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Treatment of Brewery Wastewater with Electrocoagulation: Improving the Process Performance by Using Alternating Pulse Current

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The main aim of this study is to investigate the technical and economic feasibility of electrocoagulation process on the treatment of brewing industry effluents. Effects of current type on process performance were also stated with a batch operated electrocoagulation reactor including four plate electrodes. Two electrode materials, Fe and Al, were separately employed in parallel connection. A low-moderate strength brewery wastewater was selected as wastewater and model electrolyte solution. Direct current power supply with an adjustable time relay by which rectangular wave was produced was combined with sacrificial electrodes. Performance of the electrocoagulation process was analyzed in terms of operating parameters such as, pH, current density, operating time, electrode material, and current type with removal efficiencies, only some of which were presented in figures and others were given in tables due to the numbers of parameters. Both electrode materials exposed similar pollutant removal performances while Al electrode was found cost effective one. However, alternating pulse current was found superior to direct current, namely, it provided higher removal rates in shorter operating times.

Keywords: Electrocoagulation, Brewery wastewaters, Direct current; Alternating current; Alternating pulse current

1. INTRODUCTION

The brewery industry is one of the industries which consume large volumes of water [1] and typically generates 3–10 L of wastewater per liter of beer production [2]. The wastewater contains a large amount of protein, fat, fiber, carbohydrates, yeast, hops residue, [3] ethanol, VFAs and total suspended solids (TSS) [4]. The main sources of brewery effluent are from the process steps such as bottle filling, cleaning and tank draining [5]. Typical characteristics of the untreated brewery wastewater are shown in Table 1.

Table 1. Typical characteristics of untreated brewery effluent [6].

Parameter	Value
COD (mg/L)	2000–6000
BOD (mg/L)	1200–3600
TSS (mg/L)	200–1000
TN (mg/L)	25–80
TP (mg/L)	10–50
Temperature (°C)	18–40
pH	3–12

The organic constituents in the brewery effluents yield high chemical oxygen demands (CODs) but they are not toxic because much of them in the water consist of sugar, starch, and protein [7]. Moreover, the wastewater usually contains allowable quantities of heavy metals and is easily biodegradable [8]. However, discharging of untreated brewery effluent could cause serious water pollution in both surface and ground water [6] and probable concentration increasing of these pollutants could be serious threat to plants and animals, environment and human beings [2]. Therefore, brewing wastewater with high organic content should not be discharged into sewers and receiving water bodies without any treatment [9, 10]. Besides, due to the high water demands in brewing process, the reuse of the treated brewery wastewater is crucial and the treated wastewater can be alternatively evaluated in cleaning, watering plants, and other various general purposes [11].

There are a lot of brewery wastewater reclamation methods in operation, some of which are utilized as treatment processes while the others are employed as recovery/reuse processes. Both of them are preferred depending on the purpose of the application of treated water and/or its quality requirements [2]. Previously, aerobic methods were being employed to treat brewery industry effluents [12]. However, except their own advantages, these methods consumed high energy and had high expenses of sludge disposal [13]. Currently, the methods employed individually or consecutively in treatment of brewery wastewaters can be classified as microbial fuel cells (MFC) [14]; upflow anaerobic sludge blanket (UASB) [15-17]; MBR [18-20]; food chain predation [21-25]; aerobic hydrolitic process [26-29]; quenched plasma [30]; nanofiltration [4]; reverse osmosis [31]; coagulation-flocculation [32]. Among these processes, conventional separation methods (coagulation, gravity separation) are concluded to be incapable of COD removal and generate secondary pollutants [2]; MBR processes require large scale design and high capital investment [18]; plasma methods are effective, but expensive [2]. However, electrocoagulation (EC) is widely preferred in wastewater treatment because it’s a simple, reliable and cost effective process [33]. Moreover, EC does not required supplementary chemicals and hence does not cause the secondary pollution, high sludge volumes and harmful materials [33-35]. EC utilizes soluble metal (like aluminum and iron) electrodes to form metal hydroxides by using direct current (DC) between immersed metal electrodes in wastewater and these metal hydroxides serve as coagulants and/or adsorbents for removal of inorganic and organic contaminants and pathogens [33].

EC is proposed as an efficient technique when metal hydroxides are used as coagulant, because it provides 100 times greater adsorption capacity on in situ hydroxydes rather than on preprecipitated hydroxides [34]. Moreover, since the ‘electron’ is the main reagent in the electrolytic reactor, additional chemicals are not needed, which minimize the sludge generation at the end of the process. Lack of the additional chemicals also eliminates the detrimental effects of reagents and chemicals employed in the conventional treatment process. Comparing to the other conventional process, EC generates lower quantity of sludge while it can effectively destabilizes small colloidal particles [36]. A great number of studies have been carried out on the various wastewaters treatment with EC as pretreatment and/or post treatment and successful results were obtained. These wastewaters consist of arsenic [37-40]; dyes [35, 41-45]; bilge water [46, 48]; tannery [49-51]; phenol [52]; oil [53-55]; heavy metals [56-59]; humic substances [60, 61]; pharmaceuticals [62]. Also, EC was employed for the treatment of agro-food industries’ wastewaters similar to brewery effluents containing organic materials. These wastewaters could be classified as distillery [63, 64]; winery [65, 66]; slaughterhouse [67, 68]; yeast [69, 70]; cereal [71]; meat [72]; molasses [73]; potato [74]; dairy [75, 76]; restaurant [77]; yogurt [78]; cheese whey [79]. While there are many studies on food and beverage wastewater treatment with EC, there are relatively scanty number of studies were performed on the treatment of brewing process effluents. Therefore, the aim of the study is to state the technical and economic feasibility of EC method for treatment of COD, TSS, color, turbidity, TP and TN from brewery effluents and evaluate the type of current in the electrolytic reactor after determining the optimum operating parameters.

1.1 Overview of electrocoagulation

EC is a physico-chemical process similar to conventional coagulation but it utilizes electric current to form metal hydroxides. Consumable electrodes such as iron and/or aluminum are employed in electrolytic reactor and metalic ions are produced in-situ and supplied into the wastewater flow. The stages of the process could be divided into three steps: First, sacrificial electrodes form coagulants by electrolytic oxidation; secondly, the coagulants destabilizate the contaminants and thirdly, destabilized contaminants, particulate suspensions and breaking of emulsions are aggregated by multistep reactions: (i) compression of diffuse double layer around the charged species by the interactions of ions generated by oxidation of the sacrificial anode, (ii) charge neutralization of the ionic species present in wastewater by counter ions by which produced the electrochemical dissolution of the sacrificial anode. These counter ions reduce the electrostatic interparticle repulsion to the extent that the van der Waals attraction predominates, thus causing coagulation. A zero net charge results in the process, (iii) floc formation; the floc formed as a result of coagulation creates a sludge blanket that entraps and bridges colloidal particles still remaining in the aqueous medium [36].

