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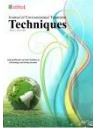

Chromium and Cadmium Removal from Synthetic Wastewater by Electrocoagulation Process

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Abstract

Electrocoagulation (EC) is one of the efficient electrochemical approaches for industrial wastewater treatment. The present work aims to reach optimum conditions for achieving simultaneous removal of chromium and cadmium ions from synthetic wastewater by EC through assessment of different parameters like electrodes material, electrode configuration, initial pH, current density, initial temperature, and initial contaminate concentration. In addition, a comparison between chemical coagulation and EC efficiency for Chromium and cadmium removal was presented. Results showed that the (Fe-Al), an anode and cathode, achieved better removal efficiency than other electrodes configurations (Fe-Fe / Al-Fe / Al- Al). Also, the increase of initial temperature and current density enhanced the removal efficiency. In contrast, the increase in the initial concentration reduced the removal efficiency. The complete removal of Chromium achieved through the use of Fe-Al electrodes and current density was 12.50 mA/cm^2 with solution pH of 5.8, temperature was 25°C and an initial concentration of 280 mg/L. On the other hand, Cadmium's complete removal was achieved through the use of Fe-Allectrodes, at pH of 5.8, applied current 1.4 A and 60°C. Therefore, EC was proved to be better approach than conventional coagulation in case of treatment of wastewater containing different types of heavy metals ions with high initial concentrations.

Keywords: Electrocoagulation, Industrial Wastewater, Heavy metals, Cadmium, Chromium, Chemical Coagulation

1 Introduction

Rising water demand due to an increase in the population, while the scarcity of regional water resources leads to the need to reuse each drop of wastewater as the available freshwater for human beings is 1% of total water in the earth, but that small part is reducing due to the miscellaneous sources of pollution particularly in third world countries (1). The challenge is to treat the wastewater to the required level with the most economical methods. The existence of heavy metals in the industrial wastewater prohibits its reuse in many applications for their toxic and carcinogenic effects; it also tends to accumulate in living organisms. In 2011, the World Health Organization (WHO) limited the concentration of Cadmium (Cd^{2+}) to less than 0.005 mg/L due to its teratogenic and carcinogenic effects (1)(2). Standard techniques used for heavy metal removal, for example, include sedimentation, adsorption (3), ion exchange (4), electrocoagulation (EC) (5–8), low-cost materials (9), and ion exchange assisted membrane separation (10). The merits of the EC than chemical coagulation are the reduced sludge volume and its low energy requirements (11).

EC was used to remove some heavy metals ions, such as lead (Pb), Cadmium (Cd), nickel (Ni) and copper (Cu) with high removal ratios which exceeded 90% (2,7,12). EC gathers many mechanisms that can be sequential and/or parallel. These mechanisms can be electrochemical (metal dissolution and water reduction, pollutant electro oxidation or electro-reduction), chemical (acid/base equilibria with pH change, hydroxide precipitation, redox reaction in bulk) and physical (physical adsorption, coagulation, flotation) (13).

EC process involves the generation of coagulants in situ as a result of the dissolution of the sacrificial anode metal with simultaneously forming metal hydroxide. EC occurs at three steps (14): the generation of coagulation through electrolytic oxidation of the electrode, the destabilization of the suspended solids, and finally, the formation of flocs through the aggregation of the destabilized phase where metal ions produced at the anode. Furthermore, electro flotation may take place for the coagulated particles due to the generation of H_2 and O_2 bubbles at the electrodes (15). All these process happen according to following reactions. The basic reaction happening: At the anode is dissolution

$$M_{(s)} \rightarrow M_{(aq)} + ne^- \quad (1)$$

Also water electrolysis happens at the cathode and the anode

$$2\ H_2O_{(l)} + 2\ e^- \rightarrow H_{2(g)} + 2\ (OH)^-\ \text{(cathodic reaction)} \quad (2)$$

$$2\ H_2O_{(l)} \rightarrow 4H^+_{(aq)} + O_{2\,(g)} + 4\ e^-\ \text{(anodic reaction)} \quad (3)$$

$$M^{n+}_{(aq)} + ne^- \rightarrow n\ M^0\ \ \text{(reduction reaction)} \quad (4)$$

The precipitation of metal ions as corresponding hydroxides and co-precipitation with hydroxides: (the metal cation (M^{n+}))

$$M^{n+}_{(aq)} + n\ OH^- \rightarrow M\ (OH)_{n\ (S)} \quad (5)$$

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Via this process, the coagulant dosage can be significantly decreased as compared with conventional methods; this process can also be used for reuse of wastewater and less sludge generation. The environmental compatibility, versatility, selectivity, energy efficiency, amenability to mechanization, safety and cost-effective are the add-on benefits of this process. EC is a potential technique for achieving these goals of sustainability (16, 17).

