

Short communication

Electrocoagulation of a real reactive dyebath effluent using aluminum and stainless steel electrodes

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Abstract

Treatment of real reactive dyebath effluent comprising of an exhausted reactive dyebath and its sequential rinses with electrocoagulation (EC) using aluminum (Al) and stainless steel (SS) electrodes was investigated. The experimental study focused on the effect of applied current density (22–87 mA/cm²; at an initial, optimum pH of 5.5) on decolorization and COD removal rates using Al and SS as electrode materials. Results have indicated that the treatment efficiency was enhanced appreciably by increasing the applied current density when Al electrodes were used for EC, whereas no clear correlation existed between current density and removal rates for EC with SS electrodes the treatment efficiency could only be improved when the applied current density was in the range of 33–65 mA/cm². It was established that EC with SS electrodes was superior in terms of decolorization kinetics (99–100% color removal after 10–15 min EC at all studied current densities), whereas EC with Al electrodes was more beneficial for COD removal in terms of electrical energy consumption (5 kWh/m³ wastewater for EC with Al electrodes instead of 9 kWh/m³ wastewater for EC with SS electrodes).

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Keywords: Reactive dyebath effluent; Electrocoagulation; Aluminum and stainless steel electrodes; Current density; Decolorization; COD abatement; Electrical energy requirements

1. Introduction

The treatment of wastewater generated by the textile preparation, dyeing and finishing industry remains a significant environmental pollution problem due to its huge quantity, variable nature and biologically-difficult-to-degrade chemical composition. In our previous studies, we have demonstrated that the biodegradability of several dye auxiliaries (surface active agents, dye carriers, tannins, etc.) and finishing agents (textile biocides) is very poor and some of these chemicals may even pose inhibitory effects on activated sludge treatment plants, although these chemicals were designated as non-toxic [1]. In particular, effluents from the textile dyeing process containing dye formulations as well as sequestering agents, surface active agents, inorganic salts (NaCl, Na₂CO₃, Na₂SO₄, etc.) not only cause aesthetic problems but also may interfere with light penetration/photosynthetic activities in receiving water

bodies if not treated properly [2,3]. The main characteristics of effluents from the reactive dyeing process deserve particular attention due to their relatively low dye fixation rates, high organic matter content (COD > 1000 mg/L) as well as inorganic (total dissolved solids (TDS) > 5000 mg/L) load, high alkalinity (>200 mgCaCO₃/L) and pH (>10) [4]. Physicochemical processes such as membrane filtration, coagulation-flocculation, ozonation at high pH, Fenton's reagent and sequential anaerobic + aerobic treatment, have been employed for the treatment of reactive dyebath effluent, however with limited success and/or at unaffordable costs [5]. For instance, ozonation cannot be employed to treat high-strength industrial wastewater requiring a specific ozone input >1 g/g of initial COD in those countries where consumer prices for electrical energy are relatively high (7 US cents/kWh in Turkey) [6]. Moreover, when chemicals such as the Fenton reagents or iron-based coagulants are used for the treatment of dyehouse effluent, the chemical sludge generated after treatment due to precipitation of ferric hydroxide after Fenton process has to be handled thus causing a secondary pollution problem. On the other hand, excessive coagulant material can be avoided when

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electrocoagulation (EC) is used to treat wastewater since in this case the coagulant is generated in the reaction solution by the dissolution of a sacrificial anode [7]. The EC process takes advantage of the combined effect of charge neutralization/surface complexation/adsorption onto the in-situ formed metal hydroxides produced from the oxidation of corrodible anode materials (Fe, Al) and the combined effect of flotation/concentration/collection of the metal hydroxide flocs plus adsorbed pollutants by the hydrogen gas bubbles formed at the cathode [8,9]. However, as opposed to former studies and information postulated in related review articles on reactive dyestuff treatment, we have observed immense sludge production during EC corresponding to extremely high (>6000–10,000 mg/L as metal salt) coagulant doses in our recent investigation [10]. Hence, sludge formation has to be minimized requiring careful control and optimization of EC conditions for its feasible application.

In fact, EC has been employed recently to treat aqueous dye solutions, synthetic dyebath effluent and actual, combined textile wastewater. However, until now, no study has been performed on real reactive dyebath effluent that is expected to be more difficult to treat than combined or simulated dye wastewater [11–13]. Moreover, the high electrolyte (e.g. NaCl) concentration used in the reactive dyeing process offers an inherent advantage for treating reactive dyebath effluent with EC. The objective of the present study was to elucidate the effect of applied electrical current density, i.e. the main operating variable affecting EC efficiency, on color and COD removals from a real reactive dyebath effluent using aluminum (Al) and stainless steel (SS) as the electrode materials. In order to assess the economical feasibility of EC as a stand-alone treatment application to completely decolorize and at least partially oxidize reactive dyebath effluent down to the national discharge consents, an economic evaluation in terms of electrical energy per volume of treated wastewater (EE/V, in kWh) was also conducted.

