



# An investigation on the new operational parameter effective in Cr(VI) removal efficiency: A study on electrocoagulation by alternating pulse current

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## ABSTRACT

The performance of an electrocoagulation (EC) process with aluminum/iron electrodes for removal of chromium on laboratory scale was studied. The effect of operational parameters such as initial pH, current density (CD), reaction time, initial concentrations (50, 100, 500, 1000 mg/L), solution conductivity, electrical energy consumption (EEC) and type of circuit were studied in an attempt to reach higher Cr(VI) removal efficiency. Alternating pulse current (APC) was used to prevent the passivity or polarization of electrodes. Important operating parameters were optimized to access higher (99%) Cr(VI) removal efficiency as follows: EEC range: 4–58 kWh/m<sup>3</sup> wastewater, CD: 56–222 A/m<sup>2</sup>, operating time: 20–110 min, pH 3–9 (pH<sub>optimum</sub> 5), voltage: 15–25 V. NaCl, KCl, PAC (poly aluminum chloride), NaNO<sub>3</sub> were used as supporting electrolytes. NaCl as well as KCl handled the EC with the best performance in every aspect; however, PAC and NaNO<sub>3</sub> did not have the same results (Applied conductivity is better than literature). The results of this work are comparable with those of recent studies. Equal removal efficiency was obtained in “direct current” (DC) and (APC); however, when “APC” was used, water recovery (0.92 m<sup>3</sup>/m<sup>3</sup> wastewater) was significant and the turbidity was 1 NTU. “APC” amazed our experimental team.

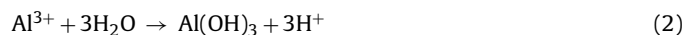
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## 1. Introduction

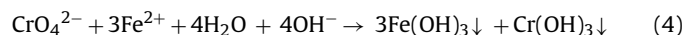
Electrocoagulation (EC) is one of the green and cheap methods used to remove heavy metals specially chromium from industrial effluents such as metallurgy, electroplating, leather tanning, chemical catalysts, pigments, corrosion inhibitors and printing inks [1]. Cr(VI) is toxic to most living organisms and has a significant mobility in the environment. It also has a high solubility in water. Cr(III) has low solubility in water and easily precipitates as Cr(OH)<sub>3</sub>; however, its toxicity is 1000 times less than that of Cr(VI). Many processes are used to remove heavy metals from effluents such as adsorption, precipitation, chemical coagulation, and electrocoagulation [2,3]. Adsorption and precipitation processes are costly and very time consuming, and therefore have low efficiency. Electrocoagulation (EC) as an electrochemical method was developed to overcome the drawbacks of conventional water and wastewater treatment technologies [4]. EC process provides a simple, reliable, and low cost method for the treatment of wastewater without any need for additional chemicals and without secondary pollution. It also reduces the amount of sludge, which needs to be disposed. EC technique uses a direct current source between metal elec-

trodes immersed in polluted water [5]. The electrical current causes the dissolution of metal plates including iron or aluminum into wastewater. A wide range of coagulated species and metal hydroxides can be formed from metal ions at an appropriate pH, which leads to destabilization and aggregation of suspended particles as well as precipitation and removal of dissolved contaminants such as heavy metals [6]. The most widely used electrode materials in EC process are aluminum (Al) and iron (Fe). In the case of aluminum, the mechanism and main reactions are as follows [7].

The electrolytic dissolution of Al anode at low pH produces Al<sup>3+</sup>, Al(OH)<sup>2+</sup>, and Al(OH)<sub>2</sub><sup>+</sup>. Then it is transformed to gelatinous ball Al(OH)<sub>3</sub> that finally is polymerized to Al<sub>n</sub>(OH)<sub>3n</sub>:



Gelatinous charged species are effectively removing Cr(VI) by adsorption on the floc surface or by enmeshment precipitating during EC process. Sacrificial iron electrode under oxidation, produces Fe(OH)<sub>n</sub> where (n = 2 or 3). Generated Fe<sup>2+</sup> under alkaline condition can reduce Cr(VI) to Cr(III), and itself is oxidized to Fe<sup>3+</sup> as:



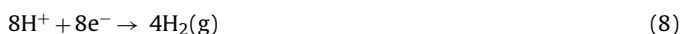
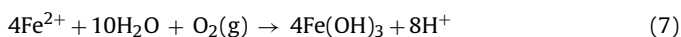
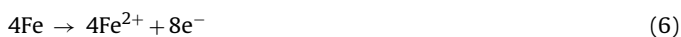
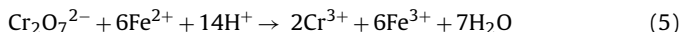
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### Nomenclature

APC	alternating pulse current
$C_0$	initial Cr(VI) concentration (mg/L)
CD	current density ( $A/m^2$ of anode)
Cr	chromium
DC	direct current
EC	electrocoagulation
EEC	electrical energy consumption ( $kWh/m^3$ wastewater)
$I$	operating current (ampere), A
PAC	poly aluminum chloride
rpm	rounds per minute
$S$	surface area of electrode ( $m^2$ )
$t_{EC}$	time of electrocoagulation or reaction time (min)
NTU	nephelometer turbidity unit
$V$	operating voltage (volt), V
$v$	volume of wastewater ( $m^3$ )
$\gamma$	specific conductivity (mS/cm)

The  $Cr^{3+}$  ion precipitates as  $Cr(OH)_3$  by raising the pH of solution. Also under acidic condition,  $Fe^{2+}$  can reduce  $Cr_2O_7^{2-}$ :



Hydrolysis of  $Fe^{3+}$  based on pH of the solution can produce these species,  $Fe(OH)^{2+}$ ,  $Fe(OH)_2^+$ ,  $Fe(OH)_3$ .

In this study, a wide range of Cr(VI) initial concentrations (50, 100, 500, 1000 mg/L) were investigated, whereas other studies worked on initial Cr(VI) concentrations up to 180 mg/L. Also in this investigation an APC mode for removal of Cr(VI) was utilized, in addition to traditional DC method. For this reason, some operational parameters corresponding to APC mode were optimized. Two processes can interfere with the electrolytic process: polarization or passivity and mass transport control [8–10]. It should be noted that, in this investigation, the influences of “APC” and various supporting electrolytes were studied to avoid electrode passivity. However, in this research “water recovery” was introduced and calculated in order to show the more economically feasible recycling of treated water.

## 2. Materials and methods

### 2.1. Wastewater sampling and electrocoagulation process

This research included a treatable batch analysis of the electrolytic process. All chemicals including potassium dichromate ( $K_2Cr_2O_7$ , 99%), sodium hydroxide pellets, concentrated sulfuric acid, and supporting electrolytes such as sodium chloride, potassium chloride, PAC (poly aluminum chloride) and  $NaNO_3$  were analytical grade (Merck, Germany). A synthetic stock solution of 1000 mg/L Cr(VI) was prepared, and solutions of lower concentrations: 50, 100, 500, 1000 mg/L were prepared by proper dilutions with deionized water (original pH of the solution was 5). All runs were performed at room temperature and stirring speed was 120 rpm.

In this study, two tasks were considered to control the passivity and Cr removal efficiency: (1) the influences of ionic strength for

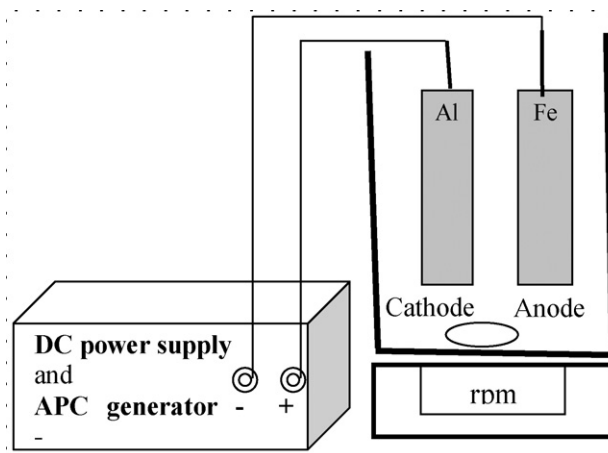


Fig. 1. Schematic diagram of the electrocoagulation reactor.