Many essential parameters affect the EC process include electrode material, pH, current density, temperature, and wastewater contaminants and concentrations while using different types of electrodes materials, such as Al, Fe, Ag, Ba, Ca, Zn, Ni (18). The selection of the electrodes is usually associated with their costs and efficiencies. Besides, pH value plays a vital role in equilibrium as it affects the solution of the generated species. In this case, neutral and alkaline media are preferred for EC (19). Also, current density has an essential role in what happens in the solution because it dominates the generation of anode hydroxides, the bubble release, and the growth of the flocs, which in return promotes the removal process. However, a high current density can lead to some adverse circumstances. High current density will result in cathode passivation give rise to energy consumption and cost (19,20). As a result, the current density is the most potent parameter in EC since it controls the performance and the cost of the process (18,21–23).

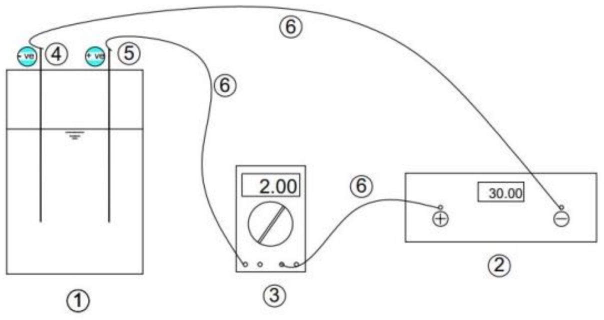
The aim of this work was to investigate the efficiency of EC for simultaneous removal of Chromium and Cadmium together at high concentrations and temperature and to reach the optimum operational parameters for best removal efficiency. Also, the work investigated the best configuration of electrodes (Fe – Fe / Fe – Al / Al – Fe / Al – Al). This work studied the efficiency of conventional coagulation in dealing with the same conditions of wastewater and presented a comparison with EC.

2 Material and Methods

Synthetic wastewater was prepared with Chromium and Cadmium as a stock solution of 1L with 560 mg/L for Chromium and 800 mg/L for Cadmium. These initial concentrations were chosen to simulate real concentrations of heavy metals in industrial wastewater like tannery industries and dyeing industries in Egypt. The stock solution all set by mixing chromium chloride hex hydrate ($CrCl_3.6H_2O$) and cadmium sulfate octahydrate ($3CdSO_4.8H_2O$) in distilled water. Figure 1 illustrates the set-up of the experiment, which consists of a cell and electrical circuit. The cell includes 12 L glass container that has dimensions (20 x 20 x 30 cm), plates with 10.50 cm in width, 30.00 cm in height, and approximately 1.00 mm thickness were made from two different materials iron and aluminium. The electrical circuit consists of a 30-Volt D.C power supply with a voltage regulator with a digital screen to show the voltage and a multi-range ammeter connected in series with the cell. The surfaces of used electrodes were frequently cleaned with sandpaper and submerged in diluted hydrochloric acid solution before each experiment to avoid the passivation of these electrodes and remove any impurities or adherent oxides on the surface of the electrodes.

The concentrations of heavy metals ions were measured by using iCE 3000 Series Atomic Absorption Spectrometer. In addition, the current and voltage were measured by the ammeter and DC power supply digital screen. Also the solution was heated using electrical heater and thermostat to control temperature and the pH was measured by using pH meter.

Many parameters were investigated for a better understanding of the EC techniques to get the most proper configuration that best removed heavy metal ions (Chromium and Cadmium). These parameters included electrodes material, electrode configuration, initial pH, current density, initial concentration of chromium and cadmium ions, and initial temperature. Moreover, a comparison between chemical coagulation and EC for removal of high concentration of Chromium and cadmium ions was presented.



1-Glass reactor 2- A 30-V digital DC power supply
3- Ammeter 4-Cathode electrode
5- Anode electrode 6- Connections

Figure 1: Schematic diagram of the electrocoagulation reactor

3 Results and Discussion

3.1 Effect of electrode material and configuration

Electrodes configurations Fe/Fe – Fe/Al – Al/Al – Al/Fe (anode/cathode) were tested at the same experimental conditions of initial metal concentrations (560 mg/L for chromium and 800 mg/L for cadmium), pH (5.0) and applied current density (7.0 mA/cm^2). Figure 2 demonstrates chromium and cadmium removal efficiencies for different anodes cathodes material and configuration.

