less to a living cell as compared with

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Cr(VI) [16]. Therefore, Cr-contaminated wastewater has to be treated before being discharged. It is to be noted that the permissible limit of discharge of Cr(VI) in surface water is 0.1 mg/L. Hence, it becomes imperative to remove Cr(VI) from wastewaters before discharging them into aquatic systems or on to land. Different methods, such as reduction and precipitation, ion exchange, electrodialysis, reverse osmosis, solvent extraction, electrochemical precipitation, activated carbon adsorption and electrocoagulation (EC) have been suggested for the removal of Cr(VI) [18].

The EC process has been successfully used for the treatment of wastewaters including electroplating wastewater [19], laundry wastewater [20], latex particles [21] and textile wastewaters [22–25]. The EC process has also been widely used to decolorize various structurally different dye containing solutions such as disperse, reactive and acidic dyes [26–29].

EC is a method of water treatment based on the electrochemical dissolution of a sacrificial metal. The sacrificial metal in solution with the help of the other related reactions, such as the electrolysis of water, forms metallic hydroxide complexes that will ensure adsorption of pollutant species. EC is regarded as a complex process with a multitude of synergistic mechanisms contributing in the treatment of pollutant. Holt et al. [30] identified three categories of mechanisms in the EC process:

- Electrochemical phenomena
- Coagulation
- Hydrodynamics

The direct action of an electric field on wastewater creates good conditions for coagulation–flocculation [31]. The electric field creates a movement of ions and charged particles. This action makes it possible to gather suspended matter in the form of flocs that are eliminated by traditional physical process (decantation, floatation and filtration). Behloul et al. summarized this process as follows [32]:

- Formation of the coagulants by the sacrificial metal electrolytic oxidation.
- Destabilization of the contaminants, the pollutants, the suspended matter and the breaking of the emulsions.
- The aggregation of the destabilized phases to form flocs.

Choice of a suitable electrode is very important in the EC process. Most common electrode materials used for EC are iron and aluminum. Both of these are cheap, easily available and effective [33].

When aluminum is used as electrode material, Al^{3+} ions are formed. The metallic cations form complexes with the hydroxides. The majority species depends on the pH of the medium. In the case of aluminum, a multitude of anion and cation complexes is formed [34]. One can distinguish:

- Monocomplexes such as $Al(OH)^{2+}$, $Al(OH)_2^+$, $Al(OH)_4$–
- Polycomplex such as $Al_2(OH)_2^{4+}$, $Al_2(OH)_5^+$, $Al_6(OH)_{15}^{3+}$, $Al_{13}(OH)_{34}^{5+}$
- Amorphous species and far from soluble species such as $Al(OH)_3$, Al_2O_3

These species play the part of coagulant and form precipitates that can easily be eliminated as flocs. The difference between EC and chemical coagulation resides mainly in the source of coagulant. In the EC process, coagulant is generated electrochemically, and in chemical coagulation, it is directly added in the form of chemical compounds. At the cathode, the water reduction leads to the hydrogen formation that allows the floatation of the flocculated particles. The size of the microbubbles is estimated between 10 and 100 µm [35]. These bubbles prevent and reduce the formation of deposits on the cathode and thus increase the performance of the EC process. Aluminum reacts with air to form a protective oxide layer of Al_2O_3. Pure aluminum does not react with water, but alloys could react with water if the protective aluminum oxide is not formed.

In water, the trivalent aluminum ion is presented in hydrated form $Al(H_2O)_6^{3+}$, but it is written Al^{3+} to simplify the writing. The Al^{3+} ion reacts with water by attracting the OH^- ions to form anion, cation or neutral complexes according to the reaction:

$$2Al^{3+} + nOH^- \leftrightarrow Al(OH)_n^{(3-n)} \tag{1}$$

By considering only the mononuclear species, the reactions of Al^{3+} are summarized in Table 1.

1.1. Treatment of hexavalent chromium

Wastewater containing Cr(VI) passes through a phase of reduction to Cr(III) that further precipitates in the form of chromium hydroxides ($Cr(OH)_3$). The simplest method for treatment of wastewater containing chromium is to lower the pH in range of 2–3 for acid reduction of Cr(VI) to Cr(III), and then increase the pH for precipitation of Cr(III) in the form of $Cr(OH)_3$. The limitation of the method is its inability to eliminate chromium fully.

1.2. Treatment of chromium by EC

The reactions that occur during the use of the aluminum electrodes are shown below:

Anode undergoes oxidation and forms aluminum ions:

$$Al \rightarrow Al^{3+} + 3e^- \tag{2}$$

The water electrolysis occurs at cathode and anode:

$$2H^+ + 2e^- \rightarrow H_2 \tag{3}$$

$$H_2O \rightarrow 2H^+ + ½O_2 + 2\ e^- \tag{4}$$

The aluminum cathode is subjected to corrosion in the presence of water, resulting in hydrogen formation:

Table 1
Reactions of Al^{3+} and its hydroxyls reduction [36]

Reactions	pk_i	Equations
$Al^{3+} + H_2O \leftrightarrow Al(OH)^{2+} + H^+$	3.03	(12)
$Al(OH)^{2+} + H_2O \leftrightarrow Al(OH)_2^+ + H^+$	3.7	(13)
$Al(OH)_2^+ + H_2O \leftrightarrow Al(OH)_3 + H^+$	6.5	(14)
$Al(OH)_3 + H_2O \leftrightarrow Al(OH)_4^- + H^+$	8.1	(15)

$$2Al + 3H_2O \rightarrow 2Al^{3+} + 3/2H_2 + 3OH^- \qquad (5)$$

Hexavalent chromium is reduced to trivalent chromium according to the reaction:

$$HCrO_4^- + 7H^+ + 3e^- \rightarrow Cr^{3+} + H_2O \qquad (6)$$

or

$$CrO_4^{2-} + 4H_2O + 3e^- \rightarrow Cr(OH)_3 + 5OH^- \qquad (7)$$

Hexavalent chromium is directly reduced at electrodes through both preceding reactions when aluminum is used.