some supporting electrolytes such as NaCl, KCl, PAC and  $NaNO_3$ , were examined and compared with each other to achieve higher removal efficiency. (2) Type of circuit, APC, was exerted to decrease the polarization and the sludge resistance around the electrodes and to hitch the sludge from anode and cathode. Initial chromium solution conductivity was increased by proper amounts of NaCl, KCl, PAC and  $NaNO_3$  before each experiment (Table 1). In order to evaluate the effect of initial pH on Cr(VI) removal efficiency, sulfuric acid solution and sodium hydroxide (0.1 M) were used. Experiments were performed in a batch system (Fig. 1). Net volume reactor was 0.7 L, the effective area of each electrode [Al (cathode) and Fe (anode)] used was  $36\text{ cm}^2$  ( $6\text{ cm} \times 6\text{ cm}$ ). The gap between electrodes was 1.5 cm. One DC power supply package having an input of 220V and variable output of 0–30V, with variable current 0–4A was used. An electro alternative pulse current generator was applied to study the APC type of circuit (from Nano Pushesh Felez, Iran). The optimum operating conditions are described below (Sections 3.1–3.6).

### 2.2. Methods of analysis

In all experiments the pH was measured with a Metrohm pH meter (Model No. 827), the conductivity was measured with an Hach/Lange conductivity meter (method 2510-B [11]), determination of chromium was based on 3500-Cr-B colorimetric method (diphenylcarbazide) from standard methods [11], using an UV-vis spectrophotometer (Hach/Lange (DR/2800)) and also an Atomic Absorption Spectrometer (Thermo-Model Solaar M5), (method 3111-B [11]). Upon completion of the process, the test samples were filtered [11,12] before Cr(VI) analysis. All experiments were repeated twice, and the experimental error of 4% was observed.

The calculation of Cr(VI) removal efficiency after EC process was performed using this formula:

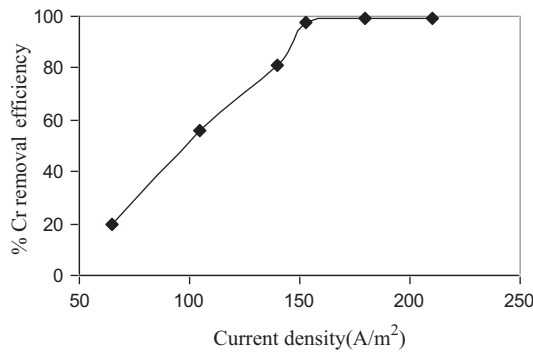
$$\text{Cr(VI) removal efficiency (\%)} = \frac{C_0 - C}{C_0} \times 100 \quad (10)$$

where  $C_0$  is the initial Cr(VI) concentration (before EC) and  $C$  is the final Cr(VI) concentration (after EC) in mg/L.

Power consumption or electrical energy consumption was determined as follows:

$$\text{(EEC) (kWh/m}^3 \text{ wastewater)} = \frac{VIt}{v} \quad (11)$$

where  $V$  is the operating voltage (volt),  $I$  is the operating current (ampere),  $t$  (or  $t_{EC}$ ) is the time of reaction (min) and  $v$  is the volume of wastewater ( $m^3$ ).



**Fig. 2.** Effect of current density on the Cr(VI) removal efficiency,  $C_0$ : 100 mg/L,  $t_{EC}$ : 25 min, electrolyte: NaCl.

The current density (CD) was measured according to Eq. (12):

$$CD = \frac{I(A)}{2S_{\text{electrode}}(m^2)} \quad (12)$$

where  $I$  is the current (A) and  $S$  is the surface area of the electrode ( $m^2$ ).

The water recovery was measured according to Eq. (13):

$$\text{Water recovery} = \frac{\text{volume of product water(after EC)}}{\text{initial volume of wastewater(before EC)}} \quad (13)$$