Regarding anode material, the data indicated the priority of the iron for better removal efficiency within the two different configurations of iron or aluminium as a cathode. For Chromium, iron anode achieved nearly 68 % and 47 % with aluminium and iron as a cathode, respectively. Conversely, for Cadmium, iron anode reached almost 64 % and 36 % with iron and aluminium as a cathode, respectively. In the case of Chromium, the results exposed that all configurations were close to each other till 40 min. Then the configuration of Fe-Al achieved the best removal ratio. But for Cadmium, the configuration of Fe – Fe showed better removal consistently. The privilege of iron as an anode possibly explained through Faraday’s law, as shown in Equation (6) (24).

$$W = \frac{i \times t \times M}{n \times F} \qquad (6)$$

where W is Concentration of metal ions dissolved from anode material (g (Fe/Al) /cm^2), I is current density (A/cm^2), t is contact time (s), M is molecular weight (Fe or Al) (gm/mol), n is number of electrons transferred (3 for Al and (2 or 3 for Fe)), and F is faraday constant (96485.4 C/mol). As the same current is applied, the amount of the produced coagulants from the anode in the case of Fe anode is more than in the case of Al anode (Fe: Al = 3:2 or 2:1 according to Fe valence).

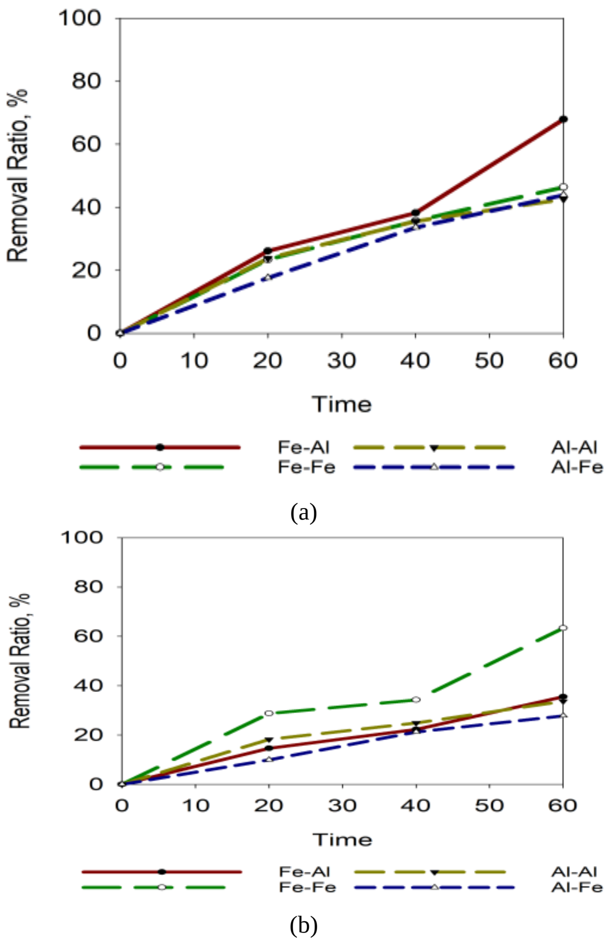


Figure 2: Effect of electrodes material and configuration on the removal of (a) Chromium (b) Cadmium

In the case of using Fe as an anode, Fe^{3+} possibly not produced, but Fe^{2+} formed at the iron anode. As most of the generated ions, Fe^{2+} will be oxidized to Fe^{3+} due to the dissolved oxygen in the EC process; as a result, the surface hydroxyl groups of Fe flocs were denser and more concentrated than the Al. Hence, the complexation reaction with the surface hydroxyl groups could be the reason for the removal of Cr and Cd, iron as anode achieved better removal ratio than Al as the anode (25). Studies revealed that the EC process with Fe as the anode has better removal efficiency than Al anode(16–19). The electro-generated Fe^{2+} ions reduced the Cr^{6+} to $Cr^{3+,}$ which could be removed by complexation and precipitation reaction. The existence of another removal mechanism rather than adsorption, as chemical reduction of Cr^{6+} to Cr^{3+} possibly is considered the reason behind the better removal efficiency of Cr than Cd. In case of Al anode, There is a competition between Cr and Al to reach the component of $Cr(OH)_3$ or $Al(OH)_3$ during consuming OH- and also using Al anode decreased the reduction of Cr^{+6} to Cr^{3+} that could be removed by complexation and precipitation reaction and that reduced the removal ratios (15). Using the same anode, the produced coagulant ions, hydroxides, and flocs could be substantially the same; hence, the removal efficiency would be constant.

Changing the material of cathode resulted in the change of removal efficiency; accordingly, the cathode material was investigated. For Chromium, Figure 2 reveals the effect of the change of cathode material. For iron as an anode, aluminium as a cathode achieved better performance for chromium removal. Conversely, the use of aluminium instead of iron as cathode decreased the removal ratio of Cadmium, which showed that Cadmium preferred the same material for anode and cathode, and that also was proved as Fe – Al configuration achieved lower removal efficiency than Fe – Fe configuration. In this case, aluminium electrode limitedly removed Cadmium, whether it served as the anode or the cathode (26). On the other hand, aluminium as a cathode with iron anode achieved higher removal efficiency for Cr, and this agreed with the results of another study which found that Fe – Al achieved better removal efficiency than other configurations (27). The results revealed the advantage of aluminium as a cathode. The direct electrochemical reduction of Cr^{6+} to Cr^{3+} at the cathode put in an additional mechanism for Cr removal with adsorption. Hence, that also could improve the removal efficiency of Chromium (28).