In EC process DC power supply is utilized to generate an electric field by which the ion transfer occurred between the active surfaces of the plate electrodes immersed into the electrolytic reactor. However, using DC power supply may lead the formation an impermeable of oxide film on the cathode, which causes the passivation of cathode bringing about an increase of the electrolytic cell resistance and decrease the ionic transfer. This promotes increases the resistance of the electrolytic cell and decreases the ionic transfer productivity between the electrodes. As a consequence, metal dissolution and metal hydroxide formation are both directly and indirectly hindered by mentioned cathode passivation phenomena. The progress of electrodes in EC cell with DC current are schematically shown in Figure. 1. As shown in the figure, deposition on the cathode and continuous expiring of the anode in DC-EC process can be minimized to some extent by the addition of parallel plate sacrificial electrodes in the cell configuration [66] as well as employ alternating current (AC) in the EC process [33, 80]. The usual electrode consumption/dissolution conditions in DC mode could be retarded by using AC instead of DC, which ensures the reasonable electrode life. Besides, AC-EC technology with frequent change of polarity can cause dipole-dipole interactions in a system containing nonspherical charged species due to the fact that the technology do not lead to electrophoretic transport of the charged particles, which may result disrupting the stability of balanced dipolar structures. This is, however, not possible in a DC-EC process [33].

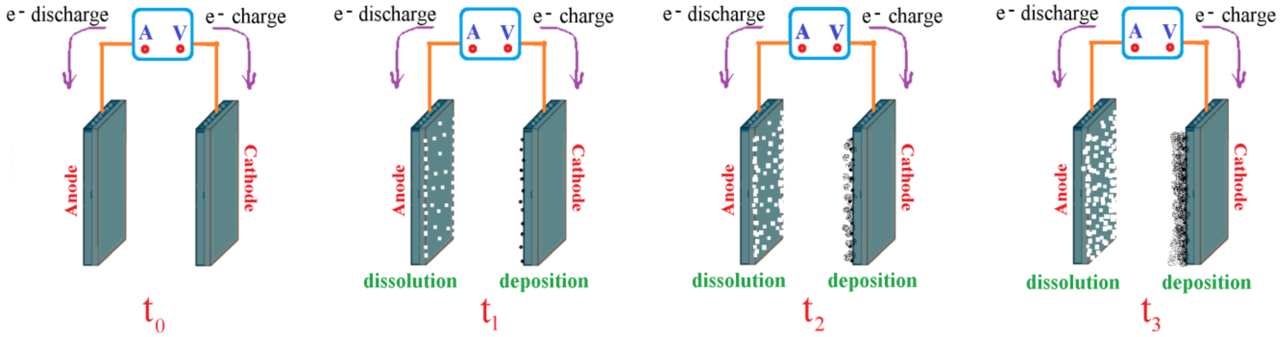

Figure 1. Schema of surface change on sacrificial electrodes in DC-EC process (t_0–t_3 are treatment times of continuous process in order) [66].

To prevent cathode passivation in DC-EC, sacrificial anodes and cathodes can be replaced periodically with each other, however, the replacement of electrodes in terms of polarity changing cannot be practically feasible for continuous operations [66]. Instead, AC power supply can be used for such a polarization operation. Similar to AC-EC technology, the alternating pulse current (APC) technology was proposed for the first time by Mao et al. [81] by using AC power supply. However, Eyvaz et al. [82] produced quasi alternating current, rectangular wave, by an adjustable time-relay integrated with already existing DC power supply for the first time in EC applications. In subsequent studies, Keshmirizadeh et al [83], Pi et al [84], Özyonar and Karagozoglu [85], Xuhui et al [86] and Yang et al [87] applied pulse current method and obtained remarkable results. Although there are many researches about EC process on the treatment of synthetic or real industrial wastewaters, very few researches have been conducted on the technical and economical applicability of AC-EC technology for the treatment of brewery effluents. Therefore, in this study, the effects of current type on EC performance employing both Fe and Al electrodes separately were investigated. A DC power supply and combining of the DC power supply with an adjustable time relay were utilized to obtain DC and APC, respectively.

2. MATERIAL AND METHOD

2.1 Brewery wastewater characteristics

The wastewater used in this work was taken from brewery factory generating approximately 2700 m^3 of wastewater per day. The characteristics of the wastewater are presented in Table 2.

Table 2. Characteristics of the brewery wastewater used in this study

Parameter	Value
pH	6.9±0.4
COD (mg/L)	3440 ± 180
BOD_5 (mg/L)	2165 ± 90
TSS (mg/L)	1180 ± 57
Turbidity (NTU)	1612 ± 103
Color (Pt-Co)	4850 ± 248
Conductivity (µS/cm)	3260 ± 135
TN (mg/L)	73±7
TP (mg/L)	21±5

2.2. Description of EC setup

A plexiglass tank with dimensions of 130 × 130 × 120 mm was used as EC reactor. It was operated in batch mode and four Al or Fe electrodes with 143 cm^2 of total effective area were used separately and the gap between the electrodes was 20 mm. The electrodes were connected to a digital DC power supply (Maksimel, Ankara, Turkey) in monopolar parallel (MP-P) mode. This mode was preferred in this study because a lower potential difference is required at similar constant currents comparing with serial connection modes. MP-P EC reactor is schematically shown in Figure. 2.

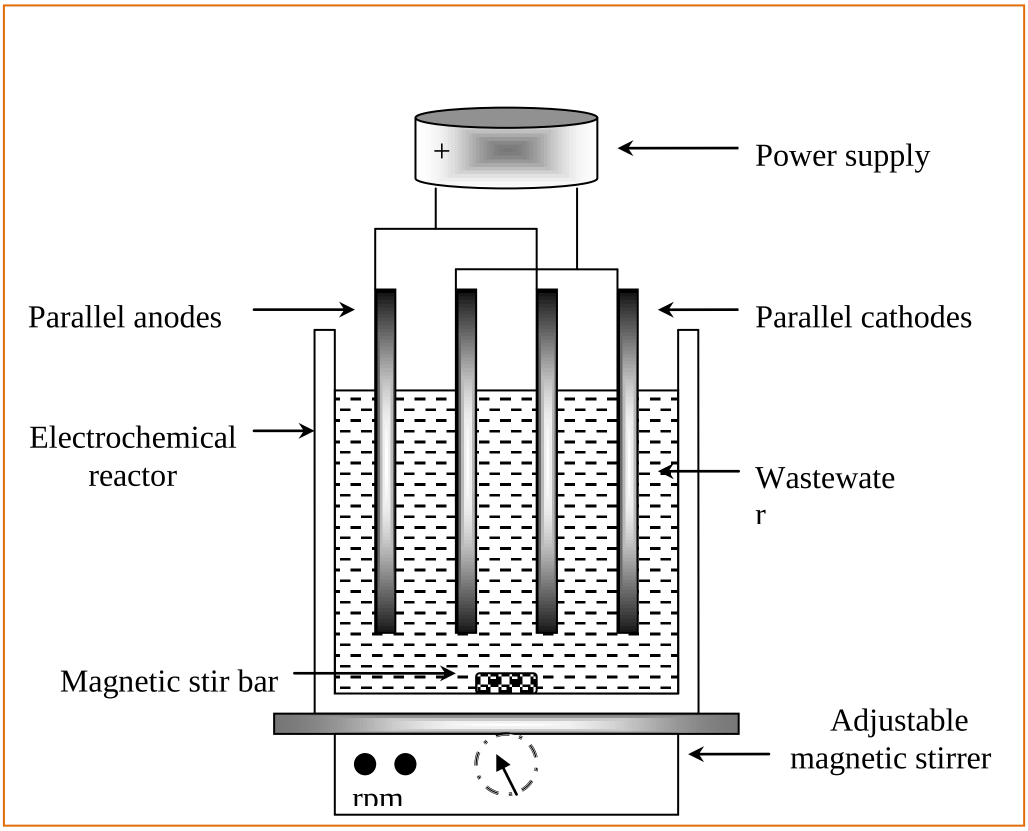

Figure 2. Schematic illustration of EC reactor used in the study [42].