2. Materials and methods

2.1. Reactive dyebath effluent

Two batches of exhausted reactive dyebath samples were collected from a local cotton dyeing and finishing mill and stored in plastic carboys at 4 °C prior to use in our experimental study. The reactive dyehouse effluent was prepared by diluting the original dyebath five times to exactly simulate the effluent that is being discharged from the dyeing and subsequent rinsing stages based upon the information received from the technical staff of the dyehouse. The character of the final dyehouse effluent obtained after diluting the concentrated exhausted reactive dyebath is given in Table 1 for both sample batches.

Electrocoagulation experiments using Al electrodes were done with dyehouse effluent simulated using sample Batch I, whereas electrocoagulation experiments with SS electrodes were accomplished employing dyehouse effluent being prepared from sample Batch II.

Table 1

Characterization of the raw effluent from the reactive dyeing and rinsing stages

Parameter	Batch I	Batch II
COD (mg/L)	500 ± 10	520 ± 10
Filtered COD (mg/L)	390 ± 20	460 ± 20
Color (absorbance, cm ⁻¹)		
436 nm	3.04 ± 0.40	2.91 ± 0.60
525 nm	6.19 ± 0.25	5.13 ± 0.35
620 nm	0.75 ± 0.03	0.65 ± 0.05
pH	11.21	11.23
Conductivity (µS/cm)	27630	27600
Chloride (mg/L)	7800	7800
Total suspended solids (mg/L)	220	250

2.2. The electrocoagulation unit

The electrocoagulation unit consisted of a 2000 mL capacity polyethylene reactor (length = 34.3 cm, width = 12.5 cm, height = 28.3 cm) equipped with six electrodes (304 stainless steel (SS) or Al) used as both anode and cathode materials. The distance between the electrodes was 2 mm and the effective area of the electrodes was 38.13 cm². The applied current was maintained by means of a high precision DC power supply. EC experiments were run as follows; first the pH of 1500 mL wastewater sample was adjusted to 5.5, i.e. the reaction pH where highest treatment efficiencies were obtained for reactive dyes and synthetic reactive dyebath effluent in a former study [10]. Thereafter, the current and voltage were adjusted on the DC power supply. EC experiments were run for up to 60 min with Al electrodes and for 90 min for SS electrodes depending on the time whenever the temperature in the EC unit started to increase. Samples were taken at regular time intervals to determine effluent color, COD, pH and suspended solids. After each experimental run, the EC reactor and electrodes were carefully rinsed twice with 50% nitric acid solution for 2–4 min and several times with deionized water. The electrodes were replaced each time when more than 10% of electrode material was lost.

2.3. Analytical procedures

Treated samples were filtered through 0.45 µm Millipore membrane filters prior to color (absorbance) and COD analyses to remove aluminum and iron hydroxide flocs + adsorbed wastewater ingredients. The color (absorbance) of the untreated and chemically treated samples was measured on a Pharmacia KB – Novaspec II model colorimeter at 436 nm, 525 nm and 620 nm wavelengths corresponding to yellow, red and blue colors representing in trichromatic dyebath mixtures according to German environmental legislations [14] in 1 cm glass cuvettes. The COD's of the untreated and chemically treated samples were measured by the open reflux, titrimetric method as described in ISO 6060 [15]. The amount of metal hydroxide sludge produced after EC was determined in accordance with Standard Methods [16] upon filtration of reaction samples through 1.2 µm Sartorius filters. All analytical measurements (COD, color, pH and suspended solids) were done in duplicate. During and after EC

treatment, percent color removal efficiency was only calculated for absorbance at $\lambda = 525$ nm wavelength (corresponding to the more dominant color of the dyebath effluent samples among the three selected wavelengths) to avoid replication of similar removal efficiencies obtained for the other absorption bands (at 436 and 620 nm wavelengths).

2.4. Kinetic evaluation

2.4.1. Color and COD abatement rates

All experimental results obtained for color and COD abatement as a function of electrocoagulation time could be fitted to pseudo-first order reaction kinetics with correlation coefficients >0.95 . The abatement of color and COD followed pseudo-first order kinetics in accordance with

$$\ln\left(\frac{C}{C_0}\right) = -k \times t \quad (1)$$

where C_0 , C are the absorbance (at $\lambda = 525$; i.e. A_{525}) and COD values at time = 0 (initial absorbance and COD values) and time = t (in min), respectively, and k is the pseudo-first order color (k_{525} , in min^{-1}) and COD (k_{COD} , in min^{-1}) abatement rate constant obtained for EC of the reactive dyebath effluent using Al and SS electrodes. Results were generally speaking presented in terms of normalized color and COD values in order to enable their prompt and easy comparison.

2.4.2. Electrical energy requirements

The major operating cost of EC is associated with electrical energy consumption during EC. The electrical energy consumed during EC was calculated in terms of kWh/m^3 of treated effluent (EE/V) using the equation given as follows:

$$\text{EE}/V = \frac{U \times I \times t}{V_r} \quad (2)$$

where U is the voltage measured during the reaction (in V), I the applied electrical current (in A), t the reaction time (in min), and V_r the reactor volume (in liters). Both the applied voltage and electrical current were continuously followed during EC.