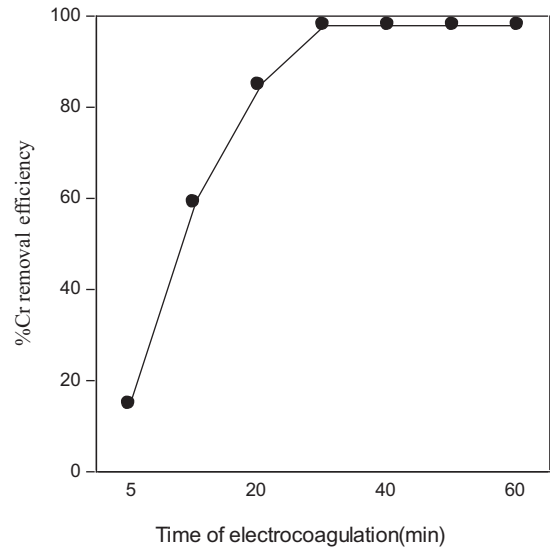
Indeed the clear supernatant is product water or treated water; however, highly dense (or dewatered) sludge remained at the reactor bottom after EC. The product water in APC mode is much more significant than the product water in DC mode (Table 2).

### 3. Results and discussion

The electrocoagulation process was controlled by several operational parameters, such as current density (CD), time of electrolysis, initial pH, initial chromium concentration, type of current, conductivity and energy consumption. In order to enhance the process performances, the influences of these parameters were studied as follows.

#### 3.1. Effect of current density on the Cr(VI) removal efficiency

In all electrochemical processes, current density (CD) is the most important parameter for reaction controlling in the reactors. According to Faraday's law [5] CD determines the coagulant production rate and regulates the rate and size of the bubbles and growth of flocs. A series of electrocoagulation tests were carried out by solutions containing constant initial Cr(VI) concentrations (50–1000 mg/L) with current densities varied from 40 to 230 A/m<sup>2</sup>. It is obvious that the Cr(VI) removal efficiency increases at higher CD. Fig. 2 shows the Cr(VI) removal efficiency versus different



**Fig. 3.** Effect of time on the Cr(VI) removal efficiency,  $C_0$ : 100 mg/L, CD: 153 A/m<sup>2</sup>, electrolyte: NaCl.

CD (for example Cr(VI): 100 mg/L, treatment time: 25 min). The results show some improvement over previous attempts [13]. Other optimized current densities have been presented in Table 2 for defined conditions achieving higher removal efficiency. It is notable that most authors studied initial Cr concentration up to 50 mg/L [12–17] and 180 mg/L [1]; however, in this study optimized current densities were introduced for removal of higher Cr(VI) concentrations (500, 1000 mg/L) based on maximum removal efficiency (99.4, 99.9% respectively) that have not been treated in the literature.

#### 3.2. Effect of time of electrolysis on the Cr(VI) removal efficiency

Based on Faraday's law [5], reaction time also influences the removal efficiency of Cr(VI) in EC process and it determines the production rate of Fe<sup>2+</sup> or Fe<sup>3+</sup> ions from electrodes. To investigate the effect of time on Cr(VI) removal efficiency a series of experiments were carried out by solutions containing constant initial Cr(VI) concentrations (50–1000 mg/L) by considering each optimized current density represented in Table 2. As can be observed in Fig. 3, Cr(VI) removal efficiency was above 99% in the first 30 min and was almost constant after that. Optimum time increases with increasing initial Cr concentration. At low Cr concentrations (100–1000 mg/L), the operating time is 25–110 min respectively.

**Table 1**  
Properties of initial wastewater based on different types of supporting electrolyte.

Initial Cr (VI) solution concentration (mg/L)	Initial pH	Electrolyte dosage <sup>a</sup> (kg/m <sup>3</sup> wastewater)	Initial conductivity of Cr solution when only NaCl used as electrolyte $\gamma$ (mS/cm)	Initial conductivity of Cr solution when only KCl used as electrolyte $\gamma$ (mS/cm)	Initial conductivity of Cr solution when only NaNO <sub>3</sub> used as electrolyte $\gamma$ (mS/cm)	Initial conductivity of Cr solution when only PAC used as electrolyte $\gamma$ (mS/cm)
50	5	0.23	0.59	0.5	0.16	0.14
100	5	0.57	1.1	1.07	0.6	0.25
500	5	0.85	2.5	2.05	1.14	0.64
1000	5	1.14	3.4	3.9	2.2	1.70

<sup>a</sup>These suggested values are optimized during several batches based on minimum energy consumption and maximum removal of Cr(VI).