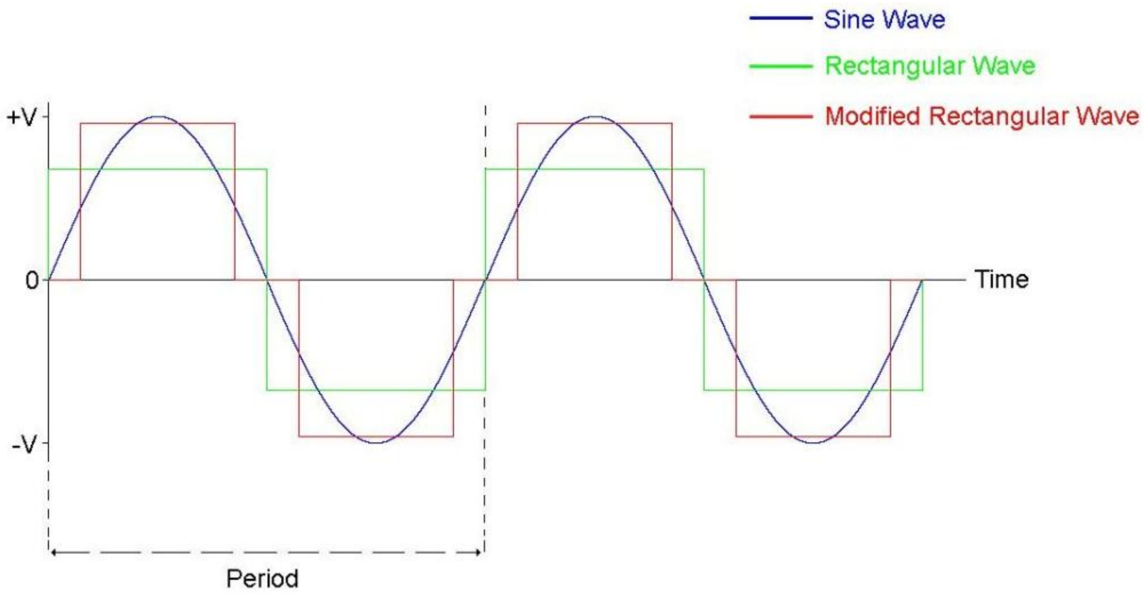

Figure 3. Schematic display of current waves of AC and APC systems [66].

Electrodes polarity was changed by an adjustable time relay (3RP1525-1BW30 Siemens Sirius Time Relay 20>240VAc/Dc) for conducting APC experiments. Turn on and turn off modes of the time relay converts anode to cathode and vice versa in a certain period and rectangular wave is obtained. This wave and pure AC (sine) wave are schematically shown in Figure 3.

2.3 Experimental procedure

In each run, 1500 ml of brewery wastewater was placed into the EC reactor and the wastewater was stirred by a magnetic stirring (250 rpm, Velp Are) to provide a homogenous solution in the reactor. Conductivity of the wastewater itself was used and no supported electrolyte was added and the conductivity of wastewater was measured with a multi meter (Hach Lange HQ40d-Düsseldorf, Germany). The initial pH was adjusted to a desired value using NaOH (Merck-Darmstadt, Germany) or H_2SO_4 (Merck-Darmstadt, Germany) before each run and the pH of the wastewater was determined by using the same multi meter mentioned before. The current related the desired current density was also fixed to the required value at the beginning of the each experiment. EC was operated in batch mode and after each run, electrode surfaces were removed by dipping for 1 min in a solution prepared by mixing 100 cm^3 HCl solution (36.5%) and 200 cm^3 of hexamethylenetetramine aqueous solution (2.80%) [41] and washed thoroughly with demineralized water to remove any solid residues on the surfaces, dried and re-weighted. Electrocoagulated wastewater was filtered through a filter paper (Whatman 40 ashless-NJ, USA) after each run and then filtrate was analyzed. Sludge amounts of each specific operating condition were calculated by weighting the dried solid residue on the filter paper. Each experiment was conducted in three replications to calculate the mean value and standard deviations. Economic data used for the evaluation of the total operating costs are given for the first quarter of 2016, Turkey market, in Table 3.

Table 3. Economic factors used in the total operating cost calculations.

Item	Cost
Maintenance and depreciation ($/$m^3$)	0.07
Electricity ($/kWh)	0.15
Labor costs ($/$m^3$)	0.2
Aluminium electrode ($/kg)	1.23
Iron electrode ($/kg)	0.95
Chemicals (acid, base, etc) ($/$m^3$)	0.05
Sludge disposal cost ($/kg)	0.015

All analytical measurements were performed according to the procedure of Standard Methods (2005) and pollutant removal efficiencies were calculated as follows:

$$\%\ Removal\ efficiency = \frac{C_0 - C}{C_0} \times 100 \qquad (1)$$

where C is COD, color, turbidity, TSS, TP or TN value of treated aqueous solution (mg/L, Pt-Co or NTU) and C_0 is the initial relating concentrations (mg/L, Pt-Co or NTU).

Energy and electrode consumptions which are the main components of the operating cost were calculated as follows:

$$C_{energy}(kWh/m^3) = \frac{V \times i \times t}{v} \quad (2)$$

$$C_{electrode}(kg/m^3) = \frac{Mw \times i \times t}{Fzv} \quad (3)$$

where *V* is the average cell voltage (volt), *i* is the current applied (ampere), *t* is the electrolysis time (hour) and *v* is the volume electrolyte solution (wastewater) in the EC reactor (m^3), *Mw* is the molecular weight, 55.86 and 26.98 g/mol for Fe and Al electrodes, respectively. *F* is Faraday constant (96485 C/mol) and *z* is the number of electrons involved in the process (2 for Fe and 3 for Al).

3. RESULTS AND DISCUSSION

There are many of operational parameters affecting the performance of the EC process, which can be mainly sorted as solution pH, current density, conductivity of the (water/wastewater) solution, electrolysis time as well as electrode spesifications such as arrangement, shape, gap between the electrodes, etc. [66]. Specific effects of each parameters on process performance can be found elsewhere in the literature. In this study, however, the main parameters such as pH of the brewery wastewater, current density, electrolysis time and especially power supply type (DC or ACP) were investigated.