3. Results and discussion

3.1. Electrocoagulation with aluminum electrodes

During EC of reactive dyebath effluent using Al and SS electrodes the initial reaction pH was adjusted to 5.5 as mentioned in Section 2.2, and continuously monitored during the reactions. Changes in pH during EC with Al electrodes were given in Fig. 1.

According to Fig. 1, pH increased with increasing treatment time and applied current density. The increase in effluent pH slowed down after 20 min EC (at around $\text{pH} \approx 9$) at the time when decolorization and partial oxidation (COD abatement) reached asymptotic values (see Figs. 2 and 3). After 60 min EC, the effluent pH's were in the range of 9.8–10.1 independent from the applied current densities. The increase in pH was a consequence of the following cathodic reaction taking place during

electrocoagulation;



Fig. 2 displays the effect of applied current density on normalized color abatement rates during EC with Al electrodes. The EC

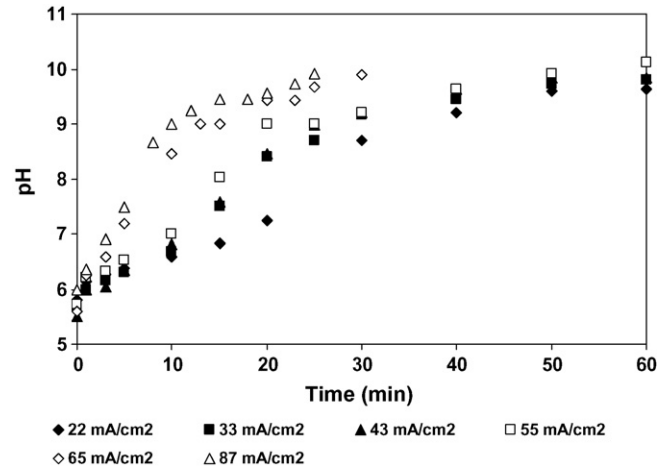


Fig. 1. Changes in pH during EC with aluminum electrodes at varying electrical current densities.

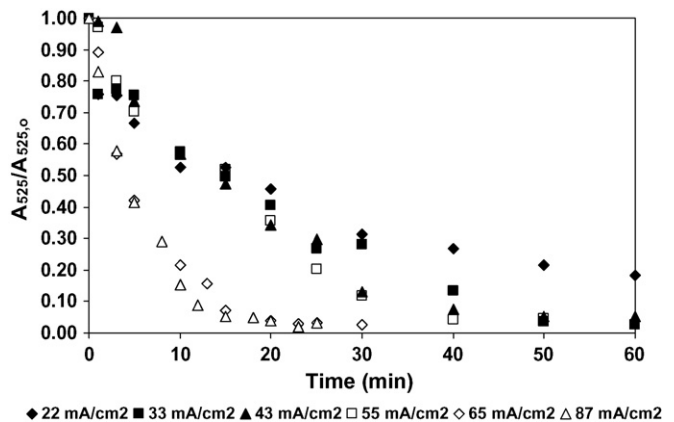


Fig. 2. Normalized color (A_{525}) values observed during EC with aluminum electrodes at varying electrical current densities.

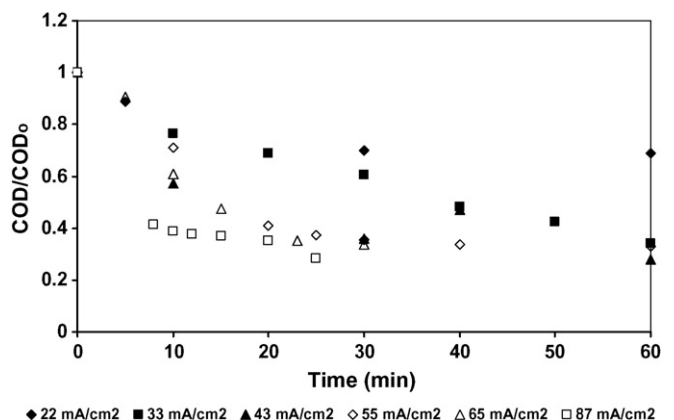


Fig. 3. Normalized COD values observed during EC with aluminum electrodes at varying electrical current densities.

Table 2

Effect of the applied current density on pseudo first-order color (A_{525}) and COD abatement rates constants and removal efficiencies obtained for EC using Al electrodes

Current density (mA/cm ²)	A_{525} removal ^a (%)	k_{525} (min ⁻¹) ^b	COD removal ^a (%)	k_{COD} (min ⁻¹) ^b
22	80	0.0269	31	0.0120
33	97	0.0629	64	0.0164
43	95	0.0615	76	0.0375
55	96	0.0750	67	0.0418
65	98	0.1454	73	0.0665
87	97	0.1963	72	0.0988

^a Removal efficiencies obtained after 60 min EC for current densities 22–55 mA/cm²; 30 min for 65 mA/cm² and 25 min for 87 mA/cm².