Another advantage of aluminium cathode depends on the nature of the solution, which means the value of the pH. The improvements in the production of Al^{3+} ions from the cathode at alkaline pH could raise the removal efficiency. Also, the existence of Al^{3+} ions in the solution with Fe^{3+} was noted that the mixed coagulants between Fe^{3+} and Al^{3+} would be more efficient coagulants for pollutant adsorption (29). That means more hydroxide flocs in the Fe and Al solution. At nearly neutral pH (6.20), the solution with lower initial concentrations (Cr = 280 ppm/Cd = 400 ppm), and aluminium cathode achieved better removal results of Chromium and Cadmium. Cr reached 98% and 90% removal ratio in the case of aluminium and iron cathode, respectively. Cadmium removal efficiencies reached 72% and 18% with aluminium and iron cathode, respectively. Furthermore, it was proved that hydrogen formation was higher in the case of aluminium cathode than in the case of steel cathode, and hydrogen generation boosted flotation, which increases the removal process of contaminants (30). Thus, the following experiments were conducted with Fe/Al electrodes.

3.2 Effect of initial pH

The effect of pH was examined toward understanding its effect on the removal efficiency of Chromium and Cadmium. The experiments were conducted with constant parameters, such as electrodes (Fe/Al), the applied current (0.8 A), initial concentration of metals (280 mg/L for Chromium and 400 mg/L for Cadmium), and 1.0 hr of contact time. The initial pH values tested were 1.90, 5.80, and 8.40. The initial pH of the solution was adjusted by using hydrochloric acid and sodium hydroxide. Figure 3 presents the effect of pH on the removal of chromium and cadmium ions. Low pH witnessed low removal efficiency. The more the pH value was increased, the more the removal efficiency increased. The removal efficiencies of Chromium amounted to 24%, 93%, and 95%, while their values in the case of Cadmium were 29%, 95%, and 100% at pH values of 1.90, 5.80, and 8.40, respectively. Moreover, the results showed that Chromium had the priority to be removed with the increase of pH. It was shown that the removal mechanism could be divided into two stages (27). At the first stage, the reduction reaction occurs by Fe^{2+} ions for Cr^{6+} conversion to Cr^{3+}, then Cr^{3+} ions combine with OH^- ions generated at the cathode and finally $Cr(OH)_3$ precipitates. There may be a competition with Fe ions to get OH- ions in that case. At the second stage, a complexation reaction occurs between insoluble Fe hydroxides and Cr^{6+} that named the specific adsorption of Fe hydroxides. The first mechanism is activated with the acidic medium and the second with the neutral medium. The first mechanism is not enough alone to achieve a higher removal ratio, and the second mechanism makes a better removal rate for Chromium because of the insoluble Fe hydroxides that prefer neutral conditions (27). Previously mentioned, with the alkaline medium, if the Al is used as a cathode, it helps Cr^{6+} ions reduced to Cr^{3+} ions that could be easily converted to $Cr(OH)_3$ and precipitate. So, the alkaline medium is better for Cr removal and Al as a cathode (28).