3.1. Effects of initial pH

The initial pH of the solution highly affects the performance of the EC process [34]. When iron electrode is used as anode in an EC reactor, it produces iron hydroxide, Fe(OH)n where n = 2 or 3 [88]. Metal hydroxide was produced by two mechanisms when iron electrodes are used [89]:

Mechanism I:

Anode: $2Fe \rightarrow 2Fe^{2+} + 4e^-$ (4)

$2Fe^{2+} + 5H_2O + 1/2O_2 \rightarrow 2Fe(OH)_{3(s)} + 4H^+$ (5)

Cathode: $4H_2O + 2e^- \rightarrow 4OH^- + 2H_{2(g)}$ (6)

Overall reaction: $2Fe + 5H_2O + 1/2O_2 \rightarrow 2Fe(OH)_{3(s)} + 4H_{2(g)}$ (7)

Mechanism II:

Anode: $Fe \rightarrow Fe^{2+} + 2e^{-}$ (8)
$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_{2(s)}$ (9)
Cathode: $2H_2O + 2e^{-} \rightarrow H_2 + 2OH^{-}$ (10)
Overall reaction: $Fe + 2H_2O \rightarrow Fe(OH)_{2(s)} + H_{2(g)}$ (11)

In the iron case, the best pH range is 6-8 for the optimum floc formation for good removal efficiencies [42].

While aluminium electrodes are considered, the main reactions are as follows [74, 90]:

Anode: $Al \rightarrow Al^{3+} + 3e^{-}$ (12)
$2H_2O \rightarrow O_{2(g)} + 4H+ + 4e^{-}$ (13)
Cathode: $3H_2O + 3e^{-} \rightarrow 3OH^{-} + 3/2\ H_{2(g)}$ (14)
$2Al + 6H_2O + 2OH- \rightarrow 2Al(OH)^{-4} + 3\ H_{2(g)}$ (15)
Overall reaction: $Al^{3+} + 3H_2O \rightarrow Al(OH)_{3(s)} + 3H^{+}$ (16)

In the aluminum case, $Al(OH)_3$ and polymeric $Al(OH)_3$ species are playing major role on the pollutant removal at pH range between 4 and 6.5, by which the precipitation mechanism occurs at this pHs. However that adsorption mechanism is effective at pH > 6.5 on the removal of pollutants is proposed [91]. Eleven pH values (4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5 and 9) were selected to investigate the optimum pH at which maximum removal efficiencies, minimum electrode and energy consumptions were observed for both of the Fe and Al electrodes. Current density and operating time were adjusted as 300 A/m^2 and 30 minutes, respectively. The effects of initial pH on COD, turbidity and color removals are featured in Figure. 4.

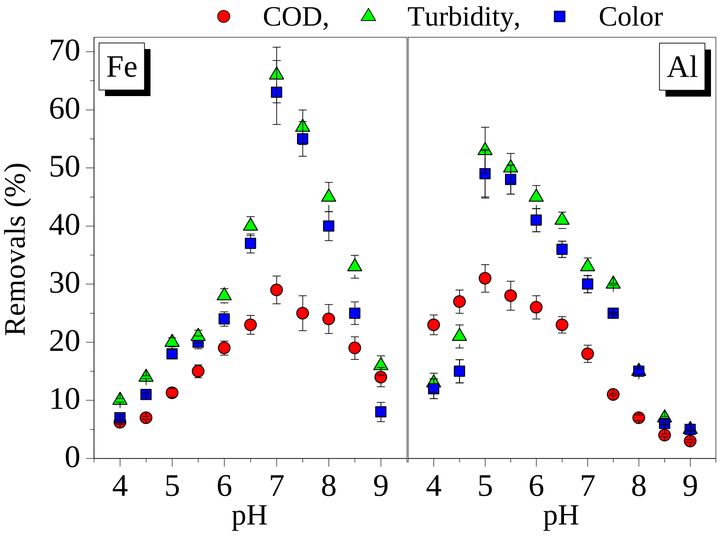

Figure 4. Effects of initial pH on removal efficiencies for Fe and Al electrodes (CD: 60 A/m^2; operating time: 7.5 min).

As seen from Figure 4, removal performances of the both electrode materials were almost similar. COD, turbidity and color removal efficiencies strongly depends on the initial pH of the wastewater (electrolytic solution) because at optimum pH where the metal hydroxide flocs occurs, destabilization and aggregation of the suspended particles via these flocs arises. The highest removal efficiencies were observed at pHs 7 and 5 for Fe and Al eletrodes, respectively. Maximum 29% of COD was removed with Fe electrodes, while Al could removed 31 % of COD from the brewery effluent. Fe was found superior to Al in view of turbidity and color removals, which were obtained as 66 and 63 % and 53 and 49 % for Fe and Al, respectively. At these pH values, it may be concluded that anodic dissolution primarily produced the metal ions which destabilized the colloidal particles. The metal ions also reacted with organic pollutions and removed them by adsorption or co-precipitation based on pH value while they were precipitating in the form of hydroxides [41, 71].