^b Correlation coefficients $R^2 > 0.96$.

time was selected as 60 min, since the temperature in the reaction solution started to increase with increasing treatment time after 25–30 min at the higher current densities (65 and 87 mA/cm², respectively). From Fig. 2 it is apparent that increasing the current density significantly enhances color abatement rates. For instance, at a current density of 33 mA/cm², an electrocoagulation time of 50 min was needed to achieve 97% reduction in color ($A_{525} = 0.191 \text{ cm}^{-1}$ after 50 min electrocoagulation), whereas 95% decolorization was obtained ($A_{525} = 0.229 \text{ cm}^{-1}$) in only 15 min when the current density was elevated to 87 mA/cm². Not more than 80% decolorization could be achieved even after 60 min EC at the lower studied current densities (i.e. 22 mA/cm²); nevertheless, a dramatic improvement in color removal rates was evident particularly above a current density of 55 mA/cm². Fig. 2 also revealed that the kinetic regime for color removal with electrocoagulation shifted from a mass-transfer to a kinetically-limited one at current densities beyond 55 mA/cm² owing to the fact that color abatement rates did not change further when the current density was elevated from 55 to 65 mA/cm². Noteworthy is the fact that color abatement profiles were parallel to changes in pH during EC with Al electrodes.

A similar trend was obvious for COD abatement rates that were portrayed in normalized form in Fig. 3. As compared to color removal profiles COD removals proceeded rather slowly, since the reactive dyebath effluent not only comprised of reactive dyes but also a variety of sequestering, surface active and other dye auxiliary agents (dispersing agents, anticreasing agents, sequestering agents, etc.) that also significantly contributed to the effluent's COD. From our previous studies conducted with synthetic reactive dyebath effluent we know that these dyebath ingredients are the main source of the overall organic load of reactive dyebath effluent, contributing to at least 80% of its total COD [10] and hence it is not surprising that decolorization occurred faster than COD removal. Again, as in the case of the color parameter, current density had an appreciable positive effect on COD abatement kinetics, only different in the observation that COD removals were significantly slower and rather incomplete (only 30% after 60 min), particularly at the lowest tried current density (22 mA/cm²). For instance, 72% COD removal was obtained after 25 min EC at the highest investigated current density (87 mA/cm²) and more or less the same overall COD removal efficiencies were observed for current densities in the range 33–65 mA/cm².

Table 2 summarizes percent color (A_{525}), COD removal efficiencies as well as pseudo-first order decolorization and COD abatement rate constants obtained for EC of the reactive dyebath effluent with Al electrodes. As apparent in Table 2, there is a strong positive correlation between current density and color as well as COD abatement rates and rate coefficients. This observation can be supported by Chen [17] who studied the effect of applied current density (investigated range = 13–38 mA/cm²) on the hydrogen gas bubble size and concluded that increasing the current density had a dramatic effect on bubble diameter resulting in a significant decrease in bubble size and accelerating the treatment efficiency of EC immensely. In the case of EC with Al electrodes, where the only expected removal mechanism is coagulation (adsorption/entrapment of pollutants on the freshly formed aluminum(III)-hydroxo complexes) and the simultaneous flotation of Al(OH)₃ together with the removed contaminants via hydrogen bubbles formed at the cathode [8], it is not surprising to observe such an effect.

3.2. Electrocoagulation with stainless steel electrodes

As can also be followed from Fig. 4, during EC of reactive dyebath effluent using SS electrodes a gradual increase from the initially adjusted effluent pH being 5.5 to pH 7–8 after 15 min EC and ultimately to around pH 12 after 90 min EC was evident.

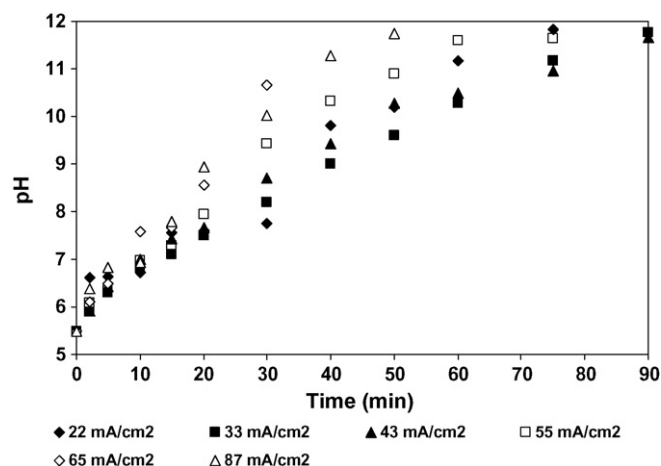


Fig. 4. Changes in pH during EC with stainless steel electrodes at varying electrical current densities.

