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Treatment Performance of Textile Wastewater Using Electrocoagulation (EC) Process under Combined Electrical Connection of Electrodes

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The electrocoagulation (EC) process (using electrically coupled interconnections) was investigated for the treatment of textile wastewater. The impact of several operating parameters such as bipolar electrode element (Fe or Al), electrolysis time (RT), current intensity (I), pH, chemical support, inter-electrode distance (IED), and stirring speed (M_{rpm}) were examined. Additionally, the consumption of electrodes and electrical energy, sludge compaction, operating costs and a comparison with the traditional chemical coagulation method has been thoroughly investigated. The most suitable EC performance was achieved by using monopolar and bipolar aluminum-type plates. These plates were alternated within the electrode pack for 90 min. Preliminary results showed the following optimal operating conditions: I=0.6 A, pH=6, NaCl=0.1 kg/m^3, IED=0.5 cm, and M_{rpm}=500. The implementation of these parameters on textile wastewater revealed a relatively high removal efficiency of COD (92.6%), TSS (96.4%), color (96.5%), BOD_5 (88%), TDS (87%), turbidity (96%), phenols (over 99%), and phosphate (95%). The overall operating cost for the EC operation was 1.76US$/$m^3$. This value was calculated based on the electrode and energy consumption, chemicals, and sludge disposal. The EC operation was found to be more efficient than the traditional chemical coagulation process.

Keywords: Electrocoagulation; textile wastewater; monopolar and bipolar connection; aluminum electrode; iron electrode

1. INTRODUCTION

The textile production industry uses highly water intensive chemical operations. This industry produces massive levels of wastewater and therefore presents great environmental and economic challenges [1]. In the past, the process of electrocoagulation (EC) has attracted much attention. It has been a cost-effective and an environmentally friendly process implemented to remove different types of pollutants, including dyes [2], heavy metals [3, 4], and organic substances [5]. This process is known for its simple equipment and process and for producing relatively low amounts of sludge. The electrochemical system comprises the in-situ generation of coagulants with the dissolution of the sacrificial anode. The anode is commonly made of aluminum or iron [6]. The metal ions react with the cathode generating OH^- ions and gaseous H_2. This reaction produces insoluble hydroxides that adsorb the pollutants and eliminate them from the solution. Additionally, this process facilitates coagulation by neutralizing the negatively charged colloidal particles. These particles tend to be more compact than the sludge. The process of electrocoagulation can be described as:

At the anode,

$M \rightarrow M^{n+} + ne^-$ (1)

At the cathode,

$nH_2O + ne^- \rightarrow n/2\, H_2 + nOH^-$ (2)

where M is the anode and n is the stoichiometric number of electrons within the oxidation or reduction reaction.

Soluble metal ions (Fe or A1) are created at the anode and have reacted with the hydroxide ions created at the cathode. The metal hydroxides are generated as shown below:

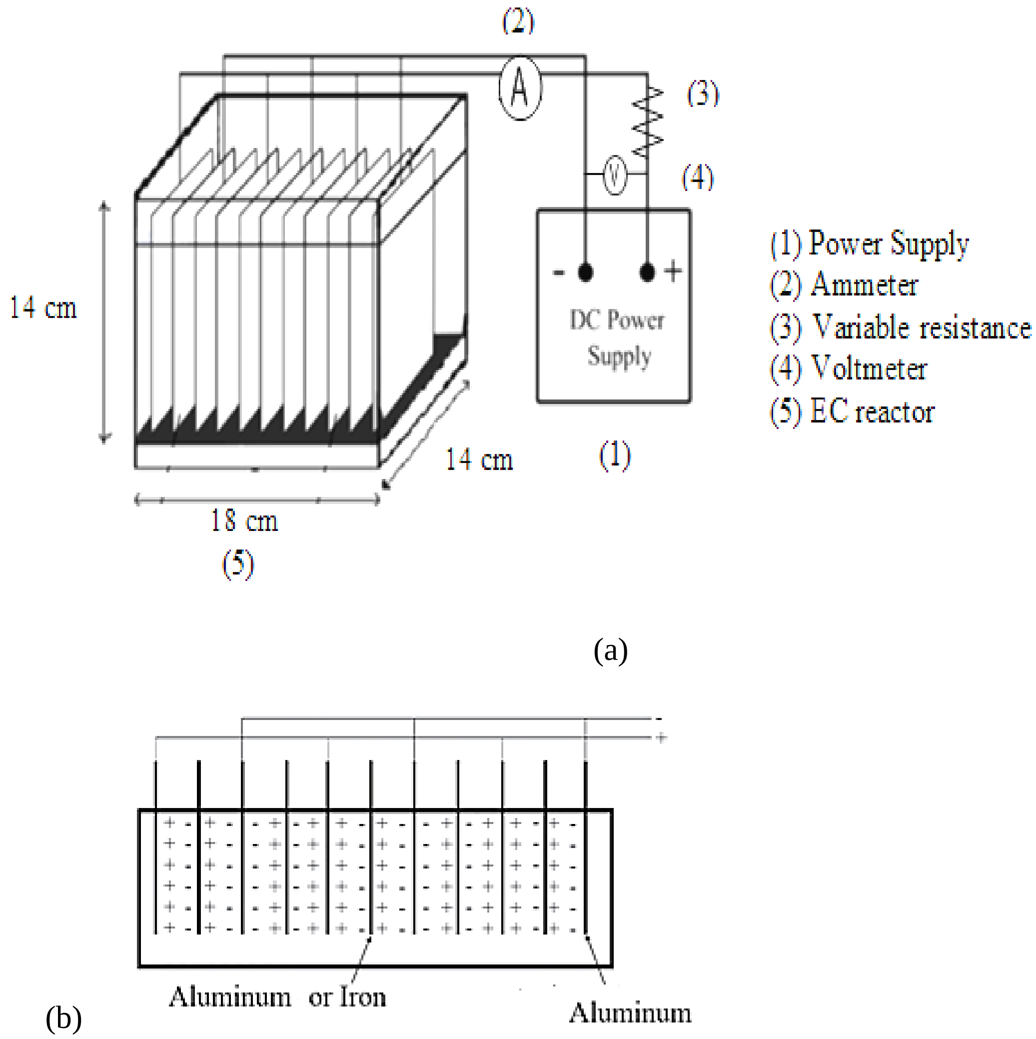
$M^{n+} + nOH^- \rightarrow M(OH)_n$ (3)

The insoluble metal hydroxides precipitate out after reacting with the colloid and suspended solids. In the existing literature, the process of electrocoagulation of textile wastewater has been conducted using parallel plates that have electrodes with either bipolar or monopolar properties. Electrochemical parallel plate cells containing two [7-11], four [12-14], five [15], and six [16] electrodes were all considered. These studies that focused on the electrochemical treatment have commonly considered electrodes created in the same fashion. In this study, EC was achieved with the use of iron or aluminum electrodes that were fixed within a bipolar structure. Within the electrolytic cell, the aluminum electrodes were organized in a monopolar structure. The electrodes were installed vertically within the electrolytic cell, and every anode was directly connected to a cathode.

The aim of this study was to investigate the most suitable operating conditions for the treatment of textile wastewater using new configuration of EC by combining electrical connections including bipolar electrodes, current intensity, reaction time, pH, electrolysis-based support, electrode gap, and stirring speed. In addition, sludge compaction that was generated after the EC treatment was also evaluated. The overall efficiency of EC process was compared to the conventional chemical coagulation process.