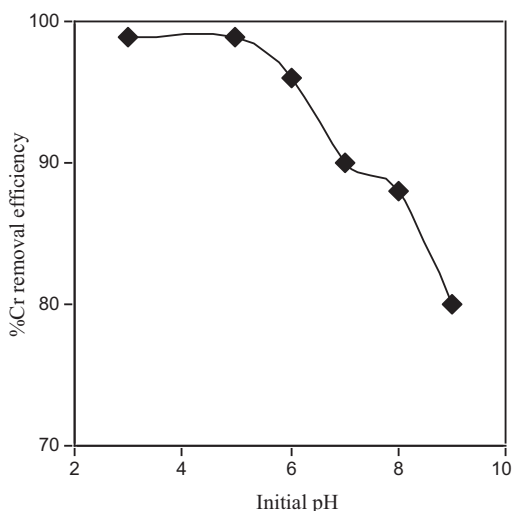


Fig. 4. Effect of initial pH on the Cr(VI) removal efficiency,  $C_0$ : 100 mg/L,  $t_{EC}$ : 25 min, CD: 153 A/m<sup>2</sup>, electrolyte: KCl.

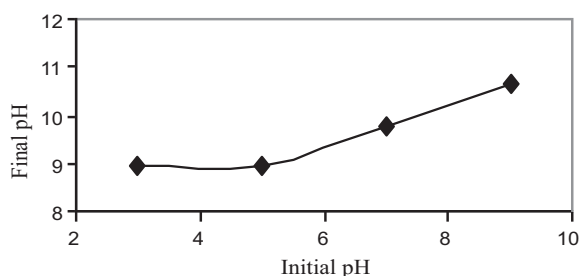


Fig. 5. Initial pH versus final pH,  $C_0$ : 100 mg/L,  $t_{EC}$ : 25 min, CD: 153 A/m<sup>2</sup>, electrolyte: NaCl.

### 3.3. Effect of initial pH on the Cr(VI) removal efficiency

The dependence of Cr(VI) removal efficiency on initial pH values was investigated over pH range of 3–9. It can be seen from Fig. 4 that the initial pH plays an important role on the performance of EC process. If pH is greater than 8, efficiency decreases to below 90%. According to Table 2, the maximum removal efficiency of Cr(VI) depending on concentrations were 98–99.9% in acidic mediums (pH 3 and 5). Since the initial pH value of the Cr(VI) solutions was near 5, no change in the pH of the solutions was needed and all later experiments were done at this initial pH. Because of hydroxyl ions production in EC process, the final pH increased during electrolysis (Fig. 5).

According to the Cr-Pourbaix diagram [18], the reduction of Cr(VI) to Cr(III) is thermodynamically favored under acidic conditions. The removal of Cr(VI) can be done by electrochemical processes under highly acidic, alkaline and neutral conditions [15–23]. However, it is still unclear whether low or high pH medium is suitable to achieve good overall performances for the EC process.

Table 2

Optimized operational parameters for various Cr(VI) initial concentration in APC mode, electrolyte: NaCl.

Initial Cr(VI) solution concentration (mg/L)	Final pH	Current density (A/m <sup>2</sup> ) (Eq. (12))	Operating time (min)	Energy consumption (kWh/m <sup>3</sup> wastewater) (Eq. (11))	Cr(VI) removal efficiency (%) (Eq. (10))	Water recovery <sup>a</sup> (m <sup>3</sup> /m <sup>3</sup> of wastewater) (Eq. (13))
50	9	56	20	4.00	98.0	0.92
100	10	153	25	16.30	98.0	0.90
500	10	153	55	20.16	99.4	0.80
1000	10	222	110	58.00	99.9	0.70

<sup>a</sup>The water recovery is less than 0.5 (m<sup>3</sup>/m<sup>3</sup> of wastewater) for DC mode.