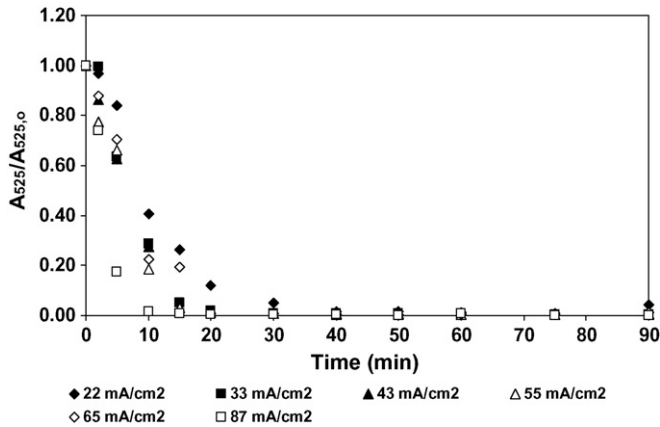


Fig. 5. Normalized color (A_{525}) values observed during EC with stainless steel electrodes at varying electrical current densities.

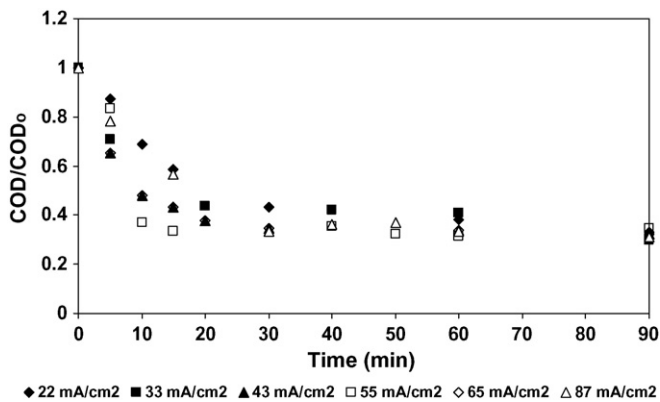


Fig. 6. Normalized COD values observed during EC with stainless steel electrodes at varying electrical current densities.

Again, there existed a positive relationship between increasing the applied current density and raise in reaction pH, but different from the EC studies conducted with Al electrodes, the increase continued almost until the end of the treatment period and did not level off. Again, pH profiles were parallel to changes in color and COD values during EC (See Figs. 5 and 6). Fig. 5 shows time-dependent changes in normalized color (absorbance) values obtained for EC of reactive dyebath effluent at varying current densities (22–87 mA/cm²). From Fig. 3 and particularly in Table 3 presenting the associated

color abatement rates and rates constants, it is clear that decolorization was much faster during EC with SS electrodes than EC with Al electrodes. For instance, 95% color was removed after 30 min even at the lowest applied current density (22 mA/cm²) and 99% in only 10 min EC at the highest applied current density (87 mA/cm²). This can be explained as follows; in addition to the adsorption of contaminants on the resulting Fe(III) hydroxides, there is evidence for partial direct oxidation at the anode and (azo dye) reduction at the cathode in case of steel electrodes, provided that the oxygen concentration in the reaction medium immediately drops to levels <1 mg/L as a consequence of oxygen depletion and the development of reducing conditions (e.g. favorable negative reduction potentials) according to the reactions taking place during EC with Fe/SS electrodes (as shown later in Eqs. (4) and (5)). Al electrodes, on the other hand, cannot act as reducing agents since they enter the solution in a single valence state [18]. In contrast, SS (or Fe) anodes cause ferrous iron release that may act as the reducing agent for azo dyes when all dissolved oxygen in the reaction medium is consumed [19]. Moreover, it was observed in a related study that reduction potentials and dissolved oxygen concentrations were appreciably lower during EC using steel electrodes than those measured for Al electrodes providing evidence that conditions were more favorable for reduction reactions when steel electrodes were employed [20]. The main difference observed for EC employing SS electrodes was that decolorization profiles did not change as a function of the applied current density in the range of 33–65 mA/cm² and hence practically the same decolorization efficiencies were obtained at these current densities.

Fig. 6 presents normalized COD abatement rates as a function of treatment time at different applied current densities for EC with SS electrodes. From Fig. 6 it is evident that COD abatement rates reached asymptotic values after 15–30 min (resulting in 65% COD removal after 30 min). The average, overall COD removal efficiency was obtained as 70% after 90 min EC. Upon closer inspection of Fig. 6 (and also obvious later in Table 3) it can be seen that COD removal proceeded appreciably faster at the current densities 33, 43, 55 and 65 mA/cm² than at the highest current density (87 mA/cm²) investigated in the present study.