2. MATERIALS AND METHODS

2.1. Experimental setup



(a)

(b)

Figure 1. Schematic view of EC experimental setup: (a) EC cell, (b) Configuration of monopolar aluminum and bipolar aluminum (or iron).

The treatment of textile wastewater was performed using a batch electrolytic cell made of Plexiglas with a length, width and height of 18, 14, and 14 cm, respectively (Figure 1 (a)). The upper cover of the cell was made of Teflon. The electrodes were composed of six aluminum plates that were connected to the main power supply. The anode and cathode were both monopolar. A total of five inner iron (or aluminum) electrodes were implemented in a bipolar form (Figure 1 (b)). Each electrode had a surface area of 120 cm^2 (12 cm × 10 cm). The space between the inter electrodes was 1 cm.

The set of electrodes was submerged into the effluent and the overall thickness of each electrode was 0.1 cm. Stirring within the cell was done using a magnetic stirrer/hot plate unit. The anode and cathode sets were connected to the positive and negative terminals, respectively, of a DC power supply (YIZHAN, 0-40V; 0-6 A, China). The primary voltage was set to 30 V for every run. The current level was maintained with variable resistance and measured using a multi-range ammeter (Aswar DT830D, China). A working volume of 3 L of effluent was used for all of the tests. The electrolytic cell was thoroughly cleaned for approximately 10 min with 5% (v/v) hydrochloric acid solution. The experiments were conducted at ambient temperatures (25-27°C). The initial pH was adjusted to between 5 and 10 with 0.5 M NaOH. A fixed amount of supporting electrolytes (Na_2SO_4 and NaCl) was added to the wastewater to investigate the effects of removal efficiency by changing conductivity levels. All chemicals used were analytical grade reagents sourced from the Mat Laboratory.

The wastewater used in this work was collected from a major textile-based industry in Iraq (Babylon). The main characteristics of the textile wastewater, the properties of the color (Imperon Violet KB), sludge compaction study and chemical analysis processes and devices have been observed by our previous research on enhancing of EC process using titanium plates [17].

Approximately 100 ml of supernatant was taken for the duplicate analysis. Equal parameters were measured for every replicate sample. The optimal conditions were tested in triplicate to validate the effectiveness and reproducibility of the EC operation. The metal concentration residue of sludge compaction study for EC that possessed optimal conditions was estimated from a 30 ml sample extract. For traditional chemical coagulation, a similar reactor with aluminum sulfate dosage, but without electrodes, was used. The results were compared with the performance of EC.

2.2. Operation costs analysis

The total operation costs for wastewater treatment process comprises of electricity, sludge disposal, chemical usage, maintenance, labor, and equipment. In the EC process, the main operating costs are of the electrode material and electricity. In this work, the cost of sludge disposal and chemical supplements were also included. Total operating costs were calculated based on the following equations [18]:

$$\text{Total operating cost} = a\, C_{energy} + b\, C_{electrode} + d\, C_{sludge} + e\, C_{chemicals} \qquad (7)$$

$$C_{energy} = U\, I\, RT / V \qquad (8)$$

$$C_{electrode} = M_w\, I\, RT / z\, F\, V \qquad (9)$$

where C_{energy}, $C_{electrode}$, C_{sludge}, $C_{chemicals}$, a, b, d, e, U, I, RT, V, M_w, z, and F denote energy intake for every cubic meter of wastewater (kWh/m^3); electrode intake for treating 1 m^3 of wastewater (kg/m^3); amount of sludge for every 1 m^3 of wastewater (kg/m^3); cost of chemicals (kg/m^3); total electricity costs (approximately 0.075US$/kWh); cost of aluminum or iron (2.5US$/kg); cost of sludge disposal, including transportation and excluding the drying (0.06US$/kg); cost of chemicals which can add (NaCl 0.06US$/kg), Na_2SO_4 (0.25US$/kg), NaOH (0.5US$/kg), and LPM 3135 polymer (3.0US$/kg); voltage; current intensity; EC electrolysis time; working volume of textile wastewater; molecular weight of the aluminum (26.98 g/mol) or iron (55.84 g/mol); amount of electrons moved (3); and Faraday constant (96500 C/mol)), respectively. In order to compare effectively with the traditional coagulation, the aluminum sulfate powder price, inclusive of the dissolution costs, is 6.3 US$/kg.

