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Investigation of technical and economic analysis of electrocoagulation process for the treatment of great and small cattle slaughterhouse wastewater

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ABSTRACT

In this study, the treatment of slaughterhouse wastewater by electrocoagulation (EC) was investigated in batch reactor using aluminum and iron electrodes. Effects of operating parameters for the EC process such as initial pH solution (3–8), current density (20–140 A/m^2) and operation time of EC (2.5–60 min) were evaluated for optimum operating conditions. The removal efficiencies for COD, oil-grease and turbidity in slaughterhouse wastewaters were obtained to be 78.3, 94.7, and 90.2% for aluminum and 76.7, 92.8, and 95.9% for iron electrodes at the optimum conditions (pH 4, 100 A/m^2, and 20 min EC time for Al; pH 6, 100 A/m^2, and 20 min EC time for Fe). Operation costs for removal of slaughterhouse wastewater at the optimum conditions were calculated for Al electrodes as 2.757 $\$/m^3$ and for Fe electrodes as 0.872 $\$/m^3$. Besides, the treatment performance of EC and chemical coagulation (CC) processes were compared. For CC process, aluminum sulfate, ferric chloride, and ferric sulfate as coagulants were compared. COD, oil-grease, and turbidity removal efficiencies were 36.4, 93.6, and 89.8% for $Al_2(SO_4)_3.18H_2O$ (pH 7–200 mg Al^{3+}/l), 27.6, 88.6, and 85.9% for $FeSO_4.7H_2O$(pH 7–200 mg Fe^{3+}/l), and 37.4, 89.9, and 75.6% $FeCl_3.6H_2O$ (pH 7–100 mg Fe^{3+}/l), respectively. As a result, the EC process is more effective in COD, oil-grease, and turbidity removal efficiencies than CC process.

Keywords: Electrocoagulation; Slaughterhouse wastewater; Iron and aluminum electrodes; COD; Oil-grease; Turbidity

1. Introduction

Slaughterhouses are one of the food industries that produce meat and meat products. Generally, the slaughterhouse wastewaters (SWW) contain high organic matter, fats, suspended solids, nitrogen, phosphorus, oil, proteins, cellulose, and inorganic matters such as phosphates, nitrates, nitrites, and salt [1–6].

The highly pollutant nature of these wastewaters means that they must be treated before being discharged into the sewage system, rivers, lakes, etc. In general, the methods used for treating SWW are physicochemical and biological methods [2,7–11]. Conventional biological wastewater treatments such as aerobic and anaerobic treatment are commonly used

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in order to treat the SWW [4–6]. Aerobic treatment processes are limited by their high energy consumption required for aeration, oxygen transfer capacity and high sludge production. Moreover, the anaerobic treatment of SWW is often slowed down or impaired due to the accumulation of suspended solids and floating fats in the reactor, which leads to a reduction in the methanogenic activity and biomass wash-out [11]. In addition, it is also reported that anaerobic treatment, as a serious disadvantage, is sensitive to high organic loading rates [1,5,12–14]. Both the biological processes require long hydraulic retention and large reactor volumes, high biomass concentration and controlling of sludge loss to avoid the sludge washout.

In recent years, electrochemical treatment methods such as electro-oxidation, electrocoagulation (EC), and electroflotation have attracted increasing attention for the treatment of various types of wastewater. EC has been reported as a primary technique for the treatment of various wastewater by virtue of various benefits, including environmental compatibility, versatility, energy efficiency, safety, selectivity, amenability to automation, and cost-effectiveness [15,16]. Compared with the conventional chemical coagulation (CC), EC has many advantages such as simple equipment, easy operation, a shortened retention time, no chemical additions and rapid settling, and decreased amount of precipitate or sludge.

Several researchers investigated EC process for the treatment of different types of wastewater. The various kinds of wastewater that have been tested successfully by EC are from textile wastewaters [17–21], domestic wastewaters [22], landfill wastewaters [23], restaurant wastewaters [24], wastewaters including arsenic [25], yeast industry wastewaters [26], olive oil wastewaters [27,28], paper-pulp industry wastewaters [29,30], oily wastewaters [31,32], poultry slaughterhouses wastewaters [33], removal of phosphorus [34], and electroplating rinse wastewater [35]. Satisfactory results are obtained especially in the wastewaters including high oil-grease concentrations, organic matters, and suspended solids [24,27,28,31–33]. Despite the impressive amount of scientific research on the treatment of industrial wastewater by EC, a literature survey has shown that the treatments of SWW by EC process are very few and need further research [33]. The treatment of slaughterhouse wastewater via electrochemical methods is also another interest area. There are a lot of studies in this field, especially EC process was examined [36–38]. Un et al. [37] studied the treatment of cattle slaughterhouse wastewater by EC process. In this study, removal efficiency of chemical oxygen demand (COD) 94.4% by adding 0.75 g/l polyaluminum chloride was obtained using aluminum electrode and in the case of iron electrode, 81.1% COD removal was achieved by adding 9% H_2O_2 [37]. In another study, Bayar et al. [38] investigated the effect of current density and stirring speed in the treatment of poultry slaughterhouse wastewater treatment using EC with aluminum electrodes. According to the results of this study, the aluminum cathode, stirring speed of 150 rpm, initial pH 3, and a current density of 1.0 mA/cm^2 were shown to be the most adequate experimental conditions for PWS removal. Under these conditions, it has been possible to decrease COD of wastewater from about 2,170 mg/l to a less than 300 mg/l within 30 min [38]. These studies were not focused on operation and pollutant parameters and operation cost in detail. So, in this study, operation cost and removal of COD, oil-grease, and turbidity in EC process were investigated in detail. Besides, the effect of chemical dosage and initial pH in the treatment of SWW by CC process was investigated.