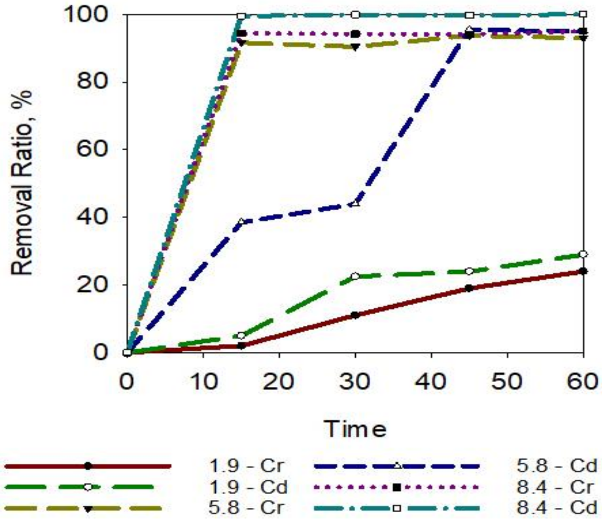


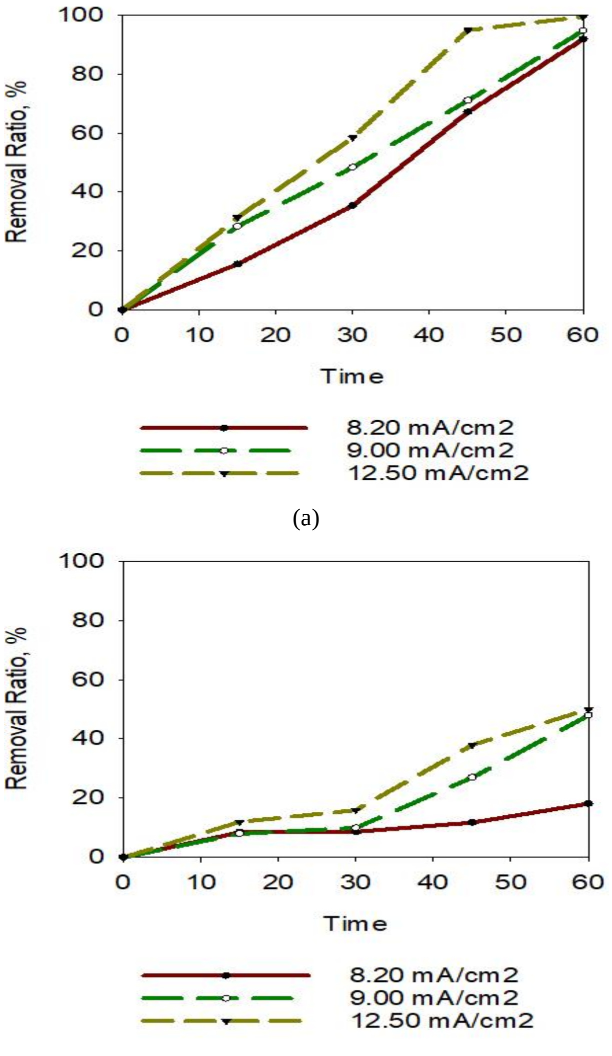
Figure 3: Effect of initial pH on Chromium and Cadmium removal ratio

The removal mechanism of Cadmium depends on the adsorption of Fe hydroxides that have a strong affinity to pollutants due to its large surface area. Higher pH enhances this mechanism and the generation of metal hydroxides; hence, the removal efficiency of Cadmium is maximized. Observed in our study, when trying to perform a trial with an initial pH of more than 9.0, a problem arises. The pH of more than 9.0 should be avoided, especially because of the generation of $Cd(OH)_{2(s)}$ Ksp = 5.27 x 10-15 at (25 C) due to the rapid consumption of OH- ions by Fe and Cd ions during the process of hydrolysis-polymerization-gelation precipitation at alkaline medium. So, the neutral condition preferred for cadmium removal (31). All of the above-explained proved that nearly neutral and mild alkaline conditions are the best for Cr removal (27,32,33) and Cd removal (26,31,34,35).

3.3 Effect of current density

In investigating the effect of current density on the removal of Chromium and Cadmium, the electrodes were Fe-Al, 4 cm spacing, and 60-minute contact time. The used current densities were 8.20, 9.0, and 12.5 mA/cm^2. Figure 4 revealed the more the current density was, the more removal efficiency rose. The increase in the current density decreased the contact time needed to achieve a definite removal ratio as the generation of coagulant hydroxides increased, and this increased the heavy metals ions removal. Higher current density enhances the hydrogen evolution at the cathode, and this boosts the sludge flotation and achieves a rapid removal process (36).s

After an hour with 280 and 400 mg/L initial concentrations for Cr and Cd, 5.80 initial pH, Fe/Al electrodes and 3.50 cm distance between electrodes, the removal efficiency of Cr was 99.4%, 94.8%, and 91.3% and for Cd was 50%, 49% and 18% for current densities 12.5, 9.0, 8.2 mA/cm^2, respectively, with best removal ratios in case of the higher current densities. Other studies achieved removal ratio for Cr and Pb equal to 68.7% and 73.1% via 55.3 and 4.9 mg/L initial concentration, respectively, in 90 min, 3.5 initial pH, iron electrodes, and 2.50 cm distance between electrodes (37).



(a)

(b)

Figure 4: Effect of current density on (a) Chromium and (b) Cadmium removal ratios

Another study investigated the effect of current density on the removal efficiency of Cd, Zn, and Mn. The study showed that the best removal efficiency for Cd was 98.58% with 10 mA/cm^2 of current density, Fe anode, and 15 mg/L initial concentration (26). Although current density improves the removal efficiency, there are electrical energy consumption costs and the metal losses of electrodes, as shown in Equation (6). Equation (7) illustrates how current density affects energy consumption and metal losses (38).

$$EEC = \frac{I \times U \times t}{V} \tag{7}$$

where EEC is electrical energy consumption (kWh/m^3), U is the voltage applied (v), I represents the applied current (A), t is the contact time (h), and V is the volume of the treated effluent (L). Table 1 shows the relation between the ions dissolved in the anode, energy consumption, removal efficiencies and the current densities used in our study.