3. RESULTS AND DISCUSSION

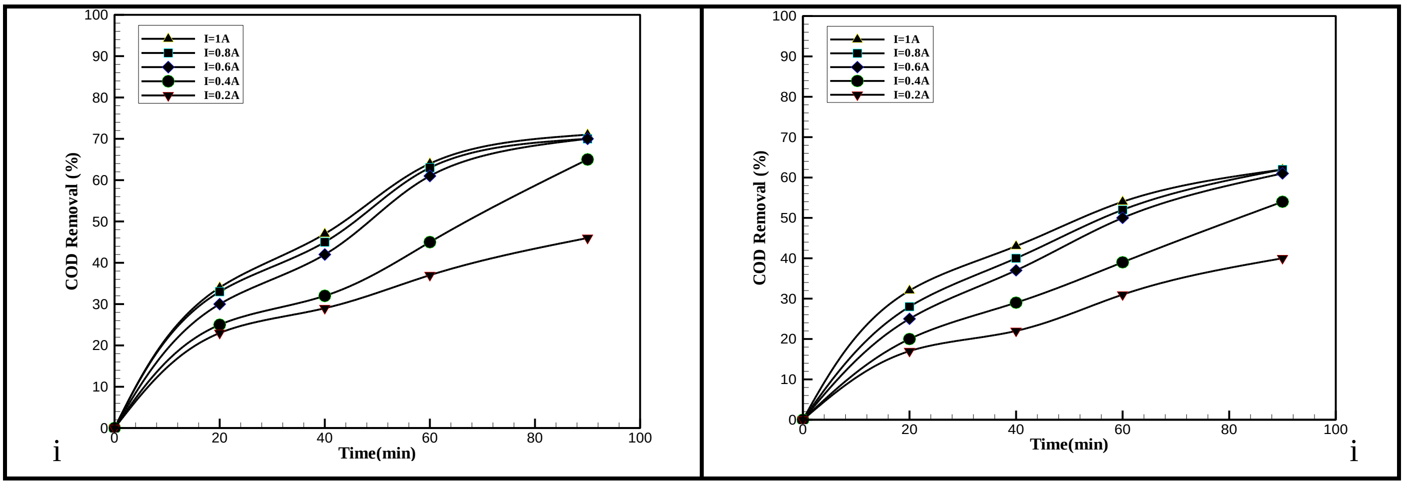
3.1. Effect of bipolar materials

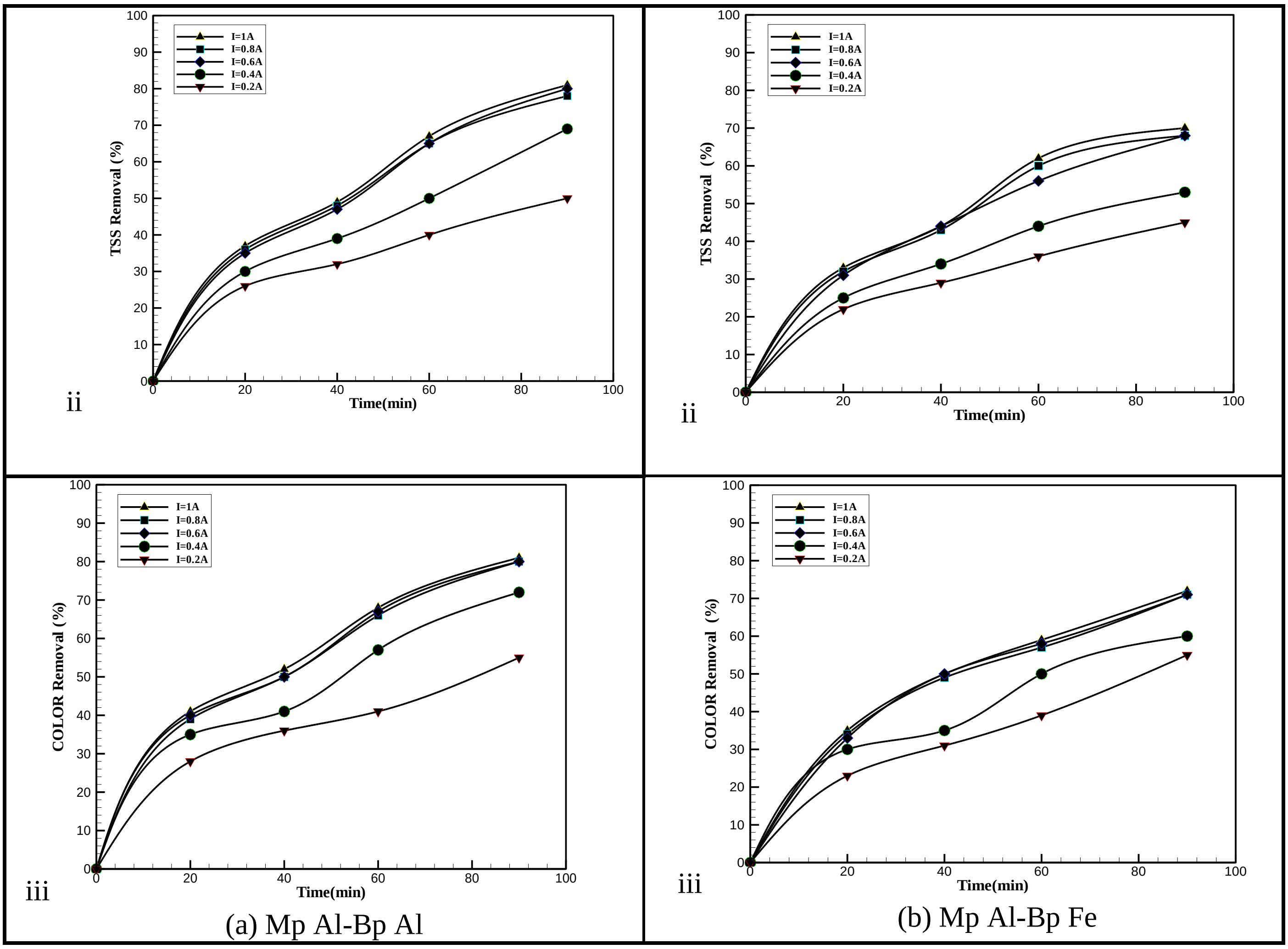
During electrolysis, the pollutants removal (COD,TSS, and color) performance relies on the total concentration of metal ions generated, the material of the electrodes, current intensity, the electrical connection mode, and the time of reaction [14, 19 - 22]. The bipolar configurations in the EC treatment process of textile wastewater were carried out using aluminum or iron electrodes at various current values, ranging from I = 0.2 to 1 A, electrolysis time until 90 min and natural pH = 4.57.

The COD, TSS and colour removal trends for aluminum and iron electrodes are shown in Figure 2 a (i, ii, iii) and b (i, ii, iii). As can be seen, an increase from 20 to 90 min in the electrolysis time caused high COD, TSS, and colour removal efficiencies for the two bipolar electrodes when increasing the current intensity, where 72% COD, 81% TSS, and 81% colour removal for aluminum; and 61% COD, 70% TSS, and 72% colour removal for iron. Both case involved an applied current of 1 A and a reaction time of 90 min. There was an increase in the amount of aluminum cations produced in solution at a higher current, and the rate of formation of Al $(OH)_3$ had also increased. No major increase in the removal efficiency was recorded greater than 0.6 A, where COD = 70%, TSS = 80%, and colour = 80% for aluminum; and COD = 61%, TSS = 68%, and colour = 71% for iron, both at 0.6 A and a time of 90 min.

In contrast, weighing the five inner electrodes (Al or Fe) prior to and after the EC process for all of the current intensities revealed that the level iron consumed was greater than the aluminum. Furthermore, the residual COD concentrations were greater in the case of iron, as compared with the case of the aluminum, as depicted in Figure 3. At a current of 0.6 A, the iron consumption was 0.138 kg/m^3, with a residual COD 383 mg/l, while the aluminum consumption was 0.045 kg/m^3, with a residual COD 295 mg/l. The performance of EC for the Mp Al-Bp Al and Mp Al-Bp Fe arrangements at 0.6 A and a 90 min reaction time is presented in Table 1.

The results indicate that the efficiency of the current for aluminum arrangements is greater, and the quantity of sludge generated is 3.0 kg/m^3, whereas the Al-Fe arrangements generally showed a low volume of sludge (at 2.4 kg/m^3).





(a) Mp Al-Bp Al

(b) Mp Al-Bp Fe

Figure 2. (a) Effect of current intensity and electrolysis time on performance of EC with Mp Al-Bp Al: i.COD removal, ii. TSS removal, iii. Color removal; (b) Effect of current intensity and electrolysis time on performance of EC with Mp Al-Bp Fe: i. COD removal, ii. TSS removal, iii. Color removal.

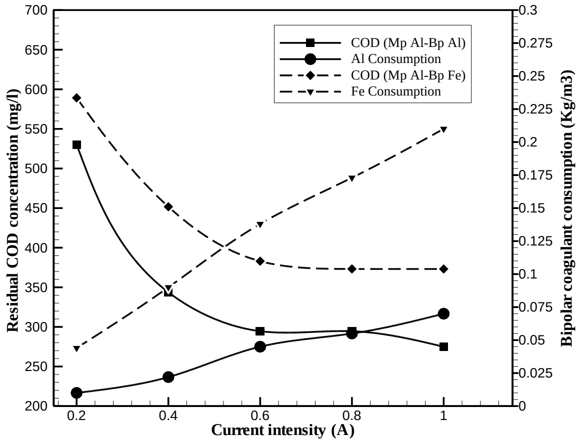


Figure 3. Effect of current intensity on consumption of bipolar electrodes (Al and Fe) and residual COD concentrations at 90 min electrolysis time.

This is mainly attributed to the higher electrical conductivity of the aluminum electrode when compared to iron electrode [23]. Due to the higher consumption of iron electrodes, the total operating costs of the EC with Al-Fe electrodes was 1.27 US$/m^3. This value is higher than the cost recorded for the EC with aluminum electrodes (at 1.09 US$/m^3). It is notable that in the bipolar case, the aluminum electrode was generally more appropriate compared to the iron electrode when at an optimal current of I=0.6 A, and a standard electrolysis process time of 90 min.