2. Materials and methods

2.1. Experimental setup

The installation assembly for chromic solution treatment is composed of an electrochemical reactor in which electrodes are placed, a peristaltic pump and a DC power supply.

A plexiglass electrochemical reactor was used to conduct all the experiments. Aluminum electrodes were connected in bipolar parallel configuration around which the solution to be treated is circulated. The electrodes were of 103 × 90 mm dimensions. A continuous DC current generator (ERMES M10-SP-303C) was used to allow uniform dissolution of metal at the anode and regular release of gas at the cathode. A peristaltic pump (EHEIM mark, type 1030, series 84122) was used to ensure the circulation of the sample in the processing circuit. The flow rate was kept constant at 150 mL/min for all the work in the present study.

2.2. Chemical analysis

Solution pH and conductivity during the experiments were measured using high precision pH meter, equipped with a combined glass electrode (WTW, model 526) and electronic conductivity meter (WTW model LF-597), respectively. Turbidity was measured using a turbidity meter (HANNA model LP 2000, Series H7 6300). The measurements of chemical oxygen demand (COD) were taken using COD meter (HI-83099 COD and Multiparameter Bench Photometer). The absorbance of the colored Cr(VI)–diphenylcarbazide complex was measured at a wavelength of 540 nm using an UV–Vis spectrophotometer (Optima SP-3000 Plus) and compared with the calibration curve. All electrolysis experiments were performed at a temperature of 25°C ± 1°C.

Flocs, thus recovered, were subjected to visualization by scanning electron microscope (SEM, Quanta 200 FEI Company. X-ray diffraction (XRD) analysis was performed, in order to know the composition of the floc having been used effectively for de-chromating. The diffractograms were obtained with diffractometer operating Xpert-Pro Analytical System Vertical Teta TDSA, with Cu Kα radiation source filtered with a nickel monochromator at a wavelength of 1.5406 Å.

3. Results and discussion

The objective of the present work was to study the influence of various operating parameters on the effectiveness of the EC process applied for removal of Cr(VI). The initial study was performed on synthetic samples of variable chromium (VI) concentrations (5, 50, 200, 300, 500 mg/L) prepared in the laboratory. The study was also performed on an industrial waste of the Domestic Apparatuses Complex, Tizi Ouzou. For the analysis of treatment process, 10 mL sample was extracted at regular intervals and were immediately filtered through a mixed cellulose acetate membrane (0.45 μm) to eliminate the mud formed during electrolysis.

In order to avoid the passivation phenomenon of electrodes, the electrochemical cell was cleaned using detergent and acetone after each experiment as described by Kobya et al. [37]. Before and after each experiment, the electrodes were cleaned, dried and weighed. The parameters selected for the study were current density (*J*), conductivity, initial pH, initial concentration (C_0), interelectrode distance (Intd) and the number of electrodes (*n*).

3.1. Effect of current density

The current density is an essential parameter in the EC process [38,39], which controls the reaction rate of the EC process. When the current density or the applied potential (*U*) increases, the treatment time decreases due to higher electrode dissolution, which results in greater destabilization of the pollutant particles and hence, greater removal. Moreover, with the increasing current density, bubble generation rate increases and the bubble size decreases. These effects are both beneficial for high pollutant removal by H_2 flotation [40]. Fig. 1(a) presents the experimental results of Cr(VI) removal for current density varying from 50 to 200 A/m². It is noted that the effectiveness of Cr(VI) removal rapidly increases with increase in current density.

It was observed that limiting value of Cr(VI) loading (0.1 mg/L) reached for various values of current density.

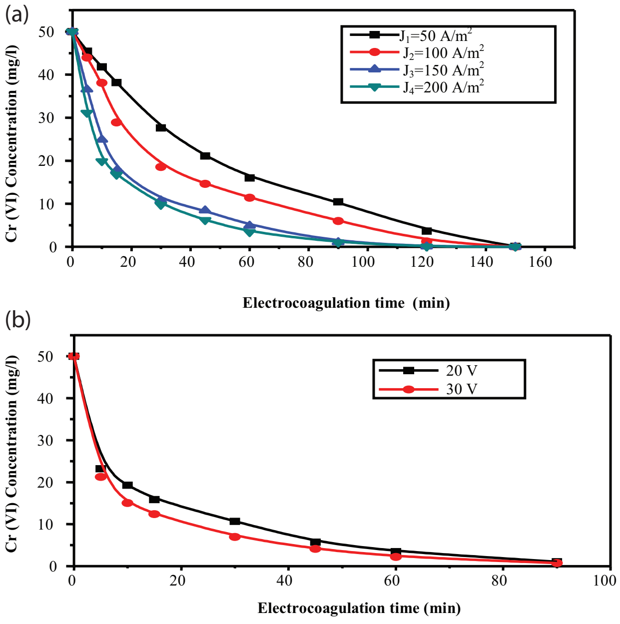


Fig. 1. Effect of current density (a) and cell tension (b) on the electrocoagulation kinetics of Cr(VI): C_0 = 50 mg/L, initial pH = 3, salinity = 1 g/L, *d* = 1 cm, *n* = 4 electrodes.

