

Decolorization of basic dye solutions by electrocoagulation: An investigation of the effect of operational parameters

N. Daneshvar^{a,*}, A. Oladegaragoze^b, N. Djafarzadeh^a

^a Water and Wastewater Treatment Research Laboratory, Department of Applied Chemistry, Faculty of Chemistry, University of Tabriz, Tabriz, Iran

^b Electrochemistry and Corrosion Laboratory, Department of Applied Chemistry, Faculty of Chemistry, University of Tabriz, Tabriz, Iran

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Abstract

Electrocoagulation (EC) is one of the most effective techniques to remove color and organic pollutants from wastewater, which reduces the sludge generation. In this paper, electrocoagulation has been used for the removal of color from solutions containing C. I. Basic Red 46 (BR46) and C. I. Basic Blue 3 (BB3). These dyes are used in the wool and blanket factories for fiber dyeing. The effect of operational parameters such as current density, initial pH of the solution, time of electrolysis, initial dye concentration and solution conductivity were studied in an attempt to reach higher removal efficiency. The findings in this study shows that an increase in the current density up to 60–80 A m⁻² enhanced the color removal efficiency, the electrolysis time was 5 min and the range of pH was determined between 5.5 and 8.5 for two mentioned dye solutions. It was found that for, the initial concentration of dye in solutions should not be higher than 80 mg l⁻¹ in order to achieve a high color removal percentage. The optimum conductivity was found to be 8 mS cm⁻¹, which was adjusted using proper amount of NaCl with the dye concentration of 50 mg l⁻¹. Electrical energy consumption in the above conditions for the decolorization of the dye solutions containing BR46 and BB3 were 4.70 kWh (kg_{dye removed})⁻¹ and 7.57 kWh (kg_{dye removed})⁻¹, respectively. Also, during the EC process under the optimized conditions, the COD decreased by more than 75% and 99% in dye solutions containing BB3 and BR46, respectively.

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Keywords: Electrocoagulation; Basic dye; Decolorization; COD reduction; Dyeing wastewater

1. Introduction

Dyeing and finishing are the two important processes generally applied in most of the textile manufacturing industries. These two processes generate considerable amount of wastewater, which may contain strong color, suspended particles, high pH and high chemical oxygen demand (COD) concentration [1]. It is estimated that 1–15% of the dye is lost during dyeing and finishing processes and is released into wastewaters. The textile industry utilizes about 10,000 dyes and pigments [2]. The disposal of these colored wastewaters poses a major problem for the industry as well as a threat to the environment. As a result, a high amount of these dyes can exist in effluents of dyeing processes. In textile industries, because of the low

efficiency (60–90%) of dye fixing on textile fibers, substantial amounts of unfixed dyes are released in wastewaters. Most kinds of synthetic dyes are toxic substances to human and aquatic life [3]. There are many processes to remove dyes from colored effluents such as adsorption, precipitation, chemical degradation, photodegradation, biodegradation, chemical coagulation and electrocoagulation [4,5]. Adsorption and precipitation processes are very time-consuming and costly with low efficiency. Chemical degradation by oxidative agents such as chlorine is the most important and effective methods, but it produces some very toxic products such as organochlorine compounds [6]. Photooxidation by UV/H₂O₂ or UV/TiO₂ needs additional chemicals, and therefore causes a secondary pollution. Although biodegradation process is cheaper than other methods, it is less effective because of the toxicity of dyes that has an inhibiting effect on the bacterial development [7]. Hence, electrocoagulation (EC) as an electrochemical method was developed to overcome the drawbacks of conventional water and wastewater treatment technologies. EC process provides a simple, reliable and cost-effective method for the treatment of wastewater without any need for additional

* Corresponding author. Tel.: +98 411 3393146; fax: +98 411 3393038.

E-mail addresses: nezam.daneshvar@yahoo.com (N. Daneshvar), aliolad@yahoo.com (A. Oladegaragoze), n.jafarzadeh@gmail.com (N. Djafarzadeh).

Nomenclature

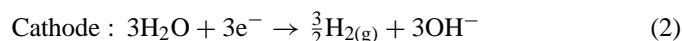
A	electrolysis surface of the electrode (m^2)
C_0	initial concentration of dye (mg l^{-1})
CR	color removal efficiency (%)
DC	decolorization capacity ($\text{kg}_{\text{dye removed}} (\text{kg}_{\text{total dissolved Fe}})^{-1}$)
E	electrical energy consumption ($\text{kWh} (\text{kg}_{\text{dye removed}})^{-1}$)
F	Faraday constant (charge on 1 mol of electrons) (=96487) (C mol^{-1})
i	current density (A m^{-2})
I	current in EC process (A)
M	molecular weight of the iron (=56) (g mol^{-1})
n	number of electron moles in dissolution reaction (=2 for iron)
OC	operating cost (US\$ ($\text{kg}_{\text{dye removed}})^{-1}$)
Secc	specific electrical energy consumption ($\text{kWh} (\text{kg}_{\text{Fe}})^{-1}$)
t_{EC}	time of electrolysis (s)
U	cell voltage (V)

Greek letters

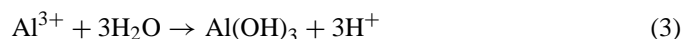
ΔM_{theo}	theoretical amount of iron electrode dissolution (mg)
ΔM_{exp}	experimental weight lose of iron electrode (mg)
γ	conductivity (mS cm^{-1})
φ	current efficiency (%)

chemicals, and thus the secondary pollution. It also reduces the amount of sludge, which needs to be disposed. EC technique uses a direct current source between metal electrodes immersed in polluted water [8]. The electrical current causes the dissolution of metal plates including iron or aluminum into wastewater. The metal ions, at an appropriate pH, can form wide ranges of coagulated species and metal hydroxides that destabilize and aggregate the suspended particles or precipitate and adsorb dissolved contaminants [9].