Table 1. Effect of bipolar materials on EC performance based on current efficiency, electrodes consumption, and operating cost.

Parameters	Mp Al -Bp Al	Mp Al –Bp Fe
Bipolar electrode	Al	Fe
Mean voltage (v)	30	30
Conductivity (µS/cm)	450	455
Final pH	6.40	6.20
Actual Al dose (mg/l)	95.00	45.00
Actual Fe dose (mg/l)	-	138.00
Theoretical Al or Fe (mg/l)	100.60	312.47
Current efficiency (%)	94.44	88.90
Energy consumption (Kw.h/m^3)	9.00	9.00
Sludge production (Kg/m^3)	3.00	2.40
Electrode consumption cost (US$/m^3)	0.237	0.457
Energy consumption cost (US$/m^3)	0.675	0.675
Sludge deposition cost (US$/m^3)	0.180	0.144
Operating cost (US$/m^3)	1.092	1.276

3.2. Effect of initial pH

The pH of solution is a vital parameter, and much research has been conducted on its effect on the electrocoagulation process for various types of wastewater [24-27]. To examine the impact of pH on COD, TSS, and color removal efficiency, several experiments were carried out by altering the initial pH from 5 to10 at optimal conditions (Mp Al-Bp Al, I= 0.6 A and reaction time=90 min). Results showed that at pH 6, up to 84% COD, 90% TSS and 91% color removal efficiencies were achieved (Figure 4). A slight increase in the overall pH was noted in the acidic solution (pH 5 and 6). In the EC process, an increase in the overall pH was linked to the increase of the bulk concentrations of hydroxide ion (OH^-) formed in the solution due to the reduction of water at the cathode [28]. The $Al\ (OH)_{3(s)}$ flocks have large surface areas, and allows for quick adsorption by organic soluble compounds and trappings by colloidal particles. When the pH was between 4 and 9, different aluminum based polymeric and monomeric species were created and were turned into insoluble amorphous $Al(OH)_{3(s)}$ via complex polymerization processes or precipitation kinetics [29]. When the pH was 10, the concentration of the soluble anion $Al\ (OH)_4^-$ increased and the concentration of $Al\ (OH)_{3(s)}$ decreased. A slight decrease in overall pH was observed based on the reaction as follows:

$$Al\ (OH)_{3(s)} + OH^- \rightarrow Al\ (OH)_4^- \qquad (10)$$

In addition, an investigation of the activity-pH diagram for the Al^{+3} species at equilibrium with the solid phase $Al(OH)_3$ showed that aluminum hydroxide was least soluble an approximate pH of 6 [30]. This is in line with the optimum pH level seen in this study.

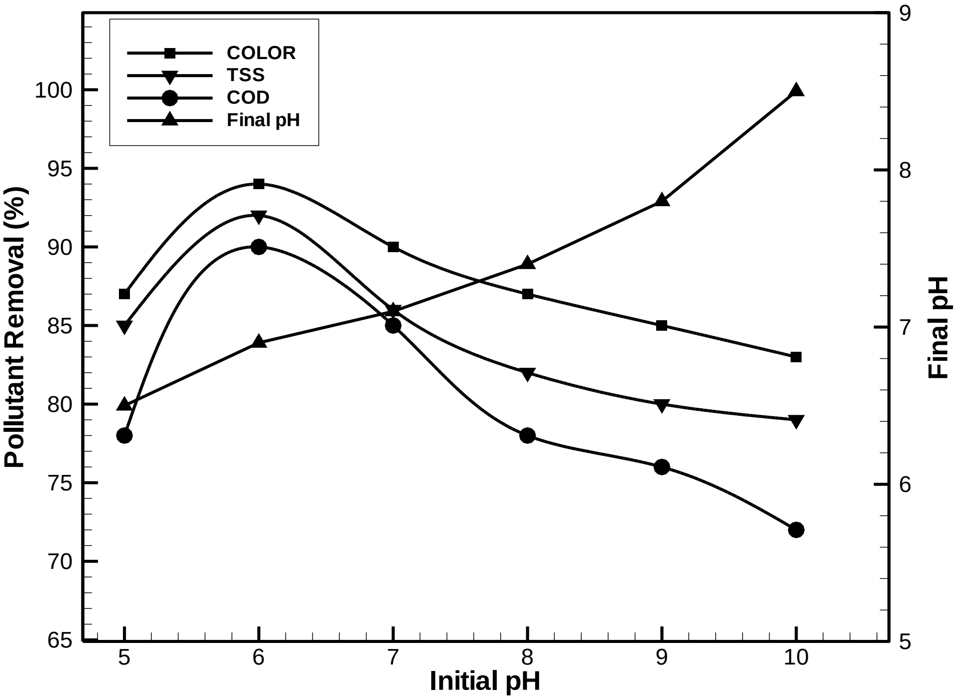
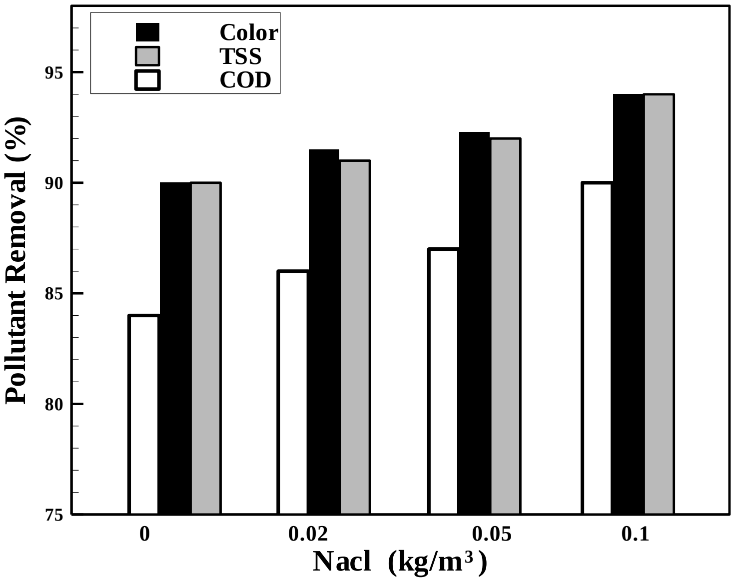
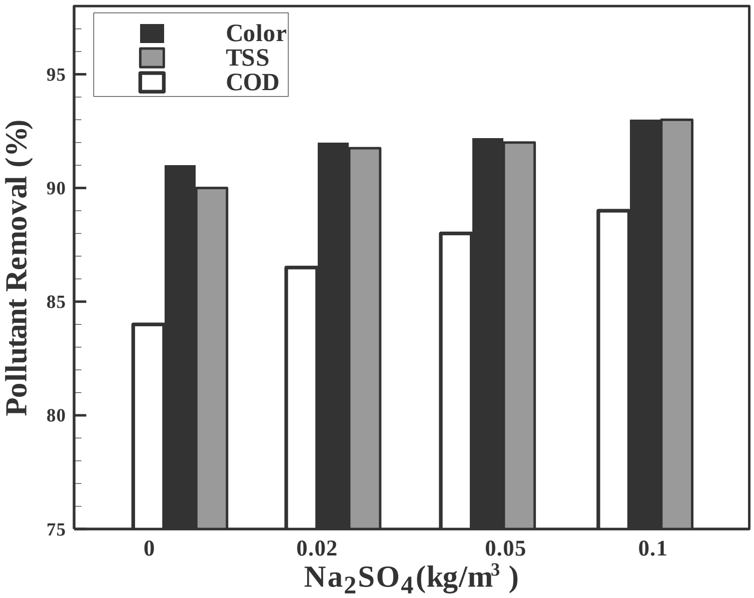


Figure 4. Effect of initial pH on COD, TSS and color removal efficiency and final pH under optimal conditions of EC (Mp Al - Bp Al, I = 0.6 A and RT = 90 min).