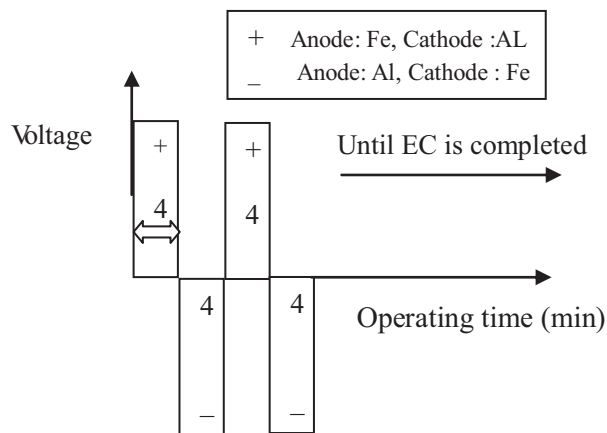


Fig. 6. Typical diagram for alternating rectangular pulse current (APC). Cathode or anode is operating for 4 min, then it is replaced or changed with each other until EC is completed, maximum voltage: 15 and 25 V based on initial Cr(VI) concentration respectively.

### 3.4. Type of circuit and its effect on EC-alternating pulse current (APC)

During EC process sludge is produced, while polarization and fouling phenomena are occurring around the anode. In other words, passivity and mass transport control [8] can interfere with the electrolytic process. For some systems, an increase in current does not lead to a corresponding dissolution of the electrode. Passivity is caused by a build up of metal oxides on the surface of the electrodes, leading to an increase in the resistance to the electrolytic process [9].

In this study, alternating pulse current (APC) was established and proposed to control the passivity [6,13,24]. Fig. 6 exhibits applied APC, where either cathode or anode is typically operating for 4 min, and then it is replaced or interchanged until EC is completed. The proposed time was optimized during a series of experiments. Applied voltage was 15–25 V based on initial Cr(VI) concentrations in each batch. Equal Cr(VI) removal efficiency was obtained in direct current and alternating pulse current.

The APC mode was found to be more efficient than the DC mode with a lower anode over-voltage, slower anode polarization and passivity. The operating time is (3%, 6%, 15%, 25%) less in APC mode based on initial Cr(VI) concentrations of (50, 100, 500 and 1000 mg/L), respectively. All the operating times in APC mode are represented in Table 2.

However, because of changing electrodes in APC mode, sludge was hitched around the electrodes and fouling phenomena were limited. Dewatered and dense sludge impressed our experimental team. Water recovery (Eq. (13)) was significant, about 0.92 m<sup>3</sup>/m<sup>3</sup> wastewater (see Table 2 for detailed operational parameters). Turbidity of clarified water or water recovery in APC and DC mode were 1 NTU and 20 NTU respectively after EC process.

### 3.5. Effect of initial Cr(VI) concentration on Cr removal efficiency

Chromium solutions with different initial concentrations in the range of 50–1000 mg/L were treated by EC process; however, other studies worked on initial Cr(VI) concentrations up to 180 mg/L [1,7,12–17,19–23]. Consequently, optimized operational parameters such as current density, time of reaction and electrical energy consumption (EEC) values are represented based on various initial Cr(VI) concentrations in Table 2.

According to the results, at high initial Cr(VI) concentrations, the Cr(VI) removal efficiency was near 99% while operating time and the energy consumption increased. Heidmann and Calmano [15] reported similar results for the removal of Cr(VI) solutions up to 50 mg/L by EC process; however, Aber et al. [14] obtained different results.

### 3.6. The effect of type of supporting electrolyte and electrolyte dosage

In this research, 2 tasks were investigated: (1) access to maximum Cr(VI) removal efficiency (2) a study on water recovery (or treated water) reuse. If the conductivity of water recovery is near 2 mS/cm or less, recycling is more economically feasible. In this study, electrolyte consumption for enhancement of EC was optimized in the range of 0.1–3.9 mS/cm for low to high concentrations of Cr(VI), and other operational parameters are reported based on these conductivity levels (Tables 1 and 2). However, other authors [3,10,14–16,25] reported a conductivity level of up to 17 mS/cm. Thus electrolyte consumption in the highest Cr(VI) concentration (1000 mg/L) was 1.2 g/L in this study, whereas in previous research values up to 17 g/L were reported.

It should be noted that the Cr(VI) removal efficiency in this study was 99.9%, the same as that in previous works. In order to limit the IR-drop [9] and solution resistance potential, conductivity of the solution should be sufficiently high. Most authors have used chloride as anion to enhance the conductivity of the solution and some have utilized nitrate and sulfate as the electrolytes [15,16,25]. The conductivity of the solution influences the current density, voltage and power consumption in EC process.