The most widely used electrode materials in EC process are aluminum and iron. In the case of aluminum, main reactions are as:

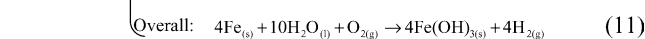
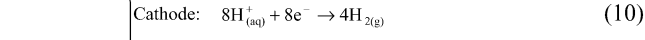
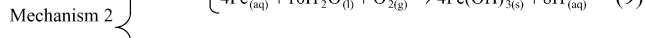
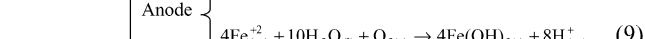
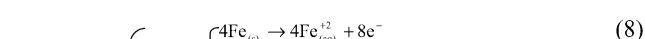
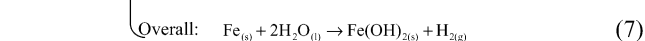
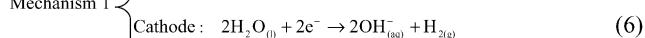
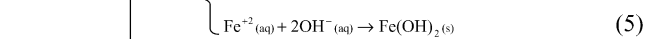
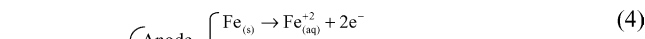


Al^{3+} and OH^- ions generated by electrode reactions (1) and (2) react to form various monomeric species, which finally transform into $\text{Al}(\text{OH})_{3(s)}$ according to complex precipitation kinetics.

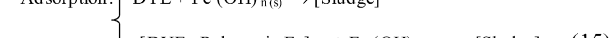
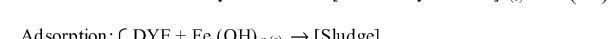
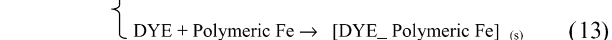
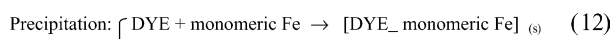


Freshly formed amorphous $\text{Al}(\text{OH})_{3(s)}$ "sweep flocs" have large surface areas, which are beneficial for a rapid adsorption of soluble organic compounds and trapping of colloidal particles. Finally, these flocs are removed easily from aqueous medium

by sedimentation or H_2 flotation [10–12]. When iron is used as anodes, upon oxidation in an electrolytic system, it produces iron hydroxide, $\text{Fe}(\text{OH})_n$ where $n = 2$ or 3. Two mechanisms for the production of the metal hydroxide have been proposed [13,14]:



The insoluble metal hydroxides of iron can remove dye molecules by surface complexation or electrostatic attraction. In surface complexation, it is assumed that the pollutant can act as a ligand to bind a hydrous iron moiety with precipitation and adsorption mechanisms [10–14]:

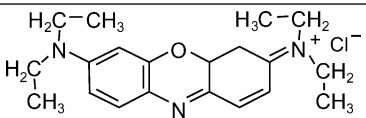
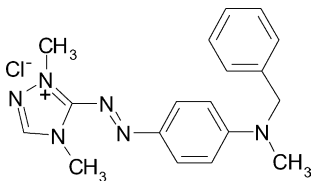


The electrocoagulation has successfully been used for the treatment of wastewaters including electroplating wastewater [15], laundry wastewater [16], latex particles [17] and textile wastewaters [3,4,10,11]. Meanwhile, EC process has been widely used to decolorize various structurally different dye-containing solutions such as disperse, reactive and acidic dyes [1,6,12–14]. In this study, the decolorization of two basic dye solutions (C. I. Basic Blue 3 and C. I. Basic Red 46) by electrocoagulation has been investigated. These dyes are soluble in water and belong to cationic basic dye group. These dyes are idoneous for acrylic fiber dyeing and are used in the wool and blanket factories, so their effluents have a great deal of these dyes. The prime objective behind this study was to apply electrocoagulation method to decolorize this type of wastewater for the first time. Moreover, the effects of operational parameters such as current density, initial pH, electrolysis time, dye concentration and solution conductivity on color removal efficiency have been investigated in this study.