When the current density is increased from 50 to 200 A/m², the time necessary for EC (t_{EC}) to reach the limiting value decreases from 150 to 90 min. Similar results were obtained when experiments were conducted at constant applied potential. Fig. 1(b) shows that the effectiveness of chromium removal is better in the case of large applied potential.

3.1.1. Study of applied potential

The value of applied potential is a function of current intensity, electrode material and conductivity. At constant current, on increasing the conductivity of the sample, a decrease in applied potential is observed if there is no deposit on electrodes surface which prevents the passage of current. Fig. 2 represents the change in applied potential during the EC process. It shows that for low values of current density, the change in potential is very little. On the other hand, with the increased current density, a reduction in tension is observed with increase in time.

3.1.2. Study of faradic output

The faradic output Φ_c is calculated using the formula in Eq. (8).

$$\Phi c = \frac{Z.F.m}{M.Q} \tag{8}$$

where *F* is the Faraday constant (96,500 C/mol), *M* is the molar mass of the considered element (g/mol), *m* is the dissolved metal mass (g), *z* is the metal valence, *Q* is the electric charge (C).

Fig. 3 shows the effect of varying current density on faradic output for the electrochemical dissolution of aluminum anode. It was observed that value of faradic output lies between 300% and 190%, and decreases significantly according to time during the first 60 min of electrocoagulation. Faradic output also decreases on increasing the current density. Similar results were reported in the literature [41,42]. This overconsumption of aluminum electrodes can be due to the chemical hydrolysis of the cathode according to Eq. (9):

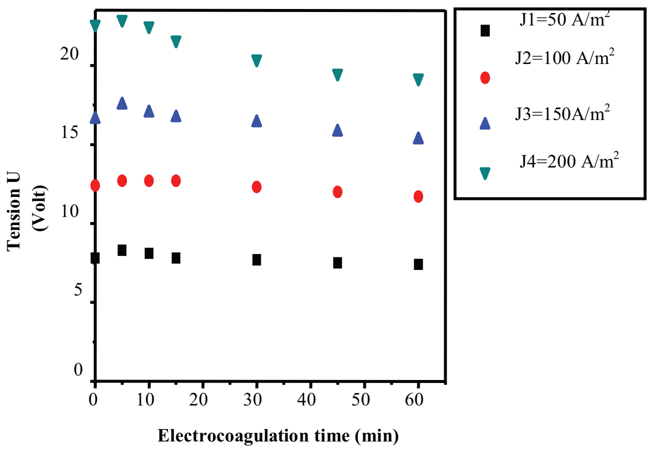


Fig. 2. Tension evolution during the treatment: C_0 = 50 mg/L, initial pH = 3, salinity = 1 g/L, Intd = 1 cm, *n* = 4 electrodes.

$$2Al + 6H_2O + 2OH^- <\!\!\longrightarrow 2Al(OH)_4 + 3H_2 \tag{9}$$

Moreover, it can be explained by corrosion phenomenon and oxidation of electrodes surface. The chloride ions catalyze the corrosion mechanism of electrodes which is explained by the following equations [42]:

$$2Al + 6HCl \rightarrow 2AlCl_3 + 3H_2 \tag{10}$$

$$AlCl_3 + 3H_2O \rightarrow Al(OH)_3 + 3HCl \tag{11}$$

3.1.3. Energy consumption study according to current density

The effect of energy consumption (W) per gram of chromium eliminated according to current density (Fig. 4) was

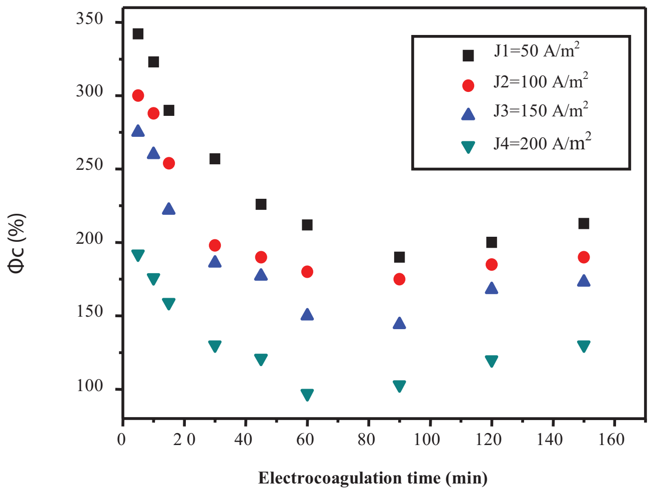


Fig. 3. Faradic output evolution compared with aluminum Φ_c according to time for various current densities *J*: C_0 = 50 mg/L, initial pH = 3, salinity = 1 g/L, *d* = 1 cm, *n* = 4 electrodes.

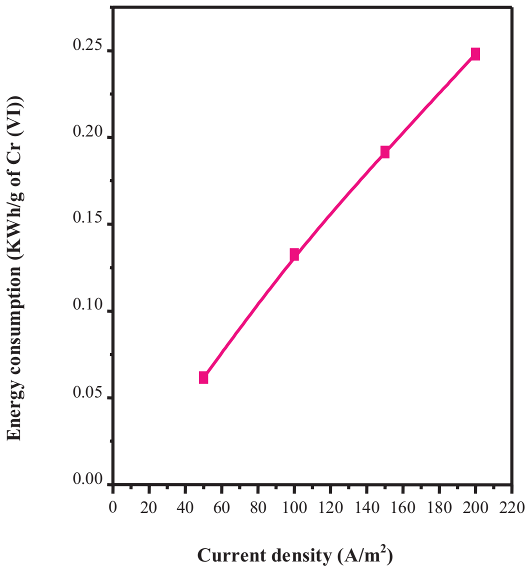


Fig. 4. Influence of current density *J* on specific energy consumption (W) to reach 90% of elimination: C_0 = 50 mg/L, initial pH = 3, salinity = 1 g/L, *d* = 1 cm, *n* = 4 electrodes.

also studied. The energy consumption during EC varies according to the product of electric potential, current intensity applied and time of treatment [43].