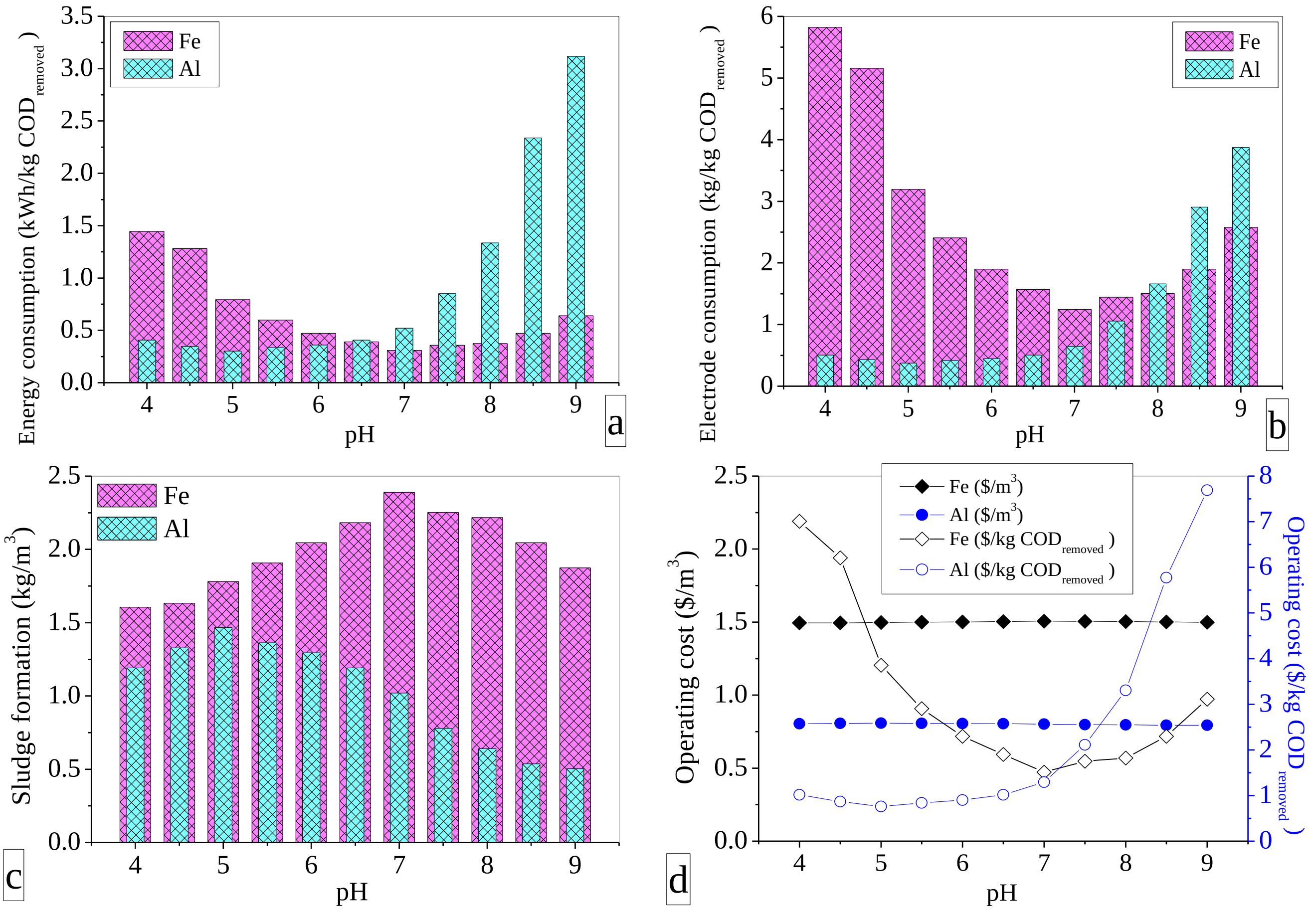

Figure 5. Effects of initial pH on (a) energy consumption, (b) electrode consumption, (c) sludge formation, (d) operating cost for Fe and Al electrodes (CD: 60 A/m^2; operating time: 7.5 min).

Energy, electrode consumptions, sludge formation and operating cost variations at different pHs are shown in Figure 5. In pH experiments, current density was constant (60 A/m^2), therefore the main factors affecting the trends of these parameters are removal ratios. Minimum energy consumptions were obtained as 0.30 and 0.31 kWh/kg COD$_{removed}$ for Fe and Al electrodes at pHs 7 and 5 where the maximum removal percentages were achieved. Similarly these values were 1.24 kg Fe and 0.37 kg Al per kg of $COD_{removed}$. Depending maximum removal efficiencies and minimum consumptions and costs, pHs 7 and 5 were chosen as the appropriate pH value for the following runs.

3.2. Effects of current density

Magnitude of current density primarily determines the amount of metal ions released from the electrodes and the rate of metal hydroxide formation [92]. Current density also directly affects the rate and size of the bubble production and the growth of flocs [93]. Therefore, current density should be carefully optimized to obtain maximum performance of the EC process. In current density experiments all the runs were applied at pHs 7 and 5 for Fe and Al electrodes, respectively with 60 min of electrolysis time. Nine current densities ranging between 30-300 A/m^2 were selected to examine the current density effects. Figure 6 denotes the effects of current density on COD, turbidity and color removals.

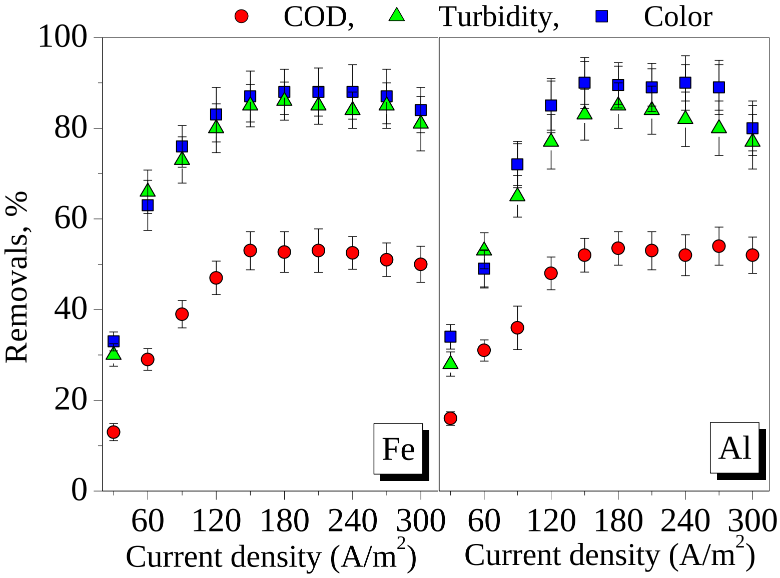

Figure 6. Effects of current density on removal efficiencies for Fe and Al electrodes (pH: 7 for Fe, 5 for Al; operating time: 7.5 min).

According to Figure 6, the removal ratios reach maximum at 150 A/m^2 and stay constant or slightly decrease at above 150 A/m^2. Hydroxide flocs formation was enhanced by higher current densities, which promoted the removal efficiencies by coagulation, however, increase of current density yielded high energy consumption. At current densities above 150 A/m^2 passivation took place on the surface of the cathode which indirectly decelerated and ceased the anode dissolution material as well as floc formation and removal efficiencies. At this current density removal rates for Fe and Al, respectively were 53 and 52 % of COD; 85 and 83 % of turbidity and 87 and 90 % of color removal.

Energy and electrode consumptions, sludge formation and operating cost highly depend on current density and each of these parameters exhibits an increasing trend with increase of current density as expected (Figure 7). 150 A/m^2 was preferred as the appropriate current density value for the following operating time experiments since this was the lowest current density have revealed both higher removal performance and minimum consumptions.