2. Experimental**2.1. Materials and methods**

The commercial dyes used in this project were purchased from Bezema (Switzerland). The chemical structure and other characteristics of these dyes are shown in Table 1. Dye solutions were prepared by dissolving dyes in distilled water. The

Table 1
Characteristics of the two commercial dyes

Dye	Structural	λ_{\max} (nm)	Chemical class	M_w (g mol ⁻¹)
BB3		654	Monoxazine	359.9
BR46		531	Monoazo	357.5

batch experimental cell is shown in Fig. 1. The conductivity of solutions was raised up and adjusted in different values by the addition of NaCl (Fluka, Switzerland). The conductivity measurement was performed using a Philips conductimeter (PW 9509, UK). The pH of the solutions was measured by pH meter (Metrohm 654, Switzerland) and adjusted by adding NaOH or H₂SO₄ (Merck, Germany) solutions. Iron (ST 37-2) plates were used as anode and steel (grade 304) plates were used as cathode. Dimensions of electrodes were 50 mm × 50 mm × 3 mm so, total areas (*A*) of these were 5.6×10^{-3} m² and the distance between two electrodes in EC cell was 15 mm in all experiments. The electrodes were connected to a DC power supply (ADAK PS808, Iran) with galvanostatic operational options for controlling the current density. All the runs were performed at room temperature. In each run, 250 ml of the dye solution was decanted into the electrolytic cell. At the end of electrocoagulation, all samples were allowed to settle for 20 min in a 250 ml vessel before any analysis. Neither centrifuging nor filtration was performed. All experiments were repeated twice, and the experimental error was around 3%.

2.2. Chemical analysis

The dye concentrations were determined from their absorbance characteristics in the UV–vis range (200–800 nm) with the calibration method. A WPA lightwave (S 2000, UK)

spectrophotometer connected to a PC was used. For these measurements, the maximum adsorption (λ_{\max}) wavelength of dyes was determined by measuring their absorbance at various wavelengths (Table 1). The calculation of color removal efficiency after electrocoagulation treatment was performed using this formula:

$$CR(\%) = \frac{C_0 - C}{C_0} \times 100 \quad (16)$$

where C_0 and C are concentrations of dye before and after electrocoagulation in mg l⁻¹, respectively.

The chemical oxygen demand (COD) of dye solutions was measured according to the standard methods for examining water and wastewater (Ampoule method) [18].

3. Results and discussion

3.1. Effect of current density on the efficiency of color removal

In all electrochemical processes, current density is the most important parameter for controlling the reaction rate within the reactor. It is well known that the amount of current density determines the coagulant production rate, and adjusts the rate and size of the bubble production, and hence affects the growth of flocs [8,9]. To investigate the effect of current density on the efficiency

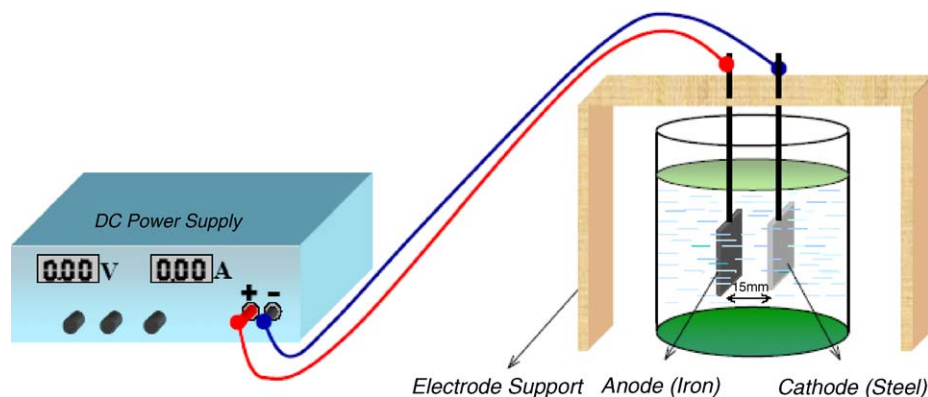


Fig. 1. An apparatus electrocoagulation cell.

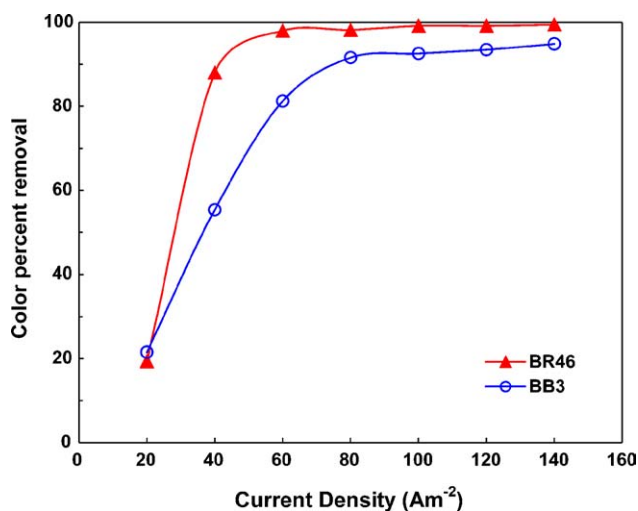


Fig. 2. Effect of current density on the color removal efficiency ($C_0 = 50 \text{ mg l}^{-1}$, $t_{\text{EC}} = 5 \text{ min}$, $\text{pH} = 5.8$ and $\gamma = 8 \text{ mS cm}^{-1}$).

of color removal, electrocoagulation process was carried out using various current densities. Fig. 2 shows the color removal percentage against current density applied to the electrodes in the EC process. Raising current density causes a corresponding increase in the oxidized iron production from electrodes. The optimum current density of 60 A m^{-2} was used for the color removal from dye solution containing BR46 and the optimum current density of 80 A m^{-2} was used for the color removal from dye solution containing BB3.