Table 1: Effect of current density on Anode ions dissolved and Electrical Energy Consumption

Current Density (mA/cm^2)	8.20	9.00	12.50
Anode ions dissolved (g/cm^2) x 10^{-3}	8.57	9.40	13.0
Anode ions dissolved (Kg/m^3)	0.417	0.417	0.548
Electrical Energy Consumption (KWh/m^3)	6.00	8.16	12.00
Removal Ratio % (Cr/Cd)	91.3/18	94.8/49	99.4/50

In other studies, the optimum results of the removal of Cd, Zn, and Mn took place at 8.00 mA/cm^2 current density, 2.73 kWh/m^3 corresponding energy consumption, 0.695 Kg/m^3 electrode consumption, and about 98% removal efficiency of Cd was achieved (26).

3.4 Effect of initial concentration

The variation in the initial concentration of Cr and Cd ions was studied to investigate its effect on the removal efficiency. For Chromium, the tested initial concentrations were (560, 280, and 140 mg/L), whereas, for Cadmium, they were (800, 400, and 200 mg/L). During the first stage, the initial concentrations of both metals were changed together. At the second stage, the initial concentration of one metal was kept constant while the other concentration was adjusted to double. These tests performed at the same conditions: electrodes, the distance between electrodes, current density, and contact time.

Figure 5 illustrates the higher initial concentration was, the higher the amount of residual of metal under the same conditions was. Consequently, the removal efficiency decreased due to the shortage of generated flocs for ions adsorption. Faraday's law Equation (6) could get to the bottom of what happened. According to Faraday's law, when the current density is still constant; the amount of coagulants at the anode will stay constant. Therefore, the amount of coagulants covers specific initial concentrations of the pollutants' ions needed to be removed. Suppose the initial concentration is higher than this particular concentration. In that case, the anode's ions will not be sufficient to remove all ions of the heavy metal needed to be removed and will cause rapid consumption (39).

The current results agreed with the previous studies showing the effect of the initial concentration of hexagonal Chromium (36) and Cadmium (35) on their removal ratio. Also, when doubling the initial concentration of one metal and the initial concentration of the second metal was remained constant, the results displayed the priority of removing Chromium in all cases. The removal percentages of Chromium and Cadmium were 98% and 72%, respectively, after 60 min in the control reactor. When only the initial concentration of Chromium was doubled, the removal percentage of Chromium and Cadmium decreased to 83% and 54%, respectively. While doubling only the initial concentration of Cadmium, the percent of Chromium was a bit less (96%) whereas the percent for Cadmium dropped to 47%. Figure 5 shows that the removal process of Cadmium was approximately the same in the two cases with different initial concentration until 50 min, after that the removal efficiency increased clearly in case of 400 mg/L but still with the same rate in case of 800 mg/L.