3.3. Effect of electrolyte support



(a)



(b)

Figure 5. Effect of electrolysis support on COD, TSS and color removal efficiency under optimal conditions of EC (Mp Al - Bp Al, I = 0.6 A, RT = 90 min and pH = 6) at different concentrations: (a) NaCl; (b) Na_2SO_4.

In general, conductivity of the solution affects the efficiency, the cell voltage, and the electrical energy needed. The addition of an electrolyte, such as Na_2SO_4 or NaCl, to the existing solution can potentially lead to the transfer of current and improve the overall wastewater conductivity [1, 31]. In this study, both NaCl and Na_2SO_4 (0.0, 0.02, 0.05, and 0.10 kg/m^3) were applied to the textile wastewater to evaluate the effect of conductivity on the COD, TSS, and color removal (Figures 5 (a and b)). Results showed a major change in the rate of removal when using a dose of 0.1 kg/m^3 NaCl (90% COD, 94% TSS, and 94% color) as the main supporting electrolyte. Using Na_2SO_4 yielded lower rates (88% COD, 93% TSS, and 93% color). It is suggested that the Cl^- anions may damage the created passivation layer on the aluminum electrode, and therefore, improve the anodic dissolution rate of metal. This leads to the creation of increased levels of aluminum hydroxide [32–34]. Consequently, a 0.1 kg/m^3 NaCl was applied in following experiments.

3.4. Effect of inter electrodes distance

Many researchers have examined the effect of the final electrode distance on the performance of removal of pollutants. Based on these studies, it may be worthwhile to note that the general evolution of the EC performance levels as a common function of inter-electrode distance is based on the pollutants' nature, the electrodes structure, hydrodynamic properties, as well as other factors [22, 26, 35, 36].

In this experiment, the effect of inter-electrode distance was investigated using 0.5, 1, and 1.5 cm as shown in Figure 6. By using optimal conditions (Mp Al-Bp Al, I= 0.6A, reaction time = 90 min, pH = 6, and NaCl = 0.1 kg/m^3), the best performances were obtained at 0.5 cm. The obtained results were 90 to 91.3% COD, 93 to 95% TSS, and 94 to 95% color for a change of 1 to 0.5 cm, respectively. An additional raise in the electrode gap of 1.5 cm leads to reduced removal efficiencies: 84% COD, 88% TSS, and 89% color.

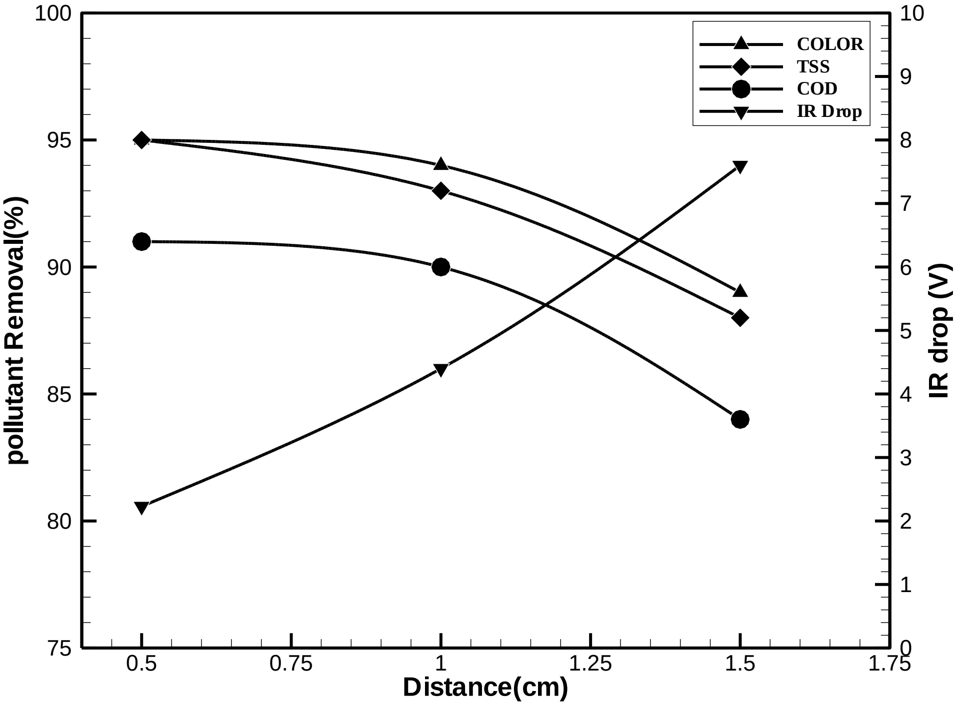


Figure 6. Effect of interelectrodes distance on COD, TSS and color removal and IR drop under optimal conditions of EC (Mp Al - Bp Al, I = 0.6 A, RT = 90 min, pH = 6 and 0.1kg/m^3 NaCl).

This outcome is in line with the results seen in Song et al. [26]. As the spacing in the interelectrode increases, a lower amount of attraction by electrodes was observed on the generated aluminum polymers; hence, they have a slower movement, and they are gathered in flocks. The greater inter electrode distance causes the cell potential (V) to increase, which in turn increases the internal resistance among the electrodes (IRdrop), and adversely affects the EC process. The internal resistance drop among the electrodes (Ohmic potential drop) is the potential drop mainly due to the solution resistance. The variation in the potential is needed to transfer ions via the solution; the variation in the IR drop is shown by the following equation [37]:

$$IR_{drop} = I.d / A.\kappa \qquad (11)$$

Where I represents the current (A); d represents the distance between the cathode and the anode (m) ; A represents the active anode surface (m^2); and κ represents the specific conductivity (mS/m).

The equation above shows that the IR drop increases as a result of increasing the overall electrode distance, as shown in Figure 6. The current drops after some time during the experiment; therefore the applied voltage was increased to preserve the current at a constant value. This scenario occurs because of the increase in the Ohmic loss (IR drop), which in turn causes reducing in the oxidation of the anode. Consequently, the increase in the IR drop by increasing the overall distance in between anode and cathode is not recommended practice during the electrocoagulation process. This improves the molecule adsorption. The coagulant and molecule interactions are also weaker when there is a distance above 0.5 cm, which causes a decrease in the removal efficiency.