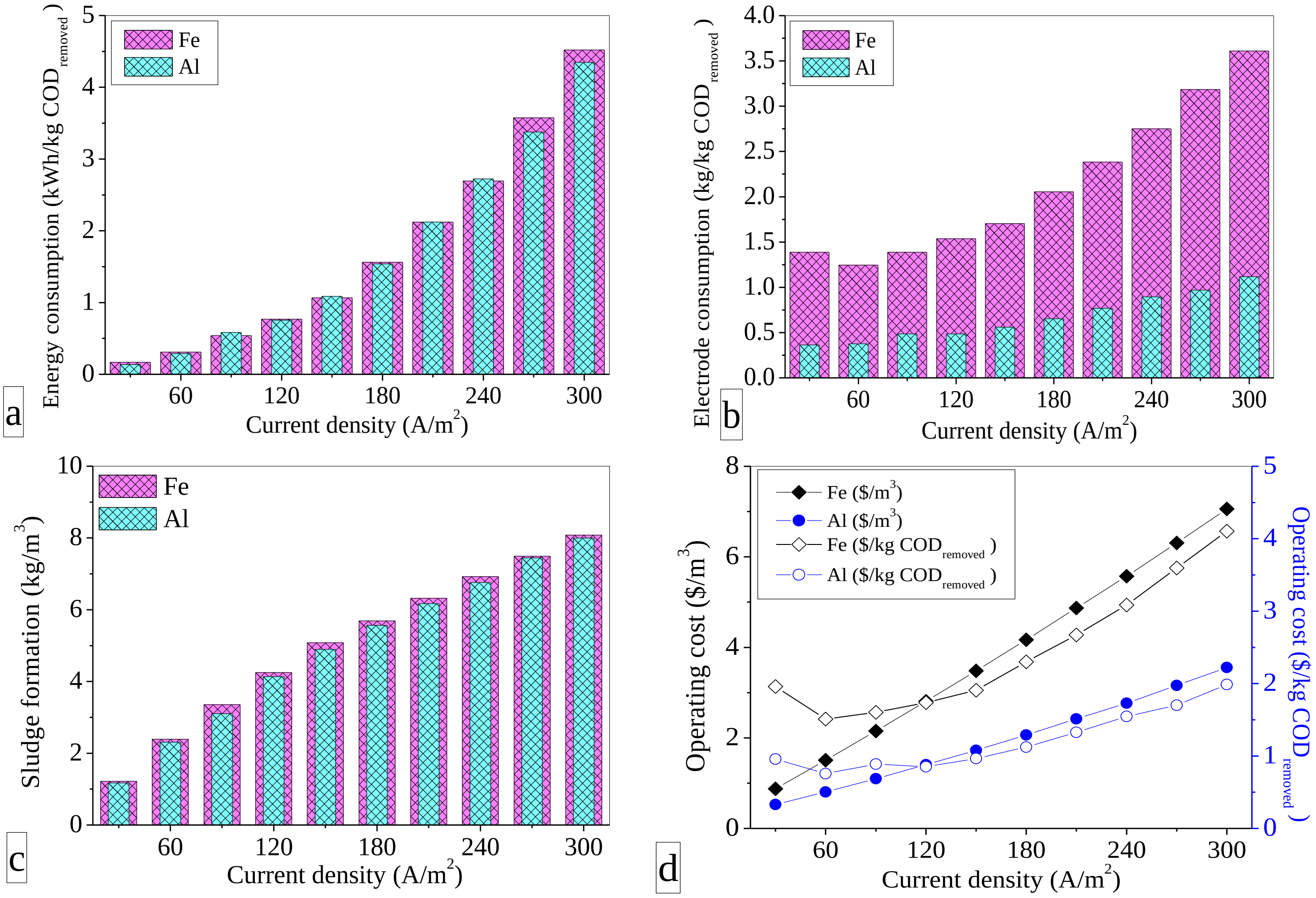

Figure 7. Effects of current density on (a) energy consumption, (b) electrode consumption, (c) sludge formation, (d) operating cost for Fe and Al electrodes (pH: 7 for Fe, 5 for Al; operating time: 7.5 min).

3.3. Effects of operating time

Similar to current density effects on electrode dissolution, reasonable electrolysis duration should be provided to ensure adequate current applied to the sacrificial electrodes where the metal ions released by the dissolution to form metal hydroxide species in the EC reactor. To investigate the effects of operating time on the EC, optimum parameters obtained from the former pH and current density experiments were used: pHs 7 and 5 for Al and Fe, respectively; 150 A/m^2 of current density. Influence of the operating time on removal efficiencies and the other parameters are presented in Figures 8 and 9, respectively.

As seen from the Figure 8, minimum 15 min of operating time is needed for reasonable removal performances. Similar to current density experiments, removal ratios for both electrode materials increase until a certain operating time value, then, remain steady or slightly decrease. It may be concluded that at higher operating times instead of the optimum electrolysis time, the pollutant removal efficiency does not increase as sufficient numbers of flocs are already available in the reactor for the removal of the pollutants [36].

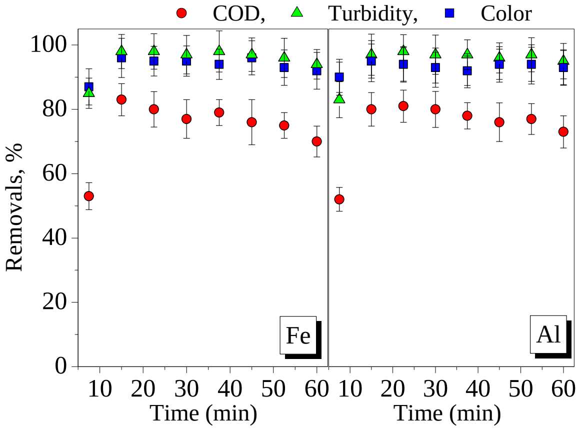

Figure 8. Effects of operating time on removal efficiencies for Fe and Al electrodes (pH: 7 for Fe, 5 for Al; CD: 150 A/m^2).