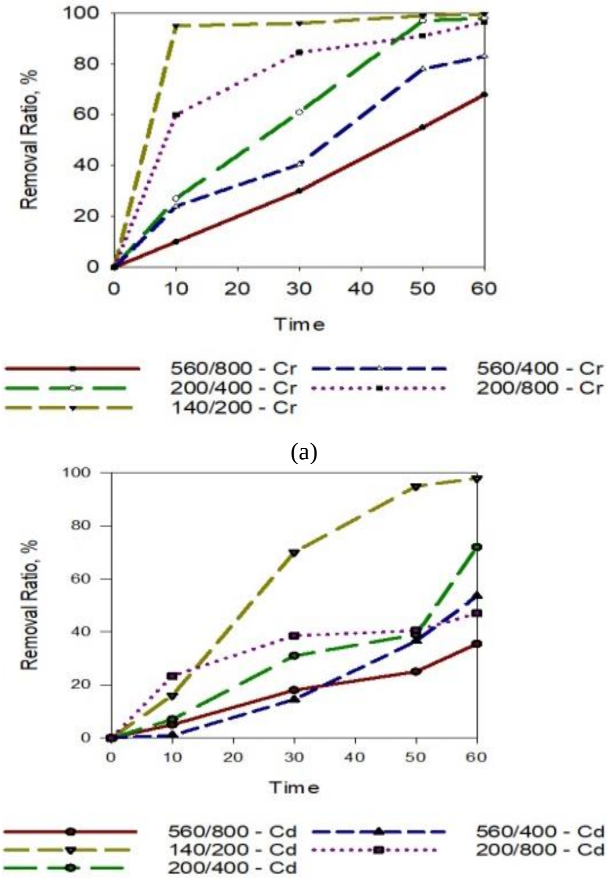


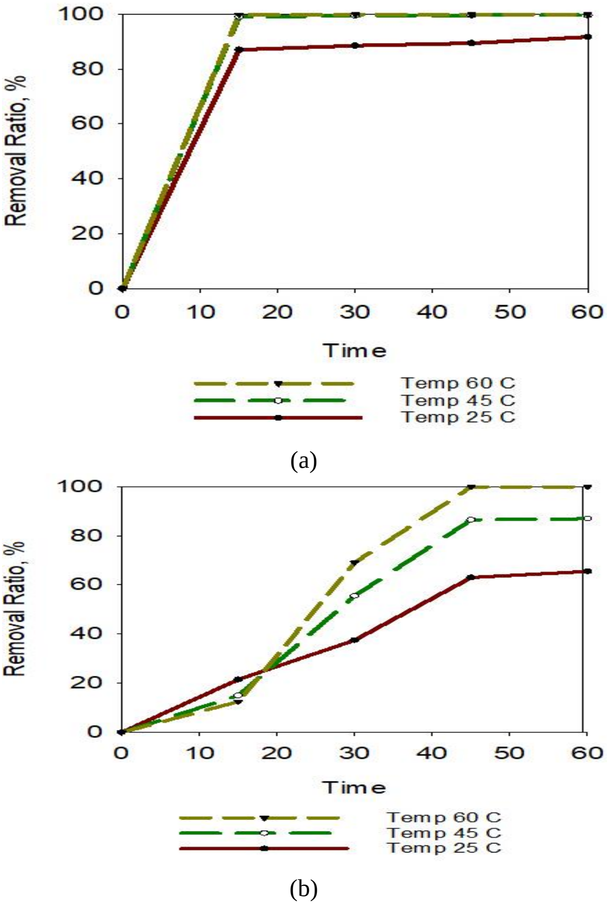
Figure 5: Removal Ratio for different initial concentration (a) Chromium (b) cadmium

Chromium removal mechanism could clarify the apparent increase in cadmium removal after 50 min while the removal rate of the Chromium became approximately constant, and this proved that Chromium had the priority to be removed first. The higher the value of (Ksp) is, the weaker the precipitation process becomes, and Cadmium has a higher value of Ksp, so the precipitation process of cadmium hydroxide was weaker than that of chromium hydroxide (Ksp equal to $6.30*10^{-31}$ and 2.50×10^{-14} for Cr and Cd, respectively). The solubility of the chromium hydroxide is less than the solubility of cadmium hydroxide, so the Chromium was persistently in progress to precipitate; hence the removal process of the Chromium was better than Cadmium. The value of the solubility product (Ksp) resulted in the priority of Chromium removal. What happened here between Cr and Cd ions was the same between Zn and Cd ions at previous investigation (26). The increase of initial concentration of Zn ions adversely affects the removal of Cd ions due to the lateness of the generation of Cd hydroxides than Zn hydroxides generation. This unfavourable relation delayed the adsorption, flocculation, and co-precipitation of Cd hydroxides; hence the values of the solubility product (Ksp) explained that conclusion.

3.5 Effect of initial temperature

As many industries like tannery industries and metal forming discharge their wastewater at high temperatures, test runs with an initial temperature of 25, 45, and 60°C were tested while fixing other parameters to the default values. The solution was heated using an electrical heater and thermostat to control the temperature. Figure 6 shows that as soon as the initial temperature increased, the removal efficiency increased. Hence the optimum removal efficiency could be achieved during less contact time, which reduced the electrical energy consumption. On the other hand, the results showed that the removal efficiencies were close at high temperatures, and that may mean that the effect of temperature was not the same at all degrees, or some metals removal efficiency did not depend on high initial temperature.

The influence of the high initial temperature appeared at the anode and the cathode. At the anode, it promoted the dissolution of the anode, improved the mobility of particles, and the collisions increased. Hence, the generation of hydroxides needed for the adsorption process was accelerated, and higher removal ratios achieved. The rate of hydrogen evolution at the cathode improved, and this boosted the flotation process, and also higher removal ratios achieved. Moreover, achieving higher removal ratios faster means less time, less energy consumption, and more cost-effective (18,21–23).



(a)

(b)

Figure 6: Effect of initial temperature on removal of (a) Chromium (b) Cadmium

For Cadmium at temperature 45^{o}C and 60^{o}C, the apparent increase happened after 15 min due to the removal mechanism of Chromium. As mentioned earlier, the Chromium had priority to be removed at 25^{o}C, and the Chromium did not reach the best removal ratio, so the rate of Cadmium removal still constant. Still, at temperatures 45 and 60^{o}C, the removal ratio of Chromium was almost constant after 15 min. Therefore the rate of cadmium removal increased sharply after the constancy of the removal rate of Chromium. The effect of the initial temperature has also investigated the removal of Cadmium, and it was proved that a higher initial temperature was sufficient for achieving higher removal ratio for Cadmium (40).