EC is a coagulation process which proceeds by in situ generation of coagulants by means of electrical dissolution of electrodes in the course of EC process. Generation of the metallic cations takes place at the anode while H_2 is produced at the cathode simultaneously [25]. The generated gas generally helps the flotation of flocculated particles, so the process is sometimes called electroflocculation [39].

The main reactions that occurred at the electrode are:

$$\text{Anode side: } \mathrm{M} \longrightarrow \mathrm{M}^{3+}_{(aq)} + 3\,\mathrm{e}^- \tag{1}$$

$$\text{Cathode side: } 3\,\mathrm{H_2O} + 3\,\mathrm{e}^- \longrightarrow \frac{3}{2}\mathrm{H_2} + 3\,\mathrm{OH}^- \tag{2}$$

where M is metal (i.e. Fe or Al). While these reactions occur, the sacrificial electrodes may be also be chemically attacked by H^+ ions or OH^- ions in acidic or alkaline media [24,33,40].

M^{3+} and OH^- ions generated via electrode reactions mentioned above will react to form various monomeric and polymeric species in the reaction medium (such as, $Al(OH)^{2+}$, $Al(OH)_2^+$, $Al_2(OH)_2^{4+}$, $Al(OH)_4^-$, monomeric species; $Al_6(OH)_{15}^{3+}$, $Al_7(OH)_{17}^{4+}$, $Al_8(OH)_{20}^{4+}$, $Al_{13}O_4(OH)_{24}^{7+}$, $Al_{13}(OH)_{34}^{5+}$ polymeric species) depending on the pH range of the media. These species will be transformed finally into $Al(OH)_{3(s)}$ via complex precipitation reactions [41,42].

$$\mathrm{M}^{3+}_{(aq)} + 3\,\mathrm{H_2O} \rightarrow \mathrm{M\,(OH)}_{3(s)} + 3\,\mathrm{H}^+_{(aq)} \tag{3}$$

After the adsorption of soluble or colloidal species on to coagulants, removal of the pollutants will be achieved by sedimentation or flotation. Formed amorphous $M(OH)_3$ (i.e. sweep flocs) have a large surface area which is highly beneficial for the rapid adsorption of soluble organic compounds onto floc surface [24,33,43]. These flocs can be polymerized to form $M_n(OH)_{3n}$ after adsorption stage and can be easily removed from aqueous medium by sedimentation and flotation [33,42,43].

The CC process is generally carried out in the following four phases [44];

(1) Addition of the chemical to the wastewater.
(2) Rapid mixing to distribute the chemical homogeneously through the wastewater.
(3) Slow mixing to encourage flocculation.
(4) Filtration, settling, or decanting to remove the flocculated solid particles.

In the coagulation process, metal salts (aluminum and iron sulfates and chlorides) are widely used as coagulants in water and wastewater treatment. pH and coagulant dosage are important parameters in the coagulation process.

The aim of this paper was to study the comparison of the treatment of SWW by EC and CC. The EC process was examined under different values of electrodes material, initial pH, current density, and operation time on removal of COD, turbidity, and oil-grease. The CC process was examined under different values of coagulant dosage and initial pH in order to determine the optimum operating conditions. In addition, the treatment performance by EC and CC were compared for removal efficiencies of the pollutants.

2. Materials and method

2.1. Wastewater source and characteristics

The wastewater used in this study was provided from a slaughterhouse (Sivas, Turkey) having a capacity of 2,400 ton/year great cattle and 4,560 ton/year small cattle. In this facility, approximately 75 m^3 wastewater is produced on a daily basis. Wastewaters from this facility come from three various sources, namely, red wastewater consisting proteins and lipids from slaughtering process, especially wastewater resulting from meat production process and barn cleaning, and the third one, domestic wastewaters from washbasins. In the current disposal system, these wastewaters are collected in a stabilization pond and are discharged to the sewage system without being treated. The wastewater samples used in this study were collected from the downstream of stabilization pond and composite sampling was implemented to cover overall processing steps in the facility. The wastewater was screened to remove hair and solids larger than 1 mm. The characteristics of the wastewater used in the study are given in Table 1.