3.2. Effect of time of electrolysis on the efficiency of color removal

Reactive time also influences the treatment efficiency of the electrochemical process. Electrolysis time (t) determines the production rate of Fe^{2+} or Fe^{3+} ions from iron electrodes. Fig. 3 shows the relationship between the color removal efficiency

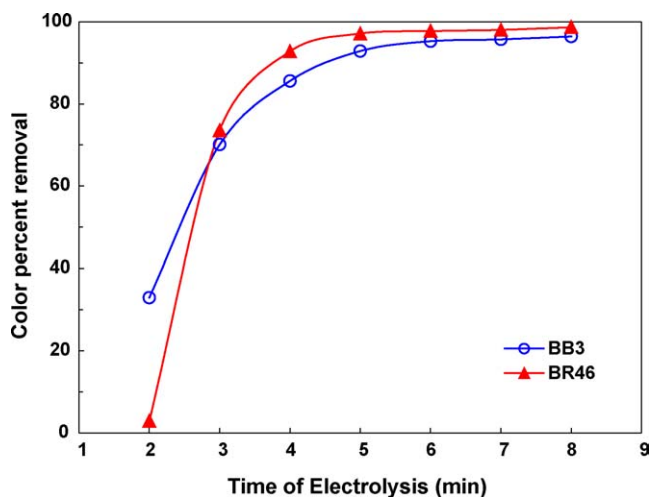


Fig. 3. Effect of electrolysis time on the color removal efficiency ($C_0 = 50 \text{ mg l}^{-1}$, $i = 60 \text{ A m}^{-2}$ for BR46 and $i = 80 \text{ A m}^{-2}$ for BB3, $\text{pH} = 5.8$ and $\gamma = 8 \text{ mS cm}^{-1}$).

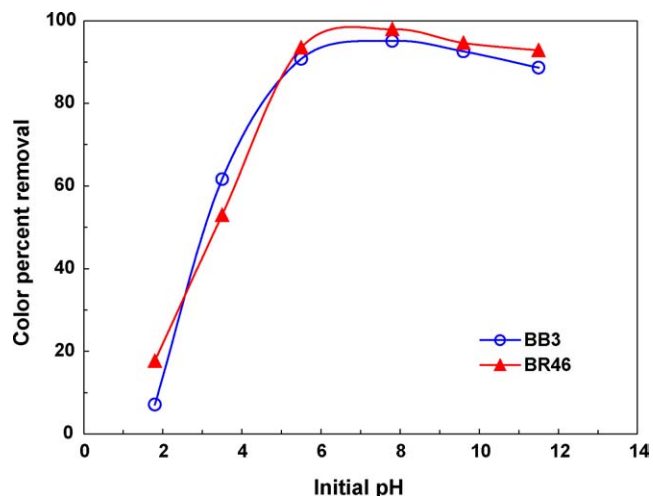


Fig. 4. Effect of initial pH on the color removal efficiency ($C_0 = 50 \text{ mg l}^{-1}$, $i = 60 \text{ A m}^{-2}$ for BR46 and $i = 80 \text{ A m}^{-2}$ for BB3, $t_{\text{EC}} = 5 \text{ min}$, $\text{pH} = 5.8$ and $\gamma = 8 \text{ mS cm}^{-1}$).

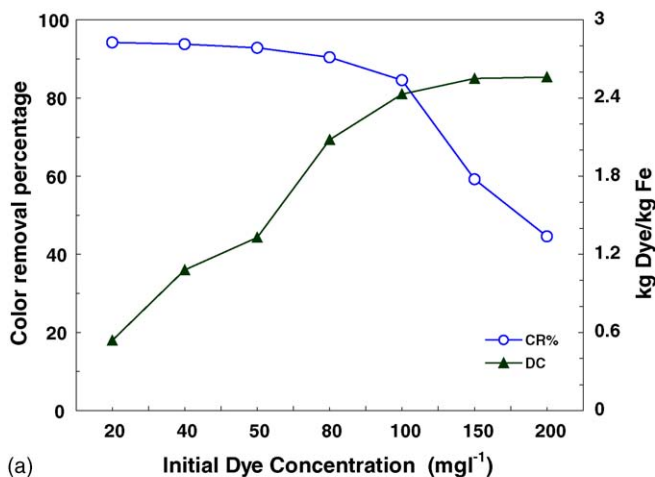
and the electrolysis time. The color removal efficiency depends directly on the concentration of hydroxyl and metal ions produced on the electrodes. Therefore, according to the results showed in Fig. 3, the optimum electrolysis time was 5 min for the color removal from both dye solutions.