3.6 Electrocoagulation versus conventional coagulation

Coagulation and flocculation, then sedimentation and filtration, are employed for removing heavy metal from wastewaters. Coagulation is the destabilization of colloids by neutralizing the forces that keep them apart. Many coagulants are widely used in conventional treatment such as aluminium, ferrous sulphate and ferric chloride (41). A new study performed to remove hex chromium from municipal wastewater while using Fe salts (42). The results showed that ferrous chloride was better in the removal of hex chromium, as it achieved Chromium to be removed from 40 µg/L to 8 µg/L with a dose of 10 mg-Fe/L. In this study, the tests were performed to compare between iron (II) sulfate heptahydrate solid, ferric sulphate solution, ferrous chloride solution, ferric chloride solution, and poly-aluminium chloride solution (42).

Another study investigated the priority of electrocoagulation and chemical coagulation to remove Chromium from drinking water contaminated by a relatively high amount of Chromium (19 mg/L). The results showed elevated removal ratio in both methods, with values reached 99%. For chemical coagulation, the used coagulant was ferrous sulphate ($FeSO_4 \cdot 7H_2O$) (43). In the present study, the effect of coagulation and flocculation then sedimentation, was investigated on the removal of Chromium and Cadmium. The used coagulants were alum and ferric chloride. The experiments performed in four stages; dosage feeding, rapid mixing (120 rpm in 1 min), gentle mixing (30 rpm in 20 min), and sedimentation in 30 min. The doses of the coagulants used in the tests were (30, 40, 50, and 125 mg/L), and the initial concentration of Chromium and Cadmium were 240 and 620 mg/L, respectively.

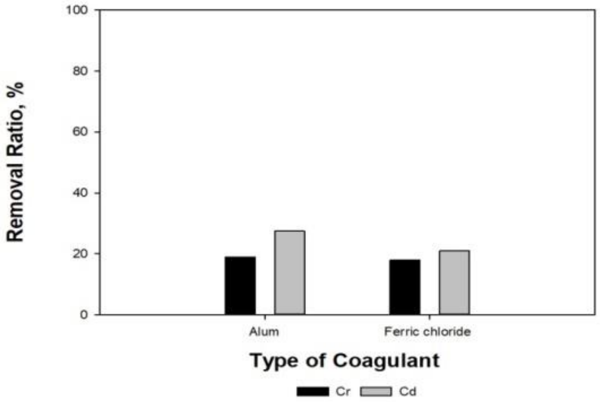


Figure 7: Removal ratio of (a) Chromium (b) Cadmium in case of conventional coagulation using alum and ferric chloride as a coagulant

As shown in Figure 7, the results showed the insufficiency of chemical coagulation for the removal of chromium and cadmium ions as the removal efficiency reached 19% and 27.5% for Chromium and Cadmium, respectively, in case of 125 mg/L alum and 18% and 21 % for Chromium and Cadmium, respectively, in case of 50 mg/L ferric chloride. The previous studies that investigated the effectiveness of chemical coagulation dealing with small concentrations achieved high removal efficiency. Still, the concentration of Chromium and Cadmium was high despite using high doses for alum and ferric chloride compared with the doses used in previous studies. An earlier study highlighted the need for high doses of coagulant for a high concentration of pollutant ions. Which, in turn, this would increase the dissolved salts in effluent treated water and produce a large amount of sludge that would be a hazardous waste during disposal. Also, electrocoagulation presented as a valuable alternative for pollutants ions removal (43).

4 Conclusions

In this line of present work, EC dealt successfully with the existence of Chromium and Cadmium together and their high initial concentration that considered a dilemma for many treatment methods. Based on the test results and limited to the study conditions, the following points can be drawn.

1. The configuration of iron as anode and aluminium as a cathode achieved better removal ratios than other configurations.
2. High current density achieved high removal efficiency; however, it consumes higher energy.
3. Neutral condition is preferred for Chromium and cadmium removal.
4. The high temperature of the electrolyte as an attempt to simulate the cases of high initial temperature of discharged wastewater showed better removal efficiency for Cr and Cd.
5. Comparing EC with conventional coagulation in removal chromium and cadmium ions from wastewater, EC technique is recommended than chemical coagulation as the later needs high dose and may fail to hit the required removal ratio.

Finally, it can be demonstrated that the electrocoagulation method is an efficient, safe, reliable, and cost-effective method for the removal of heavy metals. For possible further work, it is recommended to investigate the efficiency of EC to treat real industrial wastewater with high concentrations of heavy metals and organic load from different sources in continuous mode and compare the results with other technologies.

Ethical issue

Authors are aware of, and comply with, best practice in publication ethics specifically with regard to authorship (avoidance of guest authorship), dual submission, and manipulation of figures, competing interests and compliance with policies on research ethics. Authors adhere to publication requirements that submitted work is original and has not been published elsewhere in any language.

Competing interests

The authors declare that there is no conflict of interest that would prejudice the impartiality of this scientific work.

Authors' contribution

All authors of this study have a complete contribution for data collection, data analyses and manuscript writing.

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