It was observed that with increase in current density, the time necessary to reach the limiting value of chromium removal also decreases. However, the energy consumption (W) does not reduce, instead varies proportionally with current density. In addition, high current density causes cathode passivation by reduction according to Khaldi et al. [38]; which lead to high energy consumption by joule effect. It would, therefore, be better to work with relatively low values of current density to avoid the wastage of energy.

3.2. Effect of conductivity

Sodium chloride is used to increase the conductivity of sample in the EC process. The increase in conductivity reduces the applied potential between the electrodes at constant current density [44–46]. In addition, chloride ions prevent passivation or deposition of carbonate precipitate on the electrodes surface [42]. The energy consumption, which is proportional to the applied potential between electrodes, would thus decrease. Fig. 5 shows the influence of conductivity on the effectiveness of Cr(VI) removal and also shows that the Cr(VI) removal increases with the increase in dissolved salt quantity.

3.2.1. Energy consumption study according to conductivity

The salt addition is beneficial in terms of energy consumption (Fig. 6), but on the other hand, it was noticed that there is overconsumption of the aluminum electrodes by corrosion if the NaCl concentration exceeds 1 g/L. It is because the chloride ions catalyze the electrode corrosion [47]. For this reason, we adopted a salinity of 1 g/L, a value which seems optimal in terms of energy consumption and prevents fast electrode dissolution.

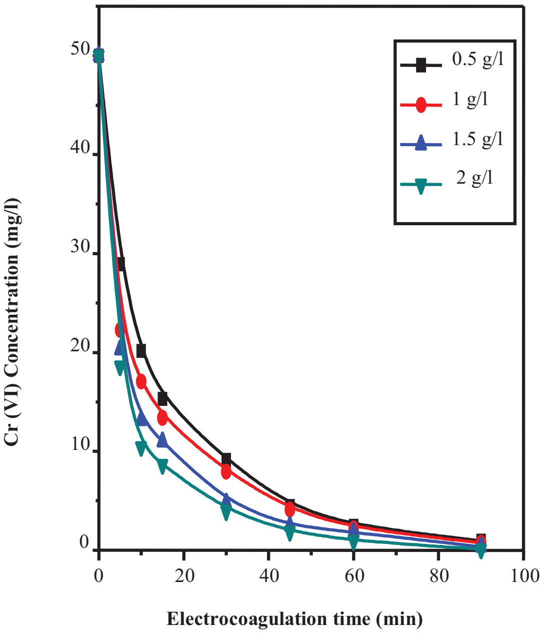


Fig. 5. Effect of salinity on the electrocoagulation of Cr(VI) kinetics: C_0 = 50 mg/L, initial pH = 3, U = 30 V, d = 1 cm, n = 4 electrodes.

3.3. Effect of initial pH

The initial pH is one of the principal factors that control the EC performance [44,46,48]. According to the Cr-Pourbaix diagram, the reduction of Cr(VI) to Cr(III) is thermodynamically favored in the acidic pH according to Eqs. (2) and (3).

In an attempt to investigate the effect of initial pH on the EC process, pH was varied in the range of 3–7. Results obtained as indicated in Fig. 7 show that the effectiveness of the process is better if the initial pH is equal to 3.

3.3.1. Energy consumption study according to initial pH

At low pH, the chromium elimination is done in a more effective way, which requires a lower current intensity to reach the same objectives. Consequently, the energy consumption increases with increase in pH. Results are shown in Fig. 8.

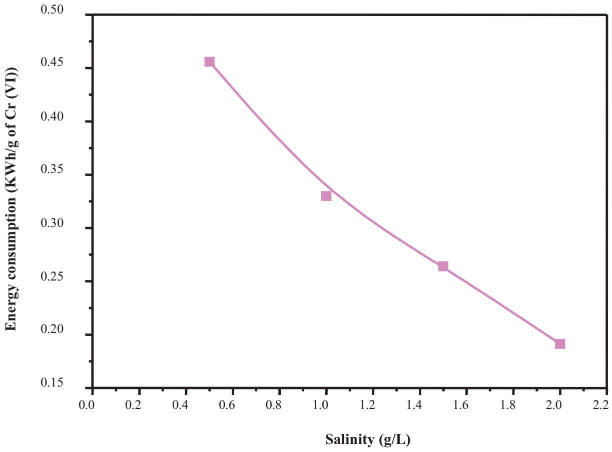


Fig. 6. Salinity influence on specific energy consumption (W) throughout electrolysis to reach 90% of elimination: C_0 = 50 mg/L, initial pH = 3, U = 30 V, d = 1 cm, n = 4 electrodes.