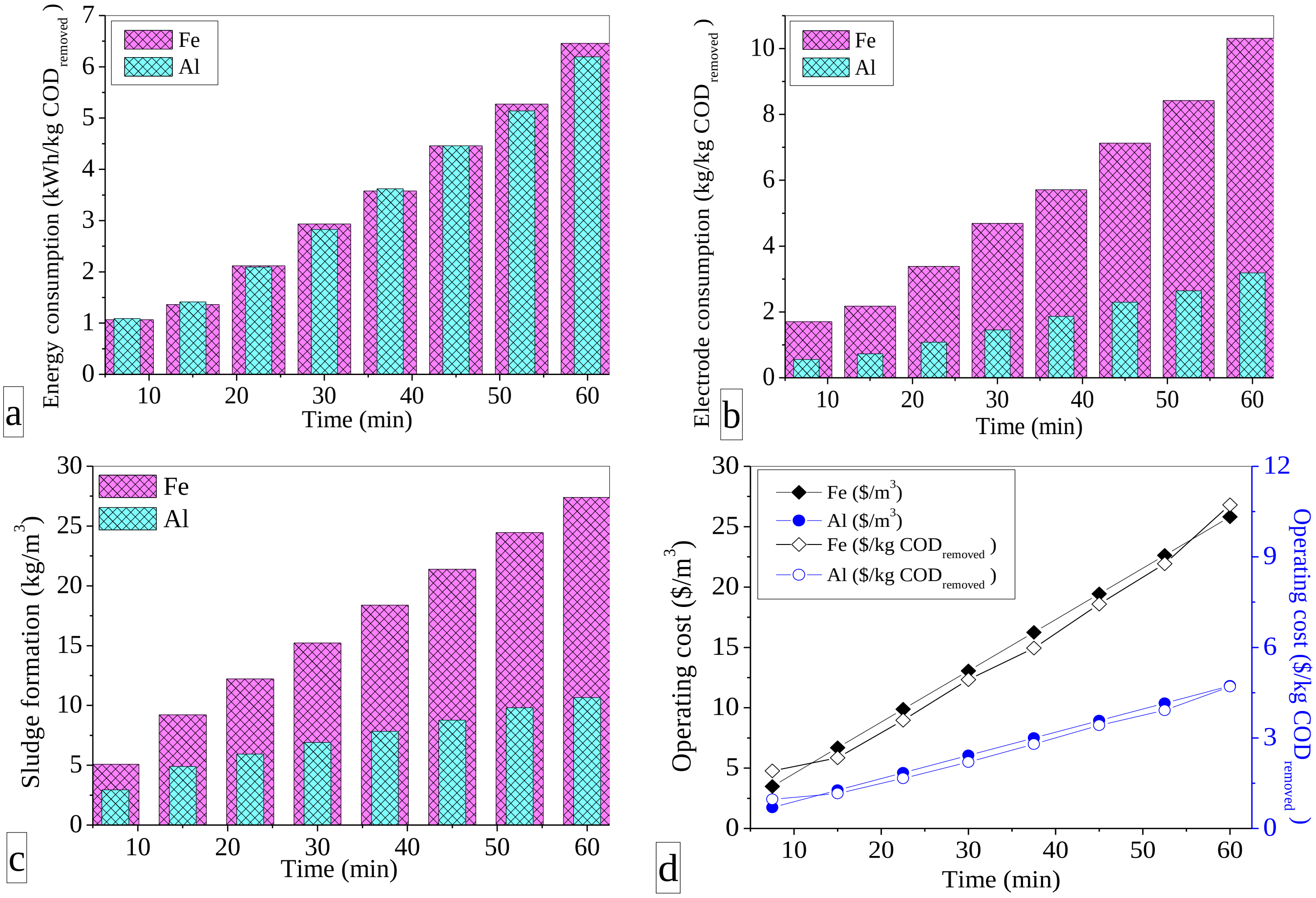

Figure 9. Effects of operating time on (a) energy consumption, (b) electrode consumption, (c) sludge formation, (d) operating cost for Fe and Al electrodes (pH: 7 for Fe, 5 for Al; CD: 150 A/m^2).

It may be also deduced that removal efficiencies do not increase at higher operating times, on the contrary, decrease due to both anodic passivation and cathodic polarization which can hinder the EC performance [82, 94]. The optimum operating time was chosen as 15 min when the maximum removal rates with minimum consumptions had been acquired. Similar to current density experiments, as seen from Figure 9, energy and electrode consumptions are dramatically increase (from about 1 to 7 kWh and from about 0.5-2 to 3-10 kg) with the increase of electrolysis time from 7.5 to 60 min and sludge formation and operating cost increase as well.

3.4 Effects of current type

Generally, DC is used in EC processes but recently some would rather utilize AC in EC unit than DC. [81, 82, 85]. The normal mechanisms of attack on an electrode are retarded and turned into more uniform by the cyclical energization in the case of AC, which ensures longer electrode life [95]. For example, Mao et al. [81] introduced a novel current feed manner in EC for the treatment of synthetic oily wastewater.

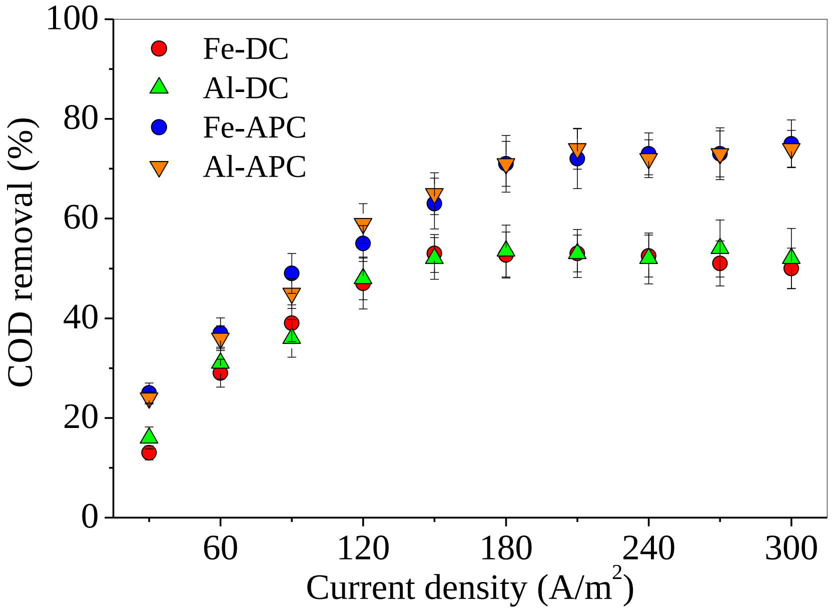

Figure 10. Effects of current type on COD removal for Fe and Al electrodes at different current densities (pH: 7 for Fe, 5 for Al; operating time: 15 min).

They did not observe passivation of Al electrodes and they obtained uniform dissolution of both anode and cathode. Similarly Eyvaz et al [82] used APC current to prevent electrode passivation of Al electrodes in EC treatment of textile dye solutions. They obtained higher removal efficiencies in shorter operation times. Therefore ACP method was investigated in EC of brewery wastewater for possibly improving the conventional (DC) EC performance. For this purpose, former current density and operating time experiments were repeated with adjustable time relay integrated with DC power supply instead of DC power supply alone. Time relay was set to 150 Hz^{-1} to generate polarization between anodes and cathodes at period of 2.5 min. The results are depicted in Figures 10 and 11 for current density and operating time, respectively. As seen in the figures, compared to DC experiments, removal efficiencies were not negatively affected from the higher current densities or operating times where the cathode passivation did not possibly occur in APC-EC case. Moreover, at some experimental conditions removal performances were obtained higher in APC case in comparison with DC case. The results of APC are presented at optimum pHs and optimum CD and operating time from the DC experiments. Overall results are presented in Tables 4 and 5.

Table 4. Comparison of DC and APC in view of current density experiments

Parameter	Fe		Al	
	DC	APC	DC	APC
Initial pH	7	7	5	5
Current density (A/m^2) (selected as optimum)	150	150	150	150
Operating time (min)	7.5	7.5	7.5	7.5
COD removal (%)	53	63	52	65
Color removal (%)	87	96	90	96
Turbidity removal (%)	85	99	83	99
TSS removal (%)	98	99	98	99
TN removal (%)	95	98	95	98
TP removal (%)	97	99	97	99
Energy consumption(kWh/ kg COD removed)	1.07	0.90	1.09	0.87
Electrode consumption (kg Al or Fe/kg COD removed)	1.70	1.43	0.56	0.45
Sludge formation (kg/kg COD removed)	2.79	2.23	1.64	1.31
Operating cost ($/kg COD removed)	1.91	1.57	0.97	0.77
Total operating cost ($/m^3)	3.48	2.87	1.73	1.38