3.5. Effect of stirring speed

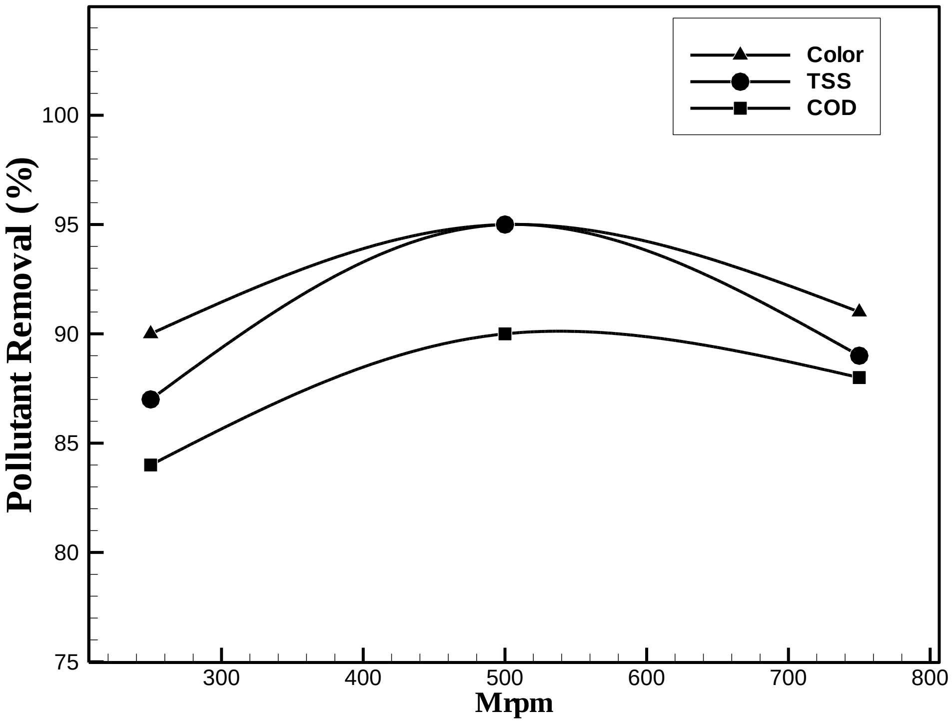


Figure 7. Effect of stirring speed on COD, TSS and color removal efficiency under optimal conditions of EC (Mp Al - Bp Al, I = 0.6 A, RT = 90 min, pH = 6, 0.1kg/m^3 NaCl and IED=0.5 cm).

The stirring mode influences the residual concentrations of the COD, TSS, and color. It has been proven that agitation may improve the kinetics of mass transfer. If coagulant matter does not efficiently disperse within the reactor, the reactor contents are not homogenous and, therefore, display regional differences. If the speed rates are too high, the flocks that are formed within the reactor will be damaged and create smaller flocks that are difficult to extract from the wastewater. As depicted in Figure 7, the largest removal efficiency was shown at 500 rpm, with a COD removal efficiency of 91.3%, TSS of 95%, and color at 95%. A lower level of removal was seen at 250 rpm, with the COD at 84%, the TSS at 87%, and the color at 90%. Increasing the stirring speed from 250 to 500 rpm resulted in the Al $(OH)_3$ flocks attaching to each other, thereby precipitating more easily. When the stirring speed was raised from 500 to 750 rpm, the COD removal efficiency dropped to 87%, TSS to 89%, and color to 91%. At this speed, the amount of flocks decreased, and the adsorbed pollutants were again desorbed, leading to a decrease in the overall removal efficiency. As a summary, the impact of stirring speed was studied for the range of 250 to 750 rpm. The results obtained in this work collaborated with prior published research [22, 38, 39]. The most suitable stirring speed was 500 rpm.

3.6. Compaction of textile wastewater sludge

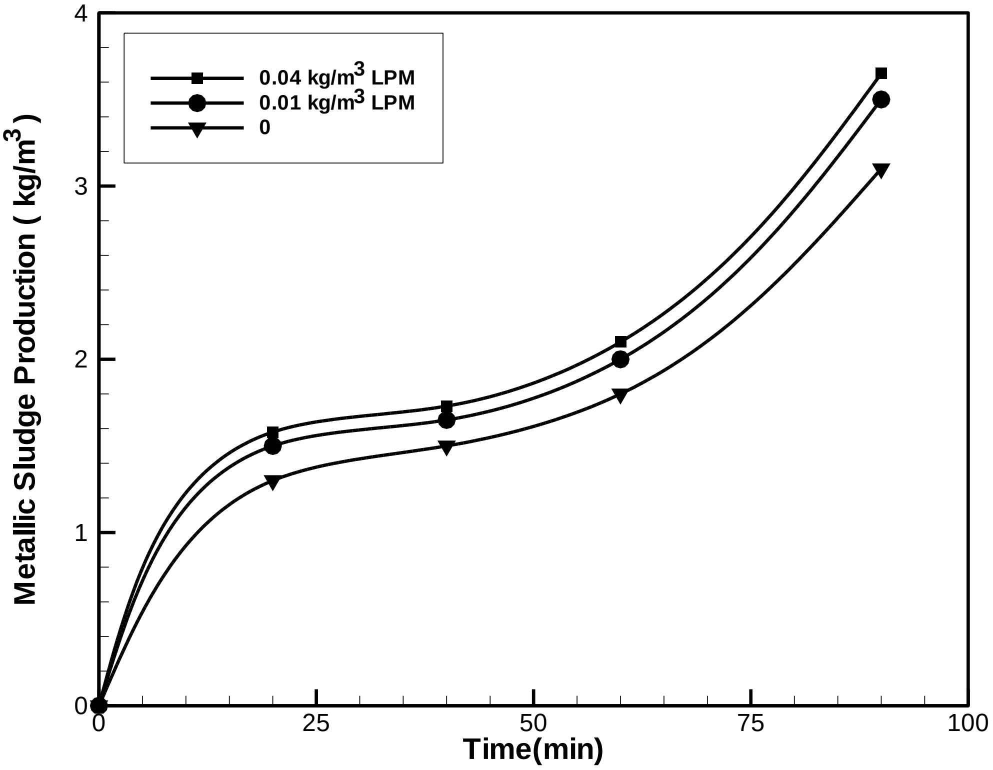


Figure 8. The effect of floculant agent on metallic residues for textile wastewater under optimal conditions of EC (Mp Al - Bp Al, I = 0.6 A, RT = 90 min, pH = 6 , 0.1kg/m^3 NaCl and IED=0.5 cm and M_{rpm}=500).

Compaction of the textile wastewater was conducted with various flocculating agents such as LPM 3135 (0.01 and 0.04 kg/m^3). These were used to enhance the settling of the sludge formed after the EC with optimal conditions (Mp Al-Bp Al; I is 0.6 A; and pH is 6). Asselin et al. [40] showed that the LPM 3135 flocculating agent was the most efficient. The addition of 0.01 kg/m^3 of LPM 3135 caused an increase in COD removal efficiency (from 68.6 to 82.3%), a change in turbidity (from 3 to 7 NTU), and a change in TSS (from 120 to 85 mg/l). Figure 8 shows the profile of electrolysis time and the production of metallic sludge with and without the flocculant agent. The maximum values of metallic sludge after the addition of 0.00, 0.01, and 0.04 kg/m^3 was 3.10, 3.55, and 3.65 kg/m^3, respectively (after 90 min of treatment). The metallic sludge was stable and fixed at a time range between 20 and 40 min. Based on these results, there were no major changes when using a dose over 0.01 kg/m^3.