3.3. Effect of initial pH on the efficiency of color removal

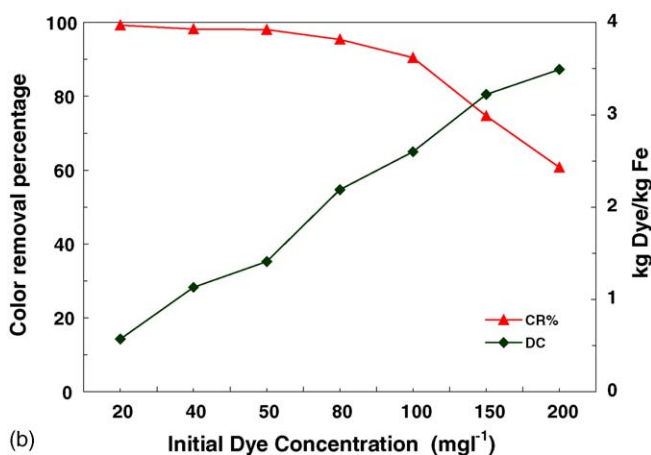
It has been established that the influent pH is an important parameter influencing the performance of the EC process [14]. To examine its effect, the dye solution was adjusted to the desired pH for each experiment by adding sodium hydroxide or sulfuric acid solution. The color removal percentages for dye solutions with various initial pH values were shown in Fig. 4. The results revealed that when pH of the dye solutions was between 5.5 and 8.5, there was maximum color removal efficiency. Because the initial pH value of these two dye solutions was around 5.8. Hence, there is no need for the addition of chemicals to change the initial pH values.

3.4. Effect of initial dye concentration on the efficiency of color removal and decolorization capacity

The dye solutions with different initial concentrations in the range of $20\text{--}200 \text{ mg l}^{-1}$ were treated by EC in optimized current density and time of electrolysis values. The initial dye concentration was plotted against related color removal percentage and decolorization capacity for both dye solutions (Fig. 5). According to the results, up to the concentration of 50 mg l^{-1} , the adsorption capacity of flocs was not exhausted and the rate of color removal was relatively constant. However, above this concentration, the adsorption capacity of flocs became exhausted, especially when it was more than 80 mg l^{-1} . However, the increase of initial dye concentration caused a steady increase in decolorization capacity. Kobya et al. [12] reported similar results for the decolorization of reactive dye solutions by EC process.



(a)

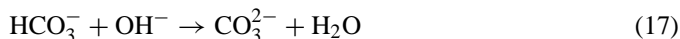


(b)

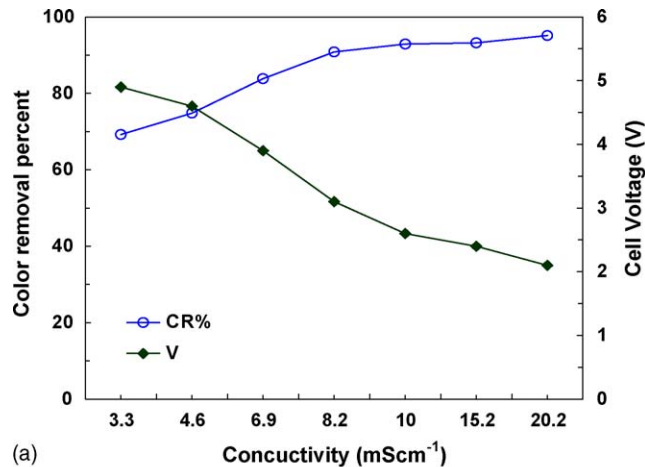
Fig. 5. Effect of initial concentration of dyes on the color removal efficiency and decolorization capacity (a) solution containing BB3 and (b) solution containing BR46 ($i = 60 \text{ A m}^{-2}$ for BR46 and $i = 80 \text{ A m}^{-2}$ for BB3, $t_{\text{EC}} = 5 \text{ min}$, $\text{pH} = 5.8$ and $\gamma = 8 \text{ mS cm}^{-1}$).

3.5. Effect of the conductivity on the efficiency of color removal

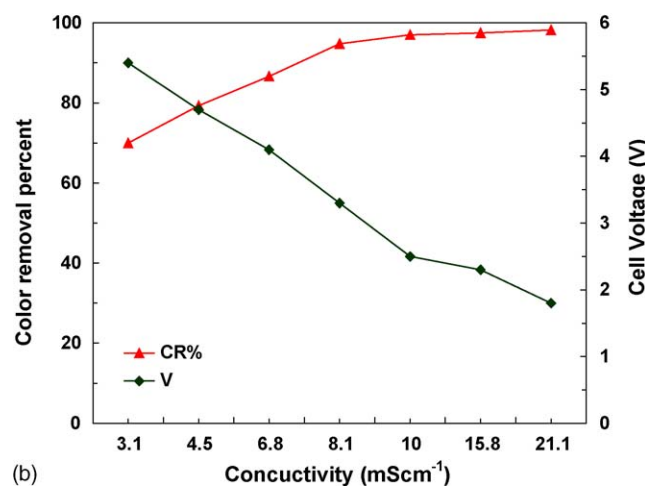
Table salt is usually employed to increase the conductivity of the water or wastewater to be treated. Solution conductivity affects the current efficiency, cell voltage and consumption of electrical energy in electrolytic cells. In addition, increasing solution conductivity using NaCl has other advantages, i.e. chloride ions could significantly reduce the adverse effects of other anions, such as HCO_3^- and SO_4^{2-} [9]. The existence of the carbonate ion would lead to the precipitation of Ca^{2+} ion that forms an insulating layer on the surface of the cathode (Eqs. (17) and (18)). These will increase the ohmic resistance of the electrochemical cell [16].