The observed color and COD abatement profiles clearly revealed that EC involving SS (or Fe electrodes) is a two-stage redox process and hence proceeds slower than EC with

Table 3
Effect of the applied current density on pseudo first-order color (A_{525}) and COD abatement rates constants and removal efficiencies obtained for EC using SS electrodes

Current density (mA/cm ²)	Time (min)	A_{525} removal (%)	k_{525} (min ⁻¹) ^a	COD removal (%)	k_{COD} (min ⁻¹) ^a
22	60	99	0.1063	69	0.0525
33	60	100	0.2148	71	0.0305
43	60	99	0.2432	66	0.0565
55	60	100	0.2379	69	0.0767
65	60	100	0.2487	57	0.0529
87	60	99	0.0463	62	0.0147

^a Correlation coefficients $R^2 > 0.95$.

Al electrodes due to the following anodic reactions taking place sequentially;

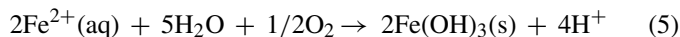


Table 3 presents color and COD removal efficiencies and associated pseudo-first order color (A_{525}) and COD abatement rate constants obtained for EC of the reactive dyebath effluent with SS electrodes. From Table 3 it is evident that overall percent color as well as COD removal efficiencies were close to each other. Quite similar k_{COD} values (in the range of $0.075\text{--}0.080\text{ min}^{-1}$) were also obtained in another, related experimental work during EC of a simulated (synthetic) reactive dyebath using SS electrodes at a current density range of $20\text{--}90\text{ mA/cm}^2$ [21]. As mentioned above, from the k_{525} and k_{COD} values calculated for different current densities it is clear that decolorization and COD abatement rates were dramatically retarded at the higher (87 mA/cm^2) and lower (22 mA/cm^2) end of the studied current densities. Hence, optimization of the applied current density appeared to be very critical in maintaining an efficient EC treatment process considering the use of different electrode materials.

3.3. Electrical energy requirements

Ultimately, not the highest removal efficiency, but the national discharge consents and electrical energy consumption (operating costs) required to achieve the desired degree of treatment will determine the feasibility of a proposed treatment method. Hence, it is crucial to calculate electrical energy requirements per unit volume of treated effluent to decide whether EC is economically as well as technically affordable for the decolorization and partial oxidation (COD removal) of reactive dyebath effluent. The following requirements were taken into consideration to select the most suitable working conditions and eliminate the other studied current densities: (1) a decolorization efficiency of at

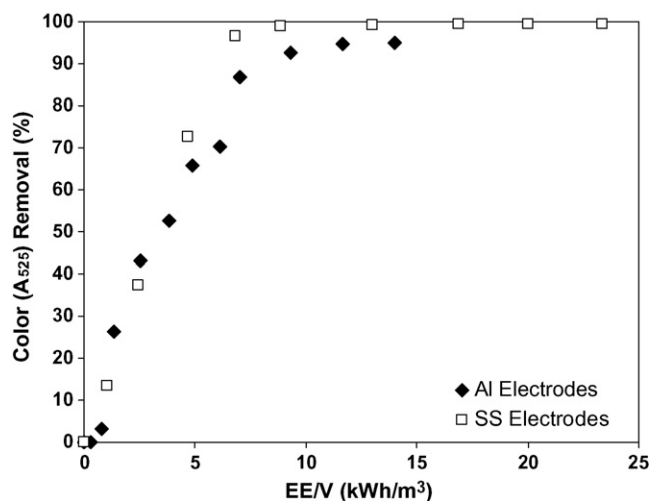


Fig. 7. Comparison of electrical energy requirements per volume of wastewater (EE/V) for color removal during EC with aluminum and stainless electrodes (applied current density: 43 mA/cm^2 ; initial pH = 5.5).

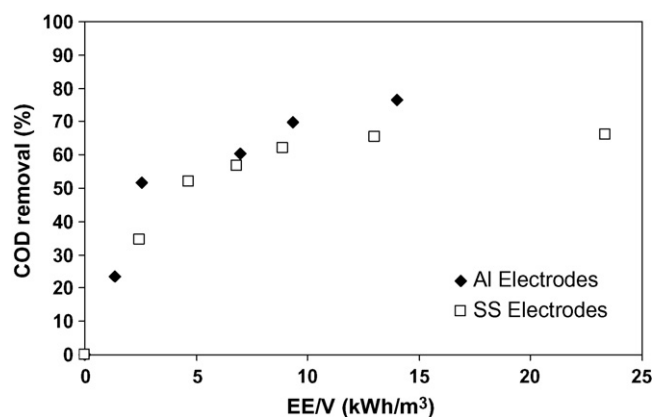


Fig. 8. Comparison of electrical energy requirements per volume of wastewater (EE/V) for COD removal during EC with aluminum and stainless electrodes (applied current density: 43 mA/cm^2 ; initial pH = 5.5).

least 90% was aimed; (2) the national COD discharge requirement (into receiving water bodies) being set as 200 mg/L for textile industries producing cotton fibers was also taken into account. Conclusively, the current density resulting in at least 90% color removal and ultimate COD's less than 200 mg/L (i.e. 185 mg/L COD, considering possible system failures that may decrease COD removal performance) were selected for the economical evaluation.