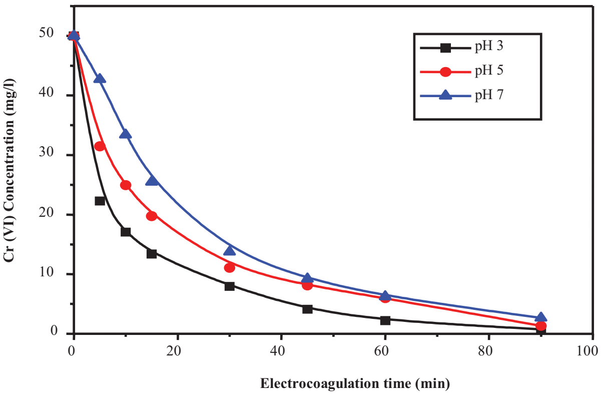


Fig. 7. Effect of initial pH on the electrocoagulation of Cr(VI) kinetics: C_0 = 50 mg/L, salinity = 1 g/L, U = 30 V, d = 1 cm, n = 4 electrodes.

3.3.2. pH evolution

It is known from various research articles [44,46,48,49] that the pH changes during the EC process. It was mentioned that this evolution depends on the initial pH and buffering capacity of the solution, because of the production and the consumption of OH$^-$ during EC, which allows avoiding an abrupt pH variation of the solution (Fig. 9).

3.4. Effect of initial chromium concentration

To study the effect of initial Cr(VI) concentration on Cr removal, experiments were conducted by varying the initial concentration from 5 to 500 mg/L. The results obtained are presented in Fig. 10. It was noticed that the effectiveness of elimination is much more for the lower concentrations (5, 50 mg/L). For high concentrations (200, 300, 500 mg/L), to reach suitable final concentrations (C), requires a higher time of EC, because of the insufficiency of hydroxyl and metal ions produced by the electrodes.

3.4.1. Energy consumption study according to initial chromium concentration

The effect of the initial concentration on the energy consumption and the effectiveness of Cr(VI) elimination were also investigated. The results are presented in Fig. 11. This study shows that the energy consumption to remove 1 g of chromium at the electric potential of 30 V, at pH 3, decreases according to the initial chromium concentration, it passes from 0.465 to 0.256 KWh/g. This reduction of energy consumption with the increase in the chromium concentration is explained by the fact that the excessive concentration of chromium supports the formation of flocs, which facilitates its elimination. However, the consumed total energy remains higher for high concentrations.

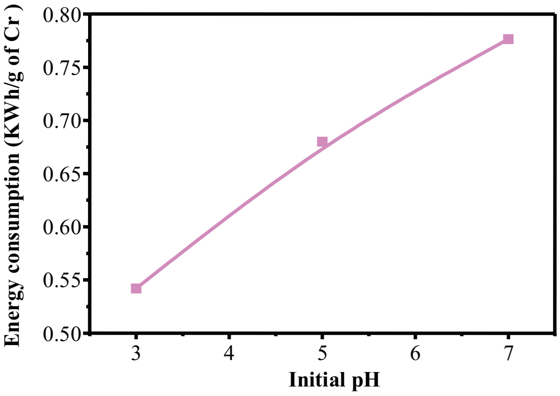


Fig. 8. Initial pH influence on specific energy consumption (W) throughout electrolysis to reach 90% of elimination: C_0 = 50 mg/L, salinity = 1 g/L, U = 30 V, d = 1 cm, n = 4 electrodes.

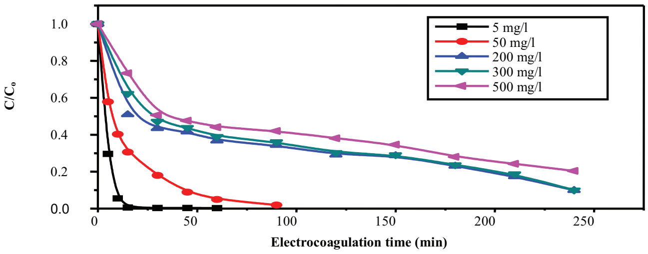


Fig. 10. Effect of initial chromium concentration on the electrocoagulation of Cr(VI) kinetics: salinity = 1 g/L, pH = 3, U = 30 V, d = 1 cm, n = 4 electrodes.

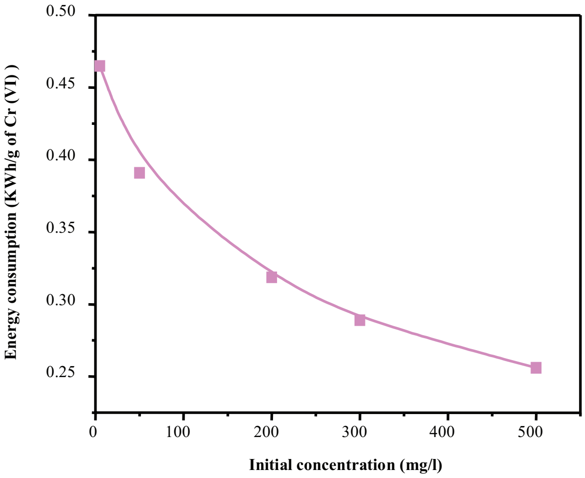


Fig. 11. Initial chromium concentration influence on specific energy consumption (W) throughout electrolysis to reach 90% of elimination: salinity = 1 g/L, initial pH = 3, U = 30 V, d = 1 cm, n = 4 electrodes.