In this investigation, NaCl, KCl, PAC (poly aluminum chloride,  $Al_2(OH)_nCl_{6-n}$ ) and  $NaNO_3$  were used as supporting electrolytes separately by using Al/Fe electrodes. The performance of each electrolyte was compared in each batch, based on high Cr(VI) removal efficiency and low operating time and energy consumption. The optimized and suggested electrolyte concentration in each initial Cr(VI) concentration is represented in Table 1. NaCl and KCl have additional advantages because chloride ions could reduce the adverse effects of other anions such as  $HCO_3^-$  and  $SO_4^{2-}$  [6] where the existence of the carbonate ion leads to the precipitation of  $Ca^{2+}$  ions that form an insulating layer on the surface of the electrodes [10]. The ohmic resistance of EC cell increases when polarization takes place. As a result, the conductivity of chromium solutions were adjusted using supporting electrolyte in the range of 0.23–1.14 kg/m<sup>3</sup> of wastewater based on initial Cr(VI) concentration.

The effect of type of supporting electrolyte (KCl and NaCl) and electrolyte dosage is shown graphically in Figs. 7 and 8 (for 100 mg/L Cr(VI) concentration, current density: 153 A/m<sup>2</sup>, pH<sub>optimum</sub> 5 and stirring speed: 125 rpm were kept constant in the experiments).

As expected, the rate of Cr(VI) reduction increased with an increase in concentration of supporting electrolyte. For example the removal efficiency of Cr(VI) was near 99% at 0.57 kg KCl/m<sup>3</sup> wastewater, and 70% at 0.3 kg KCl/m<sup>3</sup> wastewater.

In addition, energy consumption decreased with increasing concentration of supporting electrolyte because the potential

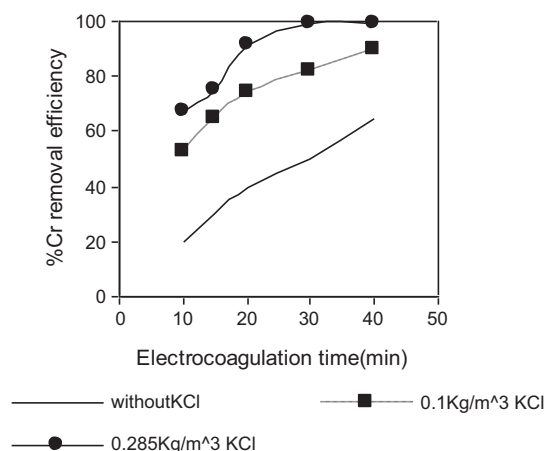


Fig. 7. Variation of Cr(VI) removal efficiency with time for different KCl concentration, CD: 153 A/m<sup>2</sup>, pH 5, initial Cr(VI) concentration: 100 mg/L.

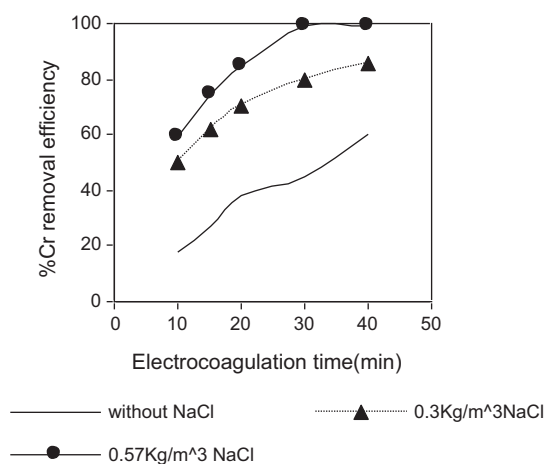


Fig. 8. Variation of Cr(VI) removal efficiency with time for different NaCl dosages, CD: 153 A/m<sup>2</sup>, pH 5, initial Cr(VI) concentration: 100 mg/L.

decreased under constant current density. Energy consumption and Cr(VI) removal efficiency were calculated by Eq. (10) and (11), respectively. Other optimized parameters are presented in Table 2. Although Cr(VI) removal increased with all supporting electrolyte types (Fig. 9), the highest Cr(VI) removal was observed when NaCl and KCl were used. The effect of PAC dosage on Cr(VI) removal efficiency was evaluated. The results showed that for removal of initial Cr(VI) concentrations of 500 and 1000 mg/L, the use of PAC is not recommended. Also the influence of  $NaNO_3$  on Cr(VI) removal efficiency was examined. As Fig. 9 demonstrates,  $NaNO_3$  is not as good an electrolyte as NaCl and KCl, based on these defined dosages.