According to percent color (Fig. 7) and COD (Fig. 8) removal efficiencies obtained as a function of EE/V (in kWh/m^3) for EC with Al and SS electrodes (Al-EC, SS-EC) at an initial pH of 5.5 and an applied current density of 43 mA/cm^2 , EC using Al electrodes became critical in terms of electrical energy requirements after 40 min treatment, however 30 min EC is almost sufficient to satisfy our color (87% removal) and COD (60% removal resulting in an effluent COD of 179 mg/L) criteria. Hence, 7 kWh/m^3 are required to achieve these goals and to offer stand-alone EC using Al electrodes as an alternative, effective treatment method. However, for practically complete (95%) color removal employing Al-EC, an electrical energy of at least 11 kWh/m^3 would be required (Figs. 5–7). On the other hand, 20 min EC with SS electrodes was sufficient for almost complete (99%) color and 62% COD removals corresponding to an EE/V value of 9 kWh/m^3 which is still below the upper feasibility limit being set as 10 kWh/m^3 for the applicability of an industrial wastewater treatment technology [22]. Hence, most appropriate working conditions were established as pH = 5.5, applied current density = 43 mA/cm^2 , and a treatment time of 20 min and 30 min for Al-EC and SS-EC, respectively.

3.4. Final effluent characterization

Table 4 presents final effluent characterization of the EC-treated reactive dyebath effluent determined at our optimized working conditions (applied current density = 43 mA/cm^2 ; initial pH = 5.5; treatment time = 30 min for Al electrodes and 20 min for SS electrodes). Obviously, high color (specially for EC with SS electrodes) and acceptable COD removals (65% for Al-EC, 73% for SS-EC) were achieved such that both EC

Table 4

Characterization of the final, treated effluent from the reactive dyeing + rinsing stages (EC conditions: applied current density = 43 mA/cm²; initial pH = 5.5; treatment time = 30 min for Al electrodes and 20 min for SS electrodes)

Parameter	Aluminum-EC	SS-EC
Soluble COD (mg/L)	136 ± 10	184 ± 25
Color (absorbance, cm ⁻¹)		
436 nm	0.590	0.106
525 nm	0.462	0.048
620 nm	0.073	0.021
pH ^a	9.21	9.65
Conductivity (μS/cm)	25800	27600
Chloride (mg/L)	8300	8400
Sludge produced (as mg TSS/L) ^b	5500	6300

^a pH monitored after 30 min EC.

^b Formed due to in situ iron(III) and aluminum hydroxide precipitation.

using Al and SS electrodes can be offered as suitable and feasible stand-alone treatment processes to eliminate color and meet the national discharge limit value for the COD parameter. In addition, upon comparison of Tables 1 and 4 it is also evident that unlike most chemical/biological treatment processes, no increase in electrical conductivity (salinity) was observed which is clearly attributable to the removal mechanism of electrocoagulation [8]. Moreover, Ciardelli et al. [23] as well as Ciardelli and Ranieri [24] reported significant sulfate ion removal during EC with Al and Fe electrodes that is thought to be mainly as a consequence adsorption of anions onto the polymeric metal-hydroxo species. In the present study, bicarbonate and carbonate ions might be removed by the same reaction mechanisms so that the overall electrical conductivity did not change significantly after applying electrocoagulation. Besides, similar amounts of metal (III) hydroxide sludge (5000–6000 mg/L) were formed after EC with Al and SS electrodes under the reaction conditions given in Table 4.

4. Conclusions and recommendations

In the present study, electrocoagulation using aluminum (Al) and stainless steel (SS) electrodes was experimentally investigated to remove color completely and COD at least partially from real reactive dyebath effluent. The following conclusions could be drawn from the experimental study;

- In terms of color removal efficiency, EC with SS electrodes was superior to EC using Al electrodes; 95% decolorization could be achieved with SS electrodes after 15 min EC at a current density of 43 mA/cm² corresponding to an electrical energy consumption of 7 kWh/m³, whereas color abatement was significantly slower for EC with Al electrodes. It took 50 min via Al-EC at the same current density to achieve the same color removal efficiency, corresponding to 11 kWh/m³ treated wastewater. Due to economical constraints, EC time should be kept 30 min when Al is used as the electrode material that will result in almost 90% (87%) color removal and hence fit the feasibility criteria set for both color and COD.

- In terms of COD removal, although almost the same treatment efficiencies were obtained at a current density of 43 mA/cm² (i.e. 50% COD removal after 10 min EC for Al electrodes and 60% COD removal obtained after 20 min EC with SS electrodes), EC with Al electrodes should be preferred due to economic reasons (e.g. electrical energy consumption was calculated as 5 kWh/m³ wastewater for EC with Al, and 9 kWh/m³ wastewater for EC with SS electrodes to achieve 50% and 60% COD removals, respectively).
- Sludge formation was in the range of 5000–6000 mg/L after 30 and 20 min EC of reactive dyebath effluent with Al and SS electrodes, respectively, under reaction conditions selected for final effluent characterization.
- Considering the above listed findings, both EC with Al and SS electrodes proved to be a feasible stand-alone treatment option for complete color and partial COD removal from reactive dyebath effluent.