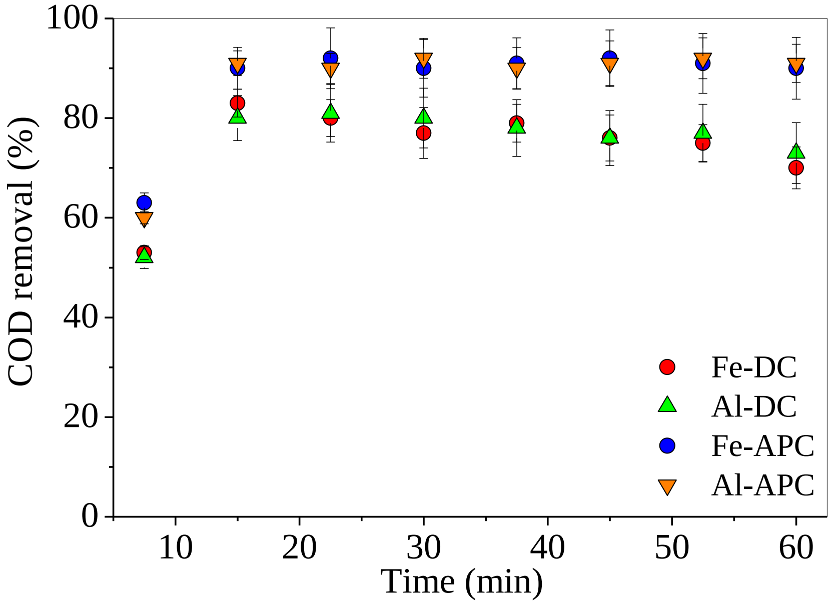

Figure 11. Effects of current type on COD removal for Fe and Al electrodes at different operating times (pH: 7 for Fe, 5 for Al; CD: 150 A/m^2).

Keshmirizadeh et al [83] reported that EC process employing APC was found to be more efficient than the DC mode because it provided lower anode over-voltage and slower anode polarization and passivity, which was yielded more cost effective EC process. They obtained equal removal performances, though. However, in this study, using APC increased the COD, turbidity, TSS and color removals (Tables 4 and 5). These results are consistent with those of Pi et al [84] who concluded that periodic electrode reversal method could effectively postpone the passivation on the cathode, hence it exhibited higher removal rates, lower energy and electrode material consumptions. Besides, the brewery wastewater in this study was compared with various distillery industry effluents treated by different electrochemical processes given in the literature in terms of some operating parameters availably found (Table 6).

Table 5. Comparison of DC and APC in view of operating time experiments

Parameter	Fe		Al	
	DC	APC	DC	APC
Initial pH	7	7	5	5
Current density (A/m^2) (selected as optimum)	150	150	150	150
Operating time (min)	15	15	15	15
COD removal (%)	83	90	80	91
Color removal (%)	96	99	95	99
Turbidity removal (%)	98	99	97	99
TSS removal (%)	99	99	99	99
TN removal (%)	95	98	95	98
TP removal (%)	97	99	97	99
Energy consumption(kWh/ kg COD removed)	1.36	1.25	1.41	1.24
Electrode consumption (kg Al or Fe/kg COD removed)	2.17	2.00	0.72	0.63
Sludge formation (kg/kg COD removed)	3.23	2.98	1.78	1.56
Operating cost ($/kg COD removed)	2.34	2.16	1.16	1.02
Total operating cost ($/m^3)	6.69	6.18	3.18	2.80

Table 6. Comparison of various similar distillery wastewaters treated by electrochemical processes

Wastewater type	Process type	Electrode material type	Current density (A/m^2)	Operating time (min)	COD of influent (mg/L)	COD removal efficiency (%)	Operating cost ($/m^3)	Ref.
Distillery Spent Wash	EC	Al	1870	120	120000	81.3	-	[36]
Alcohol distillery wastewater	EF*	Fe	600	240	4985	92.6	-	[63]
Molasses wastewater	EC (post treatment)	Fe	330	210	4150	50-60	1.5–20 (euro/kg COD removed)	[73]
Distillery effluent	EC with activated	Al-SS or Fe-SS	182	60	~18900	80.1	-	[96]

	Areca catechu nut carbon							
Distillery wastewater	EC (post treatment)	SS	~150	130	9310	61.6	-	[97]
Distillery effluent	EC with ozone	Fe	300	240	2500	83	-	[98]
Distillery spent wash effluent	EC	Fe	1200	120	98400	79 (Available as color removal)	-	[99]
Molasses distillery wastewater	EC with MF*	Al	~140	40	1000-20000 (as diluted)	~85	-	[100]
Distillery industrial effluent	EC with AOP*	Fe	30	240	8500	94	1.5	[101]
Brewery industry effluent	EC	Fe Al	15 15	150 150	3440	90 91	2.87 1.38	This study

* EF: Electro-fenton, MF: Microfiltration, AOP: Advanced oxidation processes

4. CONCLUSIONS

The EC process has gained a considerable interest in the industrial wastewater treatment applications because it is compatible to environment, versatile, efficient in energy use, safe, selective, amenable to automation, and cost effective process. The generality of the researches in the literature have traditionally utilized DC in the EC process. However, the cathode passivation phenomena in the EC reactor possibly lowers the pollutant removal efficiencies and increase the operational costs. Therefore, in this study, APC was employed to increase the performance of traditional EC for the treatment of brewery effluent which is one of the most important pollutant source among the agro-food industries. DC was obtained from a DC power supply while APC was obtained by a time relay device integrated with the existing DC power supply. Aluminium and iron materials were used as sacrificial electrodes separately for the treatment of COD, color, turbidity, TN and TP removal efficiencies. DC and APC were compared both technically and economically by which the calculation of total operation cost included various cost items of both DC and APC systems.

According to the experimental results, both electrode materials exhibited similar removal performances, however, operating cost of Fe electrode was found more expensive than that of Al electrode due to the higher electrode consumption in similar experimental conditions. It was concluded that higher removal efficiencies can be achieved in both same and shorter operation times by employing APC system. In similar current densities, APC provide 20 % more COD removal than DC for both electrode materials. Similarly, APC reach about 50 % faster to DC's COD removal performance, which indicated that polarization of anode–cathode in certain intervals shortens the electrolysis time required for metal hydroxides species for removing the pollutants. Thus, fill-and-draw periods of an EC reactor could be easily increased for batch processes by employing time relay with an already existing DC power supply for removing the passivation of the sacrificial cathode and for decreasing the operating costs for batch EC processes as well. Moreover, the electrodes will not be needed to change occasionally, if the continuous EC system is considered with APC. In this study, turbidity, TSS, color, TN and TP were completely removed while about 90 % of COD removal was achieved with APC system from the relatively low-medium strength brewery effluent. However, for high strength brewery effluents (includes about 20000 mg/L of COD) the EC system used in this study may remain incapable of providing local discharge limits. Based on the promising results of this study, EC can be used as a pre-treatment method and maybe supported by an anaerobic treatment that can remove the high COD concentrations completely. ACP system can be also evaluated for different electrode materials, wastewater types or electrolytic solutions as well as different-strength-brewery wastewaters with possibly other various treatment methods conjointly in further researches.

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