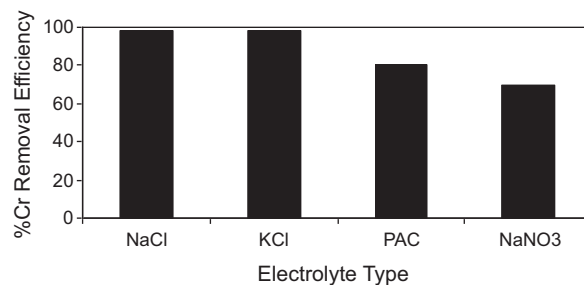


Fig. 9. Comparison of electrolytes % Cr(VI) removal efficiency development versus electrolyte type, initial Cr(VI) concentration 100 mg/L,  $t_{EC}$ : 25 min, pH 5, CD: 153 A/m<sup>2</sup>, EEC: 16.3 kWh/m<sup>3</sup> wastewater.

It was concluded that KCl was as effective as NaCl in removing Cr(VI) completely in these experiments, because of high removal efficiency and minimum energy consumption. The four types of electrolytes are compared in Fig. 9.

#### 4. Conclusions

The results of this study showed electrocoagulation (with Fe/Al electrodes) could be applied in the treatment of industrial effluents containing Cr(VI). Consequently, the following conclusions can be obtained:

- (i) The APC mode was found to be more efficient than the DC mode with a lower anode over-voltage, slower anode polarization and passivity, and lower tank voltage. The operating time is 3–25% less when APC mode is used, based on initial Cr(VI) concentration of 50–1000 mg/L, respectively. All the operating times in APC mode are represented in Table 2. Because of the reduction in operating time, less power (or energy) is consumed, which makes the APC mode more cost effective. Application of APC eliminates uneven wear (dissolution) of electrodes; typically, the anode material dissolves and electroreduction products stick to the cathodes when DC (direct current) mode is used. It is notable that when the APC mode is used, electrocoagulation produces a highly dense or compact sludge at the reactor bottom, resembling dense clay soil layers. It also produces a clear supernatant (Turbidity: 1 NTU) or high quality effluent which is feasible for reuse as treated water. In this study, water recovery was found to be from 0.7 to 0.92, based on initial Cr(VI) concentration from 50 to 1000 mg/L, respectively. The APC mode minimizes waste and increases sludge stability.
- (ii) In this research, the optimum operating conditions in solutions containing initial Cr(VI) concentrations within 50, 100, 500 and 1000 mg/L were obtained to achieve a higher removal capacity (99%). The best optimized conditions were proposed are as follows: Optimized range of electrical energy consumption (EEC): 4–58 kWh/m<sup>3</sup> wastewater, optimized range of current density: 56–222 A/m<sup>2</sup>, operating EC time: 20–110 min, pH<sub>optimum</sub> 5, applied electrical potential: 15–25 V.
- (iii) After sludge is produced, the passivity can interfere in EC and can control the mass transport. To solve this problem in this study, an alternating pulse current (APC) was established to limit these effects. Equal removal efficiency was obtained in direct current and alternating pulse current. In the APC mode, the “water recovery” was very significant, measuring as high as 0.92 m<sup>3</sup>/m<sup>3</sup> wastewater. For DC mode, the water recovery was less than 0.5 m<sup>3</sup>/m<sup>3</sup> of wastewater.
- (iv) The role of NaCl, KCl, PAC and NaNO<sub>3</sub> as supporting electrolyte and coagulant aid were evaluated. KCl was as effective as NaCl, and could remove Cr(VI) from wastewaters with the best performance in every aspect. The use of PAC was ranked second, and NaNO<sub>3</sub> was third. In this study, the electrolyte consumption for enhancement of EC is optimized in the range of 0.1–3.9 mS/cm for low to high concentration of Cr(VI). It should

be noted that, in this study, the Cr(VI) removal efficiency by APC mode was 99.9%.

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