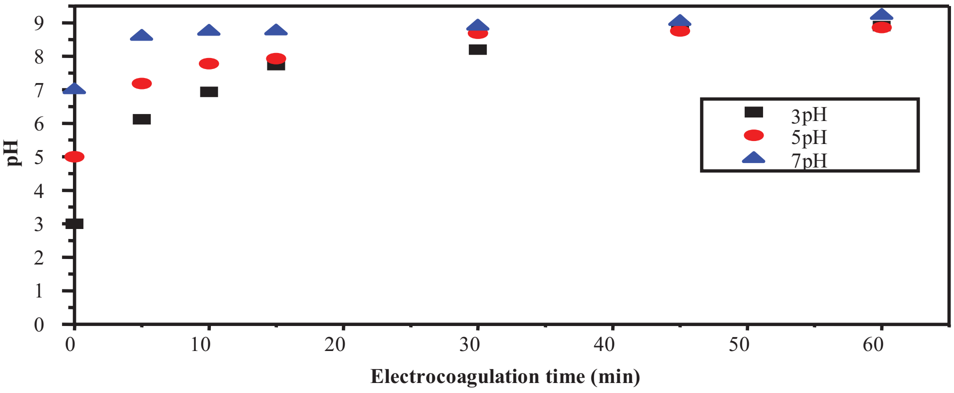


Fig. 9. pH evolution during the treatment: C_0 = 50 mg/L, U = 30 V, salinity = 1 g/L, d = 1 cm, n = 4 electrodes.

3.5. Effect of interelectrode distance

The effect of interelectrode distance (Intd) on the effectiveness of Cr(VI) elimination was also studied whose results are presented in Fig. 12. It was analyzed that despite the shape of the two curves which is appreciably the same, the results are much better for the interelectrode distance of 1 cm. As the interelectrode distance is increased, the resistance in solution also increases. For constant applied potential between electrodes, the current intensity decreases with increase in the interelectrode distance which results in a decrease of the Cr removal process. Thus, one has the interest to work with small distances in order to minimize the energy consumption. Nevertheless, a short distance can obstruct the transport and the suspension of the solid particles [47].

3.6. Effect of number of electrodes

It is known that the effectiveness of the EC process is strongly related to the electrode dissolution that produces a significant quantity of metal ions [38,39]. This is supported by an increase in number of plates. However, it is advisable not to increase the number of plates indefinitely so as to avoid ohmic fall.

The results obtained in Fig. 13 are in conformity with the above-stated assumptions. It was observed that for a higher number of electrodes (*n* = 4, 5, 6 plates) the removal is much faster; 30–40 min to reach 90% of removal, whereas 60–75 min are necessary for the same output if the number of electrodes is 2 or 3 plates.

According to the results shown in Fig. 13(b), it was noticed that the fact of increasing the number of electrodes from 4 to 6 does not bring a sensitive improvement to the kinetics of electrocoagulation.

3.7. Application on a real rejection

3.7.1. Selected effluent and its characterization

The effluent was collected from ENIEM Company (Domestic Apparatuses Complex) Tizi Ouzou. The main characteristics of the effluent are summarized in Table 2. After analysis of the effluent, it was found that conductivity is insufficient to be able to ensure an efficient treatment. In addition, the pH was higher compared with the optimal values which were selected at the time of the study carried out on synthetic solution. Therefore, the conductivity and pH of the sample was adjusted to values of 2.4 mS/cm and pH = 3, by the addition of NaCl and H_2SO_4 respectively. Adopted operating conditions and profiles of elimination obtained are shown in Fig. 14.

According to the results presented in Fig. 14, it was observed that the effectiveness of Cr(VI) abatement is checked on an industrial waste, and similar results were obtained as in the case of synthetic solution.

3.7.2. COD abatement

The effectiveness of organic pollution abatement when the effluent is treated according to the selected operating

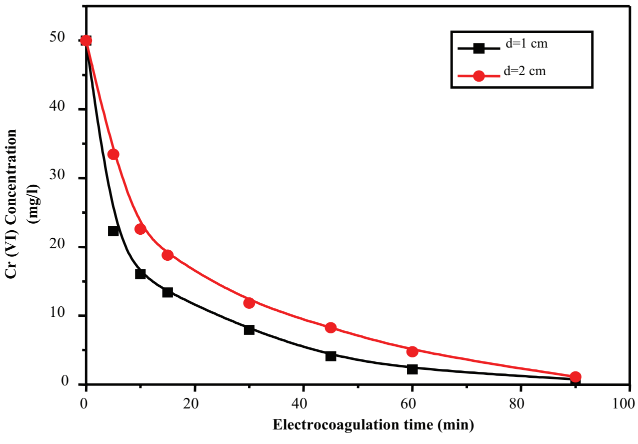


Fig. 12. Effect of interelectrode distance on the electrocoagulation of Cr(VI) kinetics: C_0 = 50 mg/L, salinity = 1 g/L, initial pH = 3, *U* = 30 V, *n* = 4 electrodes.