Meanwhile, if the anode potential is sufficiently high, other reactions may occur at the anode, such as direct oxidation of organic compounds or H_2O [16]. As a result, the conductivity of dye solutions was adjusted using NaCl in the range of



(a)



(b)

Fig. 6. Effect of solution conductivity on the color removal efficiency and cell voltage (a) solution containing BB3 and (b) solution containing BR46 ($C_0 = 50 \text{ mg l}^{-1}$, $i = 60 \text{ A m}^{-2}$ for BR46 and $i = 80 \text{ A m}^{-2}$ for BB3, $t_{\text{EC}} = 5 \text{ min}$ and $\text{pH} = 5.8$).

2–20 mS cm^{-1} and the EC process treated these dye solutions with different conductivities. Increasing solution conductivity resulted in the reduction of cell voltages that caused a decrease in electrical energy consumption. The percentage of color removal was measured as a function of dye solution conductivity. It was found that with the addition of more NaCl to the dye solutions, the color removal rate increased slightly. In other words, raising the conductivity of dye solutions has not a considerable effect on color removal efficiency. Cell voltage in this EC process was also measured and plotted against the conductivity of related dye solutions. These results have been shown for BB3 and BR46 in Fig. 6. According to the results, high color removal percentage with low cell voltages and low energy consumption can be obtained in dye solutions with a conductivity of around 8 mS cm^{-1} .

3.6. Energy consumption and operation cost

Electrical energy consumption and current efficiency are very important economical parameters in EC process like all other electrolytic processes. Electrical energy consumption was also

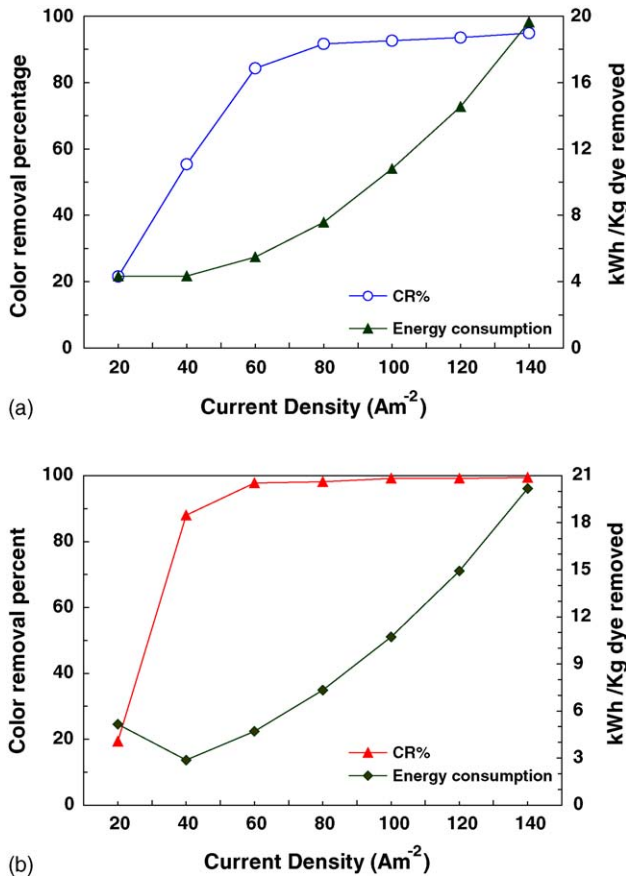


Fig. 7. Effect of current density on the color removal efficiency and energy consumption (a) solution containing BB3 and (b) solution containing BR46 ($C_0 = 50 \text{ mg l}^{-1}$, $t_{EC} = 5 \text{ min}$, $\text{pH } 5.8$ and $\gamma = 8 \text{ mS cm}^{-1}$).

calculated using the commonly used equation [17]:

$$E = UI t_{EC} \quad (19)$$

where E is the electrical energy in $\text{kWh}(\text{kg}_{\text{dye removed}})^{-1}$, U the cell voltage in volt (V), I the current in ampere (A) and t_{EC} is the time of EC process per second. The value of energy consumption as a function of treated solution volume was also calculated in different current densities for each dye solution. The results showed that an increase in the current density causes an increase in color removal efficiency (Fig. 7). It also increases energy consumption. So, to achieve an optimized current density, both color removal percent and energy consumption should be evaluated.

The current efficiency (φ) of EC process was calculated (Eq. (20)). This calculation was based on the comparison of experimental weight loss of iron electrodes (ΔM_{exp}) during EC

process with theoretical amount of iron dissolution (ΔM_{theo}) according to the Faraday’s law (Eq. (21)):

$$\varphi = \frac{\Delta M_{\text{exp}}}{\Delta M_{\text{theo}}} \times 100 \quad (20)$$

$$\Delta M_{\text{theo}} = \frac{M I t_{EC}}{n F} \quad (21)$$

where M is the molecular weight of the iron (g mol^{-1}), n the number of electron moles and F is the Faraday constant ($F = 96487 \text{ C mol}^{-1}$). As $\text{Fe}(\text{OH})_{2(\text{s})}$ is supposed to be the formed species, the number of electron moles in dissolution reaction is equal to 2. The specific electrical energy consumption (Seec) was calculated as a function of iron electrodes weight consumption during EC in $\text{kWh}(\text{kg}_{\text{Fe}})^{-1}$ using the Eq. (22) [3,8]:

$$\text{Seec} = \frac{n F U}{3.6 \times 10^3 M \varphi} \quad (22)$$

The operating cost includes material cost (mainly electrodes), utility cost (mainly electrical energy), as well as labor, maintenance and other fixed costs. In this preliminary economic study, energy and electrode material costs are taken into account as major cost items in the calculation of the operating cost as kWh per kg of dye removed [10];

$$\text{Operating cost} = a C_{\text{energy}} + b C_{\text{electrode}} \quad (23)$$

where C_{energy} and $C_{\text{electrode}}$ are consumption quantities per kg of dye removed, which are obtained experimentally. Given Iranian market in June 2005, unit prices a and b are as follows: a , electrical energy price $0.0065 \text{ US\$ kWh}^{-1}$; b , electrode material price $0.3 \text{ US\$ kg}^{-1}$.

These calculations were carried out after optimizing the operational parameters in EC process. The calculated values are shown in Table 2.

3.7. COD reduction and absorbance spectra of the dye solutions

The COD of dye solutions was measured according to the standard methods for the examination of water and wastewater [18]. Then, subsequent to decolorization in the optimized conditions ($C_0 = 50 \text{ mg l}^{-1}$, $i = 60 \text{ A m}^{-2}$ for BR46 and 80 A m^{-2} for BB3 and $t_{EC} = 5 \text{ min}$ for both dyes), the COD of the treated solutions was measured again. The COD was reduced more than 75% for BB3 solution and 99% for BR46 solution.

Fig. 8 illustrates the adsorption spectra for two dye solutions before and after EC process using optimized experimental

Table 2
Characteristics parameters calculated for EC process in optimized conditions^a

Dye	E ($\text{kWh}(\text{kg}_{\text{dye removed}})^{-1}$)	M_{exp} (mg)	M_{theo} (mg)	φ (%)	Seec ($\text{kWh}(\text{kg}_{\text{Fe}})^{-1}$)	OC ($\text{US\$}(\text{kg}_{\text{dye removed}})^{-1}$)
BB3	7.57	37	34.8	106.3	2.34	≈ 0.05
BR46	4.70	27	26.1	103.4	2.13	≈ 0.03

^a $C_0 = 50 \text{ mg l}^{-1}$, $i = 60 \text{ A m}^{-2}$ for BR46 and $i = 80 \text{ A m}^{-2}$ for BB3, $t_{EC} = 5 \text{ min}$, $\text{pH } 5.8$ and $\gamma = 8 \text{ mS cm}^{-1}$.

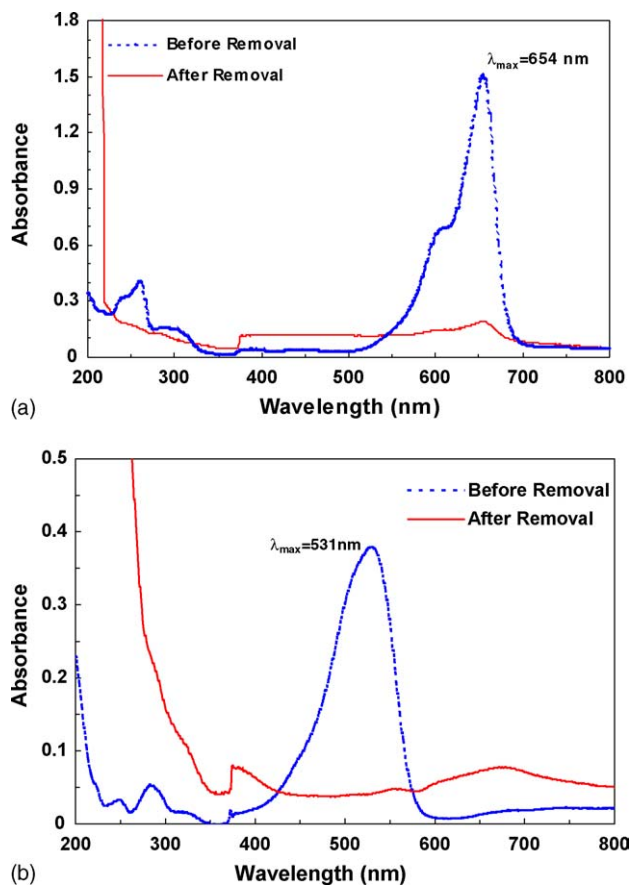


Fig. 8. Absorbance spectra of (a) dye solution containing BB3 before and after EC in the optimized conditions: $C_0 = 50 \text{ mg l}^{-1}$, $i = 80 \text{ A m}^{-2}$ and $t_{\text{EC}} = 5 \text{ min}$, pH 5.8 and $\gamma = 8 \text{ mS cm}^{-1}$ and (b) dye solution containing BR46 before and after EC in the optimized conditions: $C_0 = 50 \text{ mg l}^{-1}$, $i = 60 \text{ A m}^{-2}$, $t_{\text{EC}} = 5 \text{ min}$, pH 5.8 and $\gamma = 8 \text{ mS cm}^{-1}$.

values. It can be seen that EC process in the optimized conditions caused almost complete color removal from dye solutions.