Sludge dryness and SRF and SVI values were estimated after the EC operation with the use of 0.01 kg/m^3 LPM 3135. The overall sludge dryness was approximately 9%, and the SVI value was noted at 75 ml/g. Olmez [41] used Cr (VI) to treat contaminated industrial effluent with a TSS of 80 mg/l with iron electrodes and calculated an SVI value of 80 ml/g (TSS in textile wastewater in this study was 3280 mg/l). The mean value of the SRF recorded in this work (6.7×10^{12} m/kg) was less than that used by Olmez (7.80×10^{12} m/kg).

3.7. Efficiency and reproducibility of the EC process performance

Table 2. The validation of EC performance under optimal conditions (Mp Al - Bp Al, I = 0.6 A, RT = 90 min, pH=6, NaCI =0.1kg/m^3, IED=0.5 cm, M_{rpm}=500 rpm and LPM 3135 = 0.01 kg/m^3).

Parameter	Raw effluent	Treated effluent	Allowable Limit EPA 1996*	Pollutant Removal (%)
Electrical conductivity (µS/cm)	243	560	ID	-
Initial pH	4.50	6.0	-	-
Final pH	-	7.20	6-8	-
Energy consumption (kw h/m^3)	-	8.49	-	-
Electrode consumption (kg/m^3)	-	0.10	-	-
Sludge production (kg/m^3)	-	3.55	-	-
Polymer consumption (kg/m^3)	-	0.01	-	-
Hydroxide sodium consumption (kg/m^3)	-	1.26	-	-
Sodium chloride consumption (kg/m^3)	-	0.10	-	-
O&G (mg/l)	2.5	0.15	5-40	96.0
BOD_5 (mg/l)	112	13.44	5-45.5	88.0
COD (mg/l)	987	76.00	20-500	92.6
TSS (mg/l)	3280	131.2	60-300	96.4
Color observance at 533 NM	0.3400	0.0153	ID	96.5
TDS (mg/l)	1239	161.1	5-180	87.0
Turbidity (NTU)	392	15.0	15-50	96.0
DO (mg/l)	0.80	12.3	4.5-15	
Sulfate (mg/l)	676	20.28	ID	97.0
Phosphate (mg/l)	7.0	0.35	ID	95.0
Nitrates (mg/l)	10	0.50	ID	95.0
Phenols (mg/l)	348	0.348	10	99.9
Aluminum (mg/l)	1.43	7.80	-	-
Sludge dryness (%)	-	9.10	-	-
SRF (m/kg) * 10^{12}	-	6.80	-	-
SVI (ml/g)	145	75.25	-	-
Electrical energy cost (US\$/m^3)	-	0.636	-	-
Electrode consumption cost (US\$/m^3)	-	0.250	-	-
Sludge disposition cost (US\$/m^3)	-	0.213	-	-
Polymer cost (US\$/m^3)	-	0.030	-	-
Hydroxide sodium cost (US\$/m^3)	-	0.630	-	-
Sodium chloride cost (US\$/m^3)	-	0.005	-	-
Total operating cost (US\$/m^3)	-	1.76	-	-

ID: Insufficient Data

* EPA/625/R-96/004 Sep-1996, VOL-1, Appendices

The EC operation of the textile wastewater was carried out three times to validate the application performance using the optimal conditions (Mp Al-Bp Al, time = 90 min, current = 0.6 A, initial pH = 6, IED = 0.5 cm, M_{rpm} = 500, NaCl = 0.1 kg/m^3, and LPM 3135 = 0.01 kg/m^3). The EC process effectiveness was determined by simultaneously estimating the values of COD, TSS, color, BOD, turbidity, DO, TDS, O&G, and the concentrations of phenols, phosphates, sulfates, nitrates and aluminum in the liquid portion (Table 2). The EC process produces a COD removal efficiency of 92.6%. The concentration of BOD and O&G were 13.44 and 0.15 mg/l, respectively. In 1 L of raw effluent, the values were 112 mg for BOD_5 and 2.5 mg for O&G. The total hydrophobic capacity of the O&G created the most suitable affinity with H_2 bubbles created near the cathode. O&G-H_2 complex gathers and is subsequently skimmed from the liquid surface [42]. Once the turbidity reached 96%, the effluent was transparent and clear. The EC operation also extracted the phosphate: initially, the value prior to the EC operation was approximately 7.0 mg/l. The value dropped to 0.35 mg/l subsequent to the treatment process. In this operation, the dissolved aluminum concentration increased from 1.43 to 7.8 mg/l, and the nitrate concentration dropped (0.5 mg/l).

The overall current efficiency in 100 mg/l was 100% because the aluminum dose was similar to the theoretical dose as computed using Faraday's equation (Eq.9). The final energy intake was 8.49 kWh/m^3 due to a decrease in the primary voltage to 28.3 V as a result of the addition of NaCl. The chemicals used were sodium hydroxide (1.26 kg/m^3), NaCl (0.1 kg/m^3) and polymers (0.01kg/m^3). The quality of the sludge created subsequent to the treatment of EC was 3.55 kg/m^3. These final results show that the overall operating costs for the treatment of 1 m^3 of textile-based wastewater using the optimum operating conditions was approximately 1.76US$.

The results of this study were compared with prior research work that was performed using optimal experimental parameters and conditions. Merzouk et al. [1] studied the treatment of textile wastewater using electroflotation and electro-coagulation in a batch reactor. At optimal conditions (current density = 11.55 mA/cm^2, pH = 7.6 and electrode gap = 1 cm) the following results were achieved: TSS (85.5%), turbidity (76.2%), BOD_5 (88.9%), COD (79.7%) and color (93%). Zongo et al. [9] examined two materials (Fe and Al) for treating textile wastewater and observed a high optimized current over 1 A (100 mA/cm^2). A COD removal efficiency of 74-88% was recorded for both materials. Un and Aytac [43] used a packed-iron bed based electro-chemical reactor for the treatment of textile wastewater with an active area of 675 cm^2 and current intensity of 13.5 A (at 20 mA/cm^2). They achieved a COD removal efficiency of 96.88%. However, the color was almost fully removed within 1 h (in this research, the COD removal efficiency was 92.3% and color was beyond 95% using low current intensity of 0.6 A). Islam et al. [44] demonstrated the treatment of textile wastewater using the EC process under the following conditions: pH=9.5, DO=1.1 mg/l, turbidity=41.5 NTU, aluminum electrodes=11.02 cm^2. Two operational conditions were used: 30 v for 30 min and 40v for 60 min for cell voltage and reaction time, respectively. The following results were obtained: 79% and 76% for turbidity removal, 4.89 mg/l and 5.73 mg/l for DO, 150 mg/l and 400mg/l for aluminum dose, 26.35 kWh/m^3 and 65.78 kWh/m^3 for energy intake, and 2.27 \$/m^{3}and 5.93 \$/m^3 for operational costs (based on the energy and electrode intakes for both cases, respectively). The results of this study showed high turbidity removal (96%), a higher increase in the DO from 0.8 to 12.3 mg/l when using a low dose of aluminum (100 mg/l) and a relatively low energy loss (8.49 kWh/m^3).