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References

- [1] I. Arslan-Alaton, G. Insel, G. Eremektar, F.G. Babuna, D. Orhon, Effect of textile auxiliaries on the biodegradation of dyehouse effluent in activated sludge, *Chemosphere* 62 (2006) 1549–1557.
- [2] A. Reife, *Dyes, environmental chemistry* Reprinted from Kirk-Othmer Encyclopedia of Chemical Technology, fourth ed., vol. 8, John Wiley & Sons, Inc., New York, 1993, pp. 753–784.
- [3] C. O'Neill, F.R. Hawkes, D.L. Hawkes, N.D. Lourenco, H.M. Pinheiro, W. Delée, Colour in textile effluent – sources, measurement, discharge consents and simulation: a review, *J. Chem. Technol. Biotechnol.* 74 (1999) 1009–1018.
- [4] V.M. Correia, T. Stephenson, S.J. Judd, Characterization of textile wastewaters—a review, *Environ. Technol.* 15 (1994) 917–929.
- [5] Y.M. Slokar, A.M. le Marechal, Methods of decoloration of textile wastewaters, *Dyes Pigments* 37 (1998) 335–356.
- [6] <http://www.buyusa.gov/kern/turkeyenergyprofile2005.html>.
- [7] N. Daneshvar, H. Ashassi-Sorkhabi, A. Tizpar, Decolorization of orange II by electrocoagulation method, *Sep. Purif. Technol.* 31 (2003) 153–162.
- [8] M.Y.A. Mollah, R. Schennah, J.R. Parga, D.L. Cocke, Electrocoagulation (EC)—science and applications, *J. Hazard. Mater.* (2001) 29–41.
- [9] 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.* B114 (2004) 199–210.
- [10] I. Arslan-Alaton, I. Kabdaşlı, B. Vardar, O. Tünay, Optimization of electrocoagulation conditions for the treatment of simulated reactive dyebath effluent, *Sep. Purif. Technol.*, submitted for publication.
- [11] A. Gurses, M. Yalcin, C. Dogar, Electrocoagulation of some reactive dyes: a statistical investigation of some electrochemical variables, *Waste Manage.* 22 (2002) 491–499.
- [12] M. Muthukumar, M. Thalamadai Karuppiyah, G. Bhaskar Raju, Electrochemical removal of CI acid orange 10 from aqueous solutions, *Sep. Purif. Technol.* 55 (2007) 198–205.
- [13] M. Kobya, O.T. Can, M. Bayramoglu, Treatment of textile wastewaters by electrocoagulation using iron and aluminum electrodes, *J. Hazard. Mater.* B100 (2003) 163–178.

- [14] Deutsche Normen, Summarische Wirkungs-und Stoffkenngrößen (Gruppe H), Bestimmung des Chemischen Sauerstoffbedarfs (CSB) im Bereich über 15mg/L (H41), DIN 38 409 H41–2, 1980.
- [15] F. Gähr, F. Hermanutz, W. Oppermann, Ozonation: an important technique to comply with new German laws for textile wastewater treatment, *Water Sci. Technol.* 30 (1994) 255–263.
- [16] APHA-AWWA-WPCF, Standard Methods for the Examination of Water and Wastewater, 20th ed. American Public Health Association, Washington DC, 1998.
- [17] G. Chen, Electrochemical technologies in wastewater treatment, *Sep. Purif. Technol.* 38 (2004) 11–41.
- [18] A. Reife, H.S. Freeman, *Environmental Chemistry of Dyes and Pigments*, John Wiley & Sons, Inc., Canada, 1996, pp. 329–330.
- [19] A. Wilcock, M. Brewster, W. Tichner, Using electrochemical technology to treat textile wastewater. Three case studies, *Am. Dyestuff Rep.* 15 (1992) 81–85.
- [20] I. Alaton, Electrocoagulation and advanced oxidation as intermediate treatment steps for water reuse in textile dyeing plant, Ph.D. Thesis, Bogazici University, Institute of Environmental Sciences, 2005.
- [21] I. Kabdaşlı, B. Vardar, I. Arslan-Alaton, O. Tünay, Effect of reactive dye auxiliaries on the decolorization and COD removal by electrocoagulation, *Chem. Eng. J.*, submitted for publication.
- [22] Calgon Carbon Oxidation Technologies, *The AOP Handbook*, Calgon Carbon Oxidation Technologies, Markham, Ontario, Canada, 1995.
- [23] G. Ciardelli, G. Capannelli, A. Bottino, Ozone treatment of textile wastewater for reuse, *Water Sci. Technol.* 44 (2001) 61–67.
- [24] G. Ciardelli, N. Ranieri, The treatment and reuse of wastewater from the textile industry by means of ozonation and electroflocculation, *Water Res.* 35 (2001) 567–572.