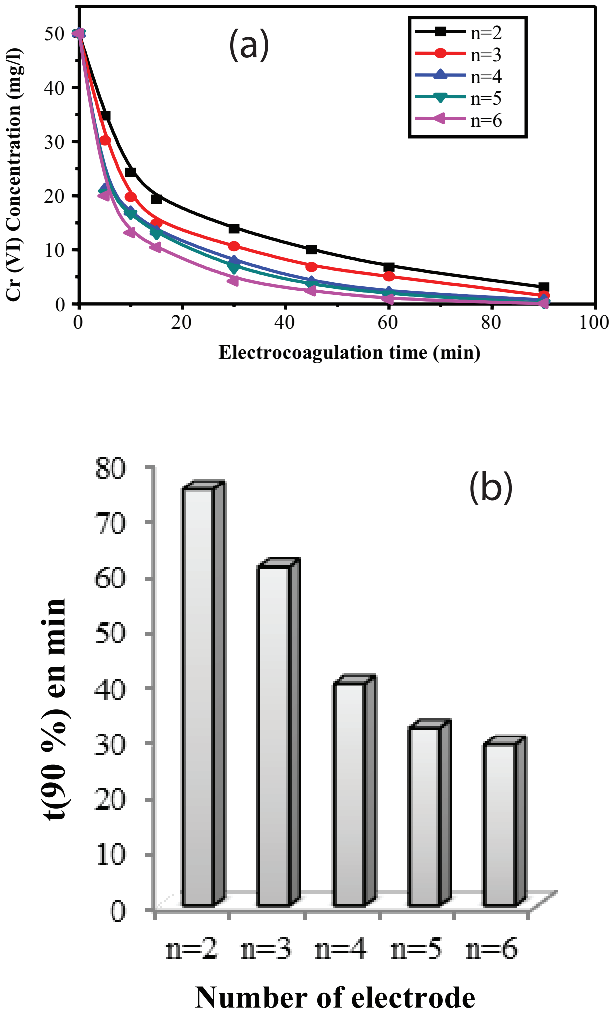


Fig. 13. (a) Effect of number of electrodes on the electrocoagulation of Cr(VI) kinetics: C_0 = 50 mg/L, salinity = 1 g/L, initial pH = 3, *U* = 30 V, *d* = 1 cm. (b) Time necessary for an elimination of 90% of Cr(VI) according to the number of electrodes: C_0 = 50 mg/L, salinity = 1 g/L, initial pH = 3, *U* = 30 V, *d* = 1 cm.

conditions was studied. It was observed that 70% of COD abatement was achieved in electrolysis duration of 60 min (Fig. 15).

3.7.3. pH evolution

The pH of the industrial effluent does not evolve in the same way as that of the synthetic solution (Fig. 16). In the case of the industrial sample an abrupt increase in pH was observed during first 10 min of the EC process, after which it tends to stabilize near pH 7. This is probably due to the decrease of production of OH^- ions because of the increase in the resistance of the effluent during the treatment.

Table 2
Characteristics of ENIEM effluent

[Cr(VI)], mg/L	34
pH	6.85
Conductivity, µS/cm	1,270
COD, mg O_2/L	324
Turbidity, NTU	5.01
Color	Yellowish

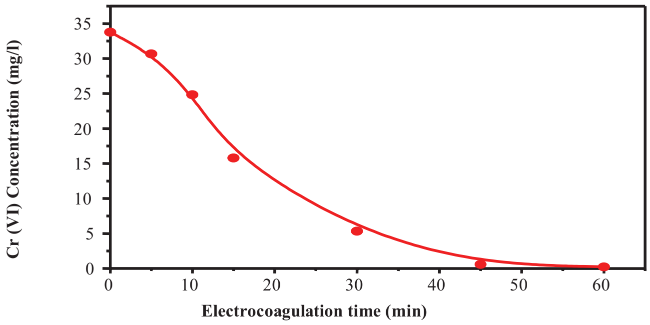


Fig. 14. Evolution of the kinetics of Cr(VI) electrocoagulation, in the case of ENIEM rejection: C_0 = 34 mg/L, conductivity = 2.4 ms/cm, initial pH = 3, U = 30 V, d = 1 cm, n = 4 electrodes.

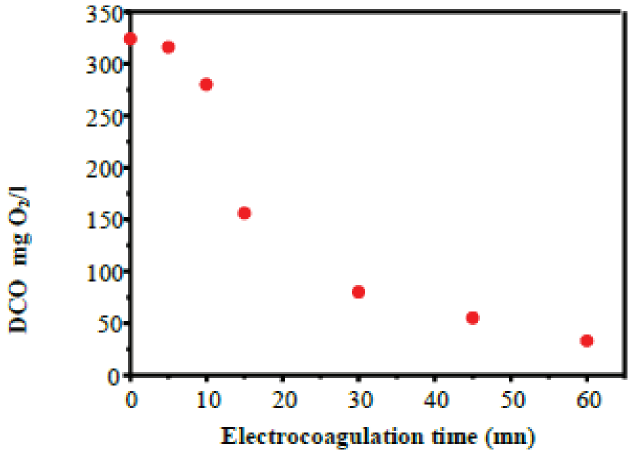


Fig. 15. Evolution of the effluent DCO during the treatment: C_0 = 34 mg/L, conductivity = 2.4 ms/cm, initial pH = 3, U = 30 V, d = 1 cm, n = 4 electrodes.

3.8. Characterization of flocs recovered

In order to know the composition of the recovered flocs, XRD was performed. Results of the analysis are shown in Fig. 17.

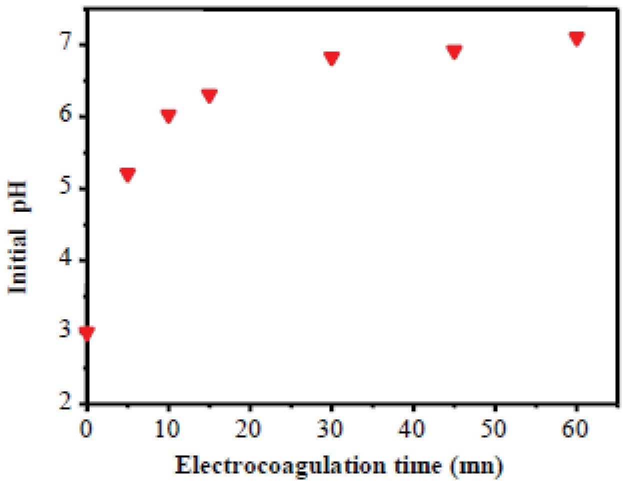


Fig. 16. pH evolution during the treatment: C_0 = 34 mg/L, conductivity = 2.4 ms/cm, initial pH = 3, U = 30 V, d = 1 cm, n = 4 electrodes.