4. Conclusion

Electrocoagulation was used to remove color from dye solutions containing C. I. Basic Red 46 and C. I. Basic Blue 3. The effect of various operational parameters on color removal efficiency was investigated and optimized. Results showed that applying optimum current densities of $60\text{--}80 \text{ A m}^{-2}$ could remove a high percentage of color from dye solutions. It was found that the proper electrolysis time for the removal of color from these dye solutions was 5 min for BB3 and BR46. The dye solutions decolorized more efficiently when the initial pH values of the solution ranged from 5.5 to 8.5. Color removal efficiency decreased when the initial dye concentrations were more than 80 mg l^{-1} . Conductivity of dye solutions should be more than 8 mS cm^{-1} to have acceptable energy consumption. That is obtained by adding proper amount of NaCl to the dye solutions. Also, with the above conditions, the COD was reduced from

dye solutions containing BR46 and BB3 more than 99 and 75%, respectively.

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References

- [1] Y.A. Mohammad, R. Saurabh, K. Prashanth, V. Madhavi, S. Tejas, A.G. Jewel, K. Mehmet, L. David, Treatment of orange II azo-dye by electrocoagulation (EC) technique in a continuous flow cell using sacrificial iron electrodes, *J. Hazard. Mater. B* 109 (2004) 165–171.
- [2] N. Daneshvar, M. Rabbani, N. Modirshahla, M.A. Behnajady, Photooxidative degradation of Acid Red 27 in a tubularcontinuous-flow photoreactor: influence of operational parameters and mineralization products, *J. Hazard. Mater. B* 118 (2005) 155–160.
- [3] M.N. Pons, A. Alinsafi, M. Khemis, J.P. Leclerc, A. Yaacoubi, A. Benhammou, A. Nejmeddine, Electro-coagulation of reactive textile dyes and textile wastewater, *Chem. Eng. Process.* 44 (2005) 461–470.
- [4] Y.M. Slokar, A.M.L. Marechal, Methods of decoloration of textile wastewaters, *Dyes Pigments* 37 (1998) 335–356.
- [5] N. Daneshvar, D. Salari, S. Aber, Chromium adsorption and Cr(VI) reduction to trivalent chromium in aqueous solutions by soya cake, *J. Hazard. Mater. B* 94 (2002) 49–61.
- [6] T. Kim, C. Park, E. Shin, S. Kim, Decolorization of disperse and reactive dyes by continuous electrocoagulation process, *Desalination* 150 (2002) 165–175.
- [7] N. Daneshvar, D. Salari, A.R. Khataee, Photocatalytic degradation of azo dye acid red 14 in water: investigation of the effect of operational parameters, *J. Photochem. Photobiol. A* 157 (2003) 111–116.
- [8] M.Y.A. Mollah, P. Morkovsky, J.A.G. Gomes, M. Kesmez, J. Parga, D.L. Cocke, Fundamentals, present and future perspectives of electrocoagulation, *J. Hazard. Mater. B* 114 (2004) 199–210.
- [9] G. Chen, Electrochemical technologies in wastewater treatment, *Sep. Purif. Technol.* 38 (2004) 11–41.
- [10] M. Koby, O.T. Can, M. Bayramoglu, M. Sozbir, Operating cost analysis of electrocoagulation of textile dye wastewater, *Sep. Purif. Technol.* 37 (2004) 117–125.
- [11] M. Koby, O.T. Can, M. Bayramoglu, Treatment of textile wastewaters by electrocoagulation using iron and aluminum electrodes, *J. Hazard. Mater. B* 100 (2003) 163–178.
- [12] M. Koby, O.T. Can, M. Bayramoglu, Decolorization of reactive dye solutions by electrocoagulation using aluminum electrodes, *Ind. Eng. Chem. Res.* 42 (2003) 3391–3396.
- [13] N. Daneshvar, H. Ashassi-Sorkhabi, A. Tizpar, Decolorization of orange II by electrocoagulation method, *Sep. Purif. Technol.* 31 (2003) 153–162.
- [14] N. Daneshvar, H. Ashassi-Sorkhabi, M.B. Kasiri, Decolorization of dye solution containing Acid Red 14 by electrocoagulation with a comparative investigation of different electrode connections, *J. Hazard. Mater. B* 112 (2004) 55–62.
- [15] N. Adhoum, L. Monser, N. Bellakhal, J. Belgaied, Treatment of electroplating wastewater containing Cu^{2+} , Zn^{2+} and Cr(VI) by electrocoagulation, *J. Hazard. Mater. B* 112 (2004) 207–213.
- [16] J. Ge, J. Qu, P. Lei, H. Liu, New bipolar electrocoagulation–electroflotation process for the treatment of laundry wastewater, *Sep. Purif. Technol.* 36 (2004) 33–39.
- [17] E. Vorobiev, O. Larue, C. Vu, B. Durand, Electrocoagulation and coagulation by iron of latex particles in aqueous suspensions, *Sep. Purif. Technol.* 31 (2003) 177–192.
- [18] L.S. Clesceri, A.E. Greenberg, R.R. Trussell (Eds.), *Standard Methods for the Examination of Water and Wastewater*, 17 ed., 1989, pp. 5–16.