Yavuz et al. [45] integrated the EC process with EF using both Fe and Al electrodes for treating dairy wastewater containing 1200 mg/l of COD, turbidity of 320 NTU, and pH of 6.5. The most suitable current intensity was 1.5 A (15 mA/cm^2), and the surface area was 100 cm^2. This generated a COD removal efficiency of 79%. Compared to this study, the initial concentration of the COD and the turbidity were similar. However, the peak current in this study was lower (0.6A), which caused a higher COD removal (up to 92%) and higher turbidity (up to 96%). El-Ashtoukhy et al. [46] studied phenol removal from oil refinery plant wastewater using an electrochemical based reactor that had a stable bed anode with randomly oriented raschig rings (made of aluminum). These rings were organized in a perforated plastic basket and placed over the horizontal cathode. The following optimum conditions were achieved: current density=8.59 mA/cm^2, pH=7, NaCl=1 g/l and temperature=25°C. A high removal efficiency of 80% was observed for phenol after 2 h of reaction time (phenol concentration was 40 mg/l). In this study, the phenol concentration dropped from 348 to 0.348 mg/l (99.9% removal at 90 min).

A comparison with the international textile wastewater quality standards [47, 48] showed that the EC process used in this study could be applied for the treatment of textile wastewater. The analysis and evaluation showed that the TDS, BOD, DO, turbidity, COD, pH, O & G, and phenol were all below the allowable range. The overall SRF, SVI, and sludge dryness were 6.8×10^{12} m/kg, 75.25 ml/g, and 9.1 %, respectively.

3.8. Comparison of EC performance with chemical coagulation

Several experiments were conducted to make a comparison to the overall performance of the EC operation. Some factors included were traditional chemical coagulation under similar conditions of reactor size and operational reaction time. Aluminum sulfate ($Al_2(SO_4)_3.14H_2O$) was used as the chemical coagulant and it was used in a chemical unit of a textile wastewater plant in Babylon, Iraq. A higher level of COD removal efficiency was achieved using aluminum electrodes during the EC operation.

In general, the chemical coagulation operation depends on pH [49]. Therefore, experiments were carried out at different pH levels in the range of 5 to 10, including a pH 4.52 (natural pH). Two concentrations of aluminum sulfate (coagulant) were used: EC (100 mg/l) and those used in a treatment plant (250 mg/l). The solution was allowed to settle for 1 h. The final results are shown in Figure 9. It can be seen that the removal efficiencies of the COD when compared with the EC operation were lower 39.3% versus 49.4%, respectively, for the same dose of EC and chemical unit in treatment plants at pH=10. Table 3 shows the cost analysis comparison between EC and conventional coagulation for both cases of optimal pH levels (6 and 10). It can be observed that the operation cost under optimal removal of COD for EC is lower than that of the traditional treatment with use of two doses (100 mg/l and 250 mg/l).

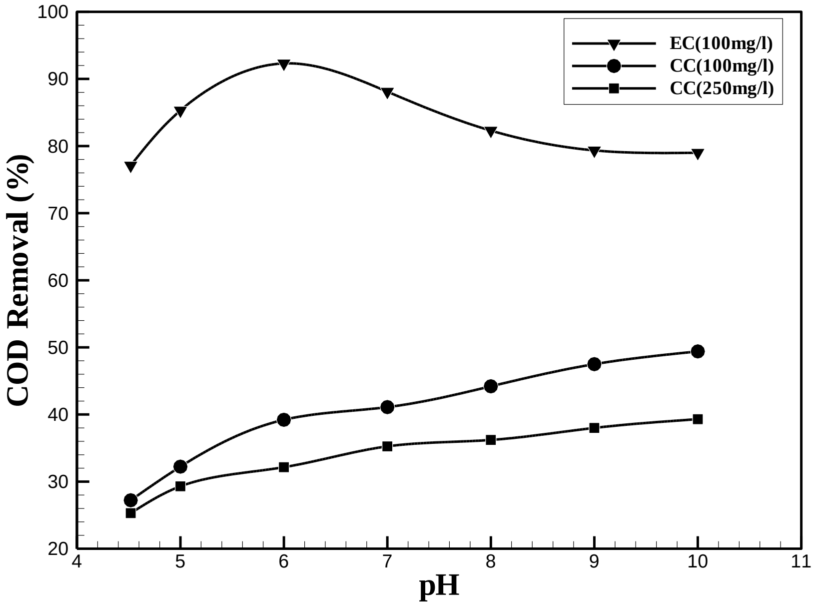


Figure 9. Removal efficiency of COD by EC and chemical coagulation (CC) with variation of pH and dose under similar conditions.

Table 3. Comparison the EC process performance with conventional coagulation at optimal pH (pH=6 and 10) and dose of coagulants for two cases.

Parameter	EC	Conventional coagulation			
Initial pH	6.00	6.00	10.00	6.00	10.00
COD removal (%)	92.60	31.15	39.30	39.21	49.40
Coagulant consumption (kg/m^3)	0.1	0.1	0.1	0.25	0.25
Energy consumption (kw h/m^3)	8.49	-	-	-	-
Sludge production (kg/m^3)	3.55	3.41	3.49	3.48	3.59
Polymer consumption (kg/m^3)	0.01	0.01	0.01	0.01	0.01
Hydroxide sodium consumption (kg/m^3)	1.26	1.50	2.09	1.50	2.09
Sodium chloride consumption (kg/m^3)	0.1	0.1	0.1	0.1	0.1
Aluminum sulfate cost (US$/m^3)	-	0.63	0.63	1.57	1.57
Electrical energy cost (US$/m^3)	0.636	-	-	-	-
Electrode consumption cost (US$/m^3)	0.250	-	-	-	-
Sludge disposition cost (US$/m^3)	0.213	0.204	0.209	0.208	0.215
LPM 3135 Polymer cost (US$/m^3)	0.030	0.030	0.030	0.030	0.030
Hydroxide sodium cost (US$/m^3)	0.630	0.75	1.04	0.75	1.04
Sodium chloride cost (US$/m^3)	0.005	0.005	0.005	0.005	0.005
Total operating cost (US$/m^3)	1.76	1.62	1.91	2.56	2.86

4. CONCLUSIONS

The electrocoagulation process with integrated electrical interconnections showed an efficient treatment for highly polluted textile wastewater. The overall findings of this study could be summarized as follows:

- The Mp Al-Bp Al electrodes were more effective in the removal of pollutants from the textile wastewater compared with the Mp Al-Bp Fe complex.
- The EC with aluminum electrodes and a 90 min reaction time was influenced by the current intensity (I), initial pH, chemical support, inter-electrode distance (IED) and the mixing string speed (M_{rpm}). The most suitable conditions achieved were: I = 0.6 A, pH = 6, NaCl = 0.1 kg/m^3, IED =0.5 cm and M_{rpm} = 500.
- Using these optimal conditions, the pollutant removal efficiencies during the treatment of textile wastewater were: 92.6% (COD), 96.4% (TSS), 96.5% (color), 88% (BOD_5), 87% (TDS), 96% (turbidity), >99% (phenol) and 95% (phosphate). The concentration of DO was enhanced from 0.8 to 12.3 mg/l.
- The main polymer agent, LPM 3135 (0.01 kg/m^3) improved the settling process.
- The total operating cost of the EC process for treating the textile wastewater using these experimental conditions was approximately 1.76US$/$m^3$.
- The performance of EC was higher than the traditional chemical coagulation based on the difference between the removal efficiency of COD and the Al dosage within the pH range.

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