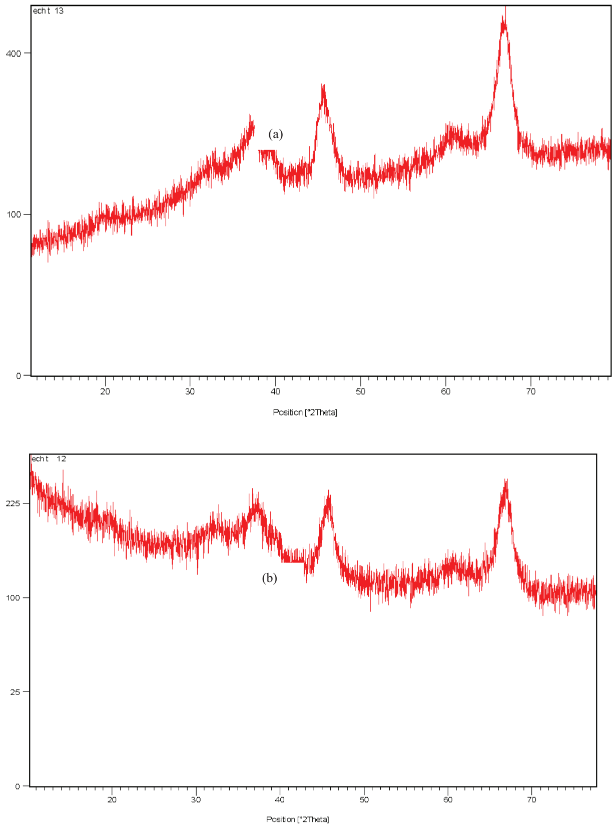
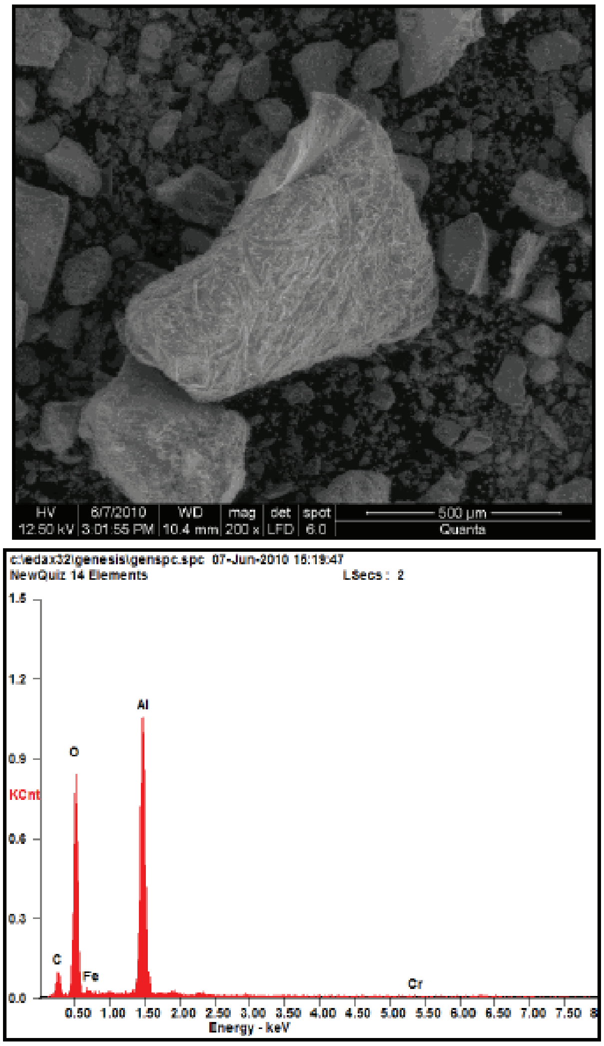


Fig. 17. Results of XRD analysis of the recovered flocks: (a) C_0 = 5 mg/L, salinity = 1 g/L, initial pH = 3, U = 30 V, d = 1 cm; (b) C_0 = 50 mg/L, salinity = 1 g/L, initial pH = 3, U = 30 V, d = 1 cm, n = 4 electrodes.

Figs. 17(a) and (b) show that the flocs consist of aluminum in $Al(OH)_3$ form and chromium in Cr_2O_3 form. In addition, visualization by SEM is carried out on the recovered flocs. The texture and the elementary composition of the floc were obtained. Fig. 18 illustrates the results of visualization by SEM.

4. Conclusion

Optimum conditions for the EC process were selected from the results of the present study. Better Cr(VI) abatements were obtained for high current density (J = 200 A/m^2; or high applied potential, 30 V), the optimum of initial pH is found to be 3, and optimal conductivity is estimated at approximately 2.4 mS/cm. These operating conditions made it possible simultaneously to reach a good mixture, a good floatation, the flocs stability and thus an efficient removal of chromium, which enabled to reach and even go beyond the allowed limiting value (0.1 mg/L) in a relatively short reaction time and low costs. The application of this process on an industrial waste led to very satisfactory results.



Element	*Wt %*	*At %*
C K	18.70	28.52
O K	39.27	44.97
FeL	05.20	01.71
AlK	36.21	24.58
CrK	00.62	00.22

Fig. 18. Elementary composition of the recovered flock, C_0 = 5 mg/L, pH = 3, U = 30 V, n = 4 electrodes.

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