Table 1
General characteristics of the slaughterhouse wastewater

Parameter	Range
pH	6.72–7.27
COD (mg/l)	3,337–4,150
BOD (mg/l)	1950–2,640
Suspended solids (mg/l)	980–1,200
Oil-grease (mg/l)	275–376
Conductivity (μS/cm)	1,616–2,270
Turbidity (NTU)	265–356

The percentage removal efficiency of COD, turbidity, and oil-grease was calculated using the following equation, Eq. (4).

$$\text{Percentage removal efficiency } (\%) = \left(\frac{(C_0 - C)}{C_0}\right) \times 100 \tag{4}$$

where C_0 is the initial concentration and C is the final concentration of the pollutant (mg/l and NTU).

2.2. EC reactor and operating conditions

In this study, the experimental setup is given schematically in Fig. 1. The thermostated, plexiglass electrocoagulator with the dimensions of 130 mm $(H) \times 100$ mm $(L) \times 100$ mm (W), was equipped with four parallel monopolar electrodes; two anodes and two cathodes with the dimensions of 72 mm $(H) \times$ 48 mm $(L) \times 3$ mm (W) were made of aluminum (99.53%) and iron (99.32%) plates. The total effective electrodes' area was 216 cm^2 and the spacing between the electrodes was 20 mm. The electrodes were connected to DC digital power supply (GPC 6030D; 30 V, 6A) with potentiostatic and galvanostatic operational options.

All runs were performed at constant temperature (25˚C), mixing speed (250 rpm), and with 1,000 ml of wastewater solution. Before each run, the electrodes were washed with acetone to remove surface grease, then the impurities on electrodes' surfaces were removed by dipping for 5 min in a solution freshly

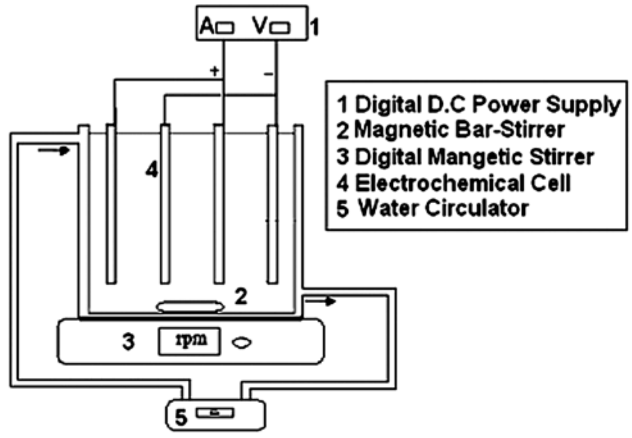


Fig. 1. Schematic diagram of EC process experimental setup.

prepared by mixing 100 ml of HCl solution (35%) and 200 ml of hexamethylenetetramine aqueous solution (2.80%) [33]. After the electrodes had been washed, they were dried for the removal of the residuals on their surfaces and the next step of the experiment was started.

2.3. CC reactor and operating conditions

In CC tests, effects of coagulant dose and pH on wastewater treatment have been examined. For this purpose, coagulation–flocculation tests at room temperature with six jar tests (Velp brand, FC6S model) have been carried out (Fig. 2). For CC, as coagulants, alum and iron salts ($Al_2(SO_4)_3.18H_2O$, $FeSO_4.6H_2O$, $FeCl_3.6H_2O$) have been used. In CC tests, 500 ml of wastewater were taken and pH adjustments done for each coagulant. Then, 5 min fast mix at 200 rpm, 15 min slow mix at 45 rpm were conducted and waited for 60 min for precipitation.

At the end of the EC and CC experiments, the solution was filtered and then, the filtrate was analyzed (COD, oil-grease, and turbidity).

2.4. Analysis

COD, oil-grease content, turbidity, pH, and TSS determinations were carried out by implementing standard analysis methods [45]. The COD of the samples were determined by using a single-beam spectrophotometer (UV-VIS, Chebios, Italy), the turbidity measurements were conducted by turbidity meter (Micro TPI, HF scientific, USA), and the pH and conductivities of samples were measured by means a pH meter (C931, Consort, Belgium) and conductivity meter (340I, WTW, USA), respectively. The pH adjustments were done using concentrated $NaOH/H_2SO_4$ (Merck).

2.5. Operating cost

The operating cost (OC) is one of the most important parameters in the EC process because it affects the application of any method of wastewater treatment. The operating cost includes material (mainly electrodes) cost, electrical energy cost, as well as labor, maintenance, and other costs. The latter cost items are largely independent of the electrode material [31–34]. Thus, in this study, the operating cost was calculated with electrodes and electrical energy costs. So, both energy and electrode consumption costs are taken into account as major cost items. Calculation of operating cost is expressed as:

$$\text{Operating cost (OC)} = a\,\text{Energy}_{\text{consumption}} + b\,\text{Electrode}_{\text{consumption}} \quad (5)$$

where energy consumption and electrode consumption are consumption quantities per m^3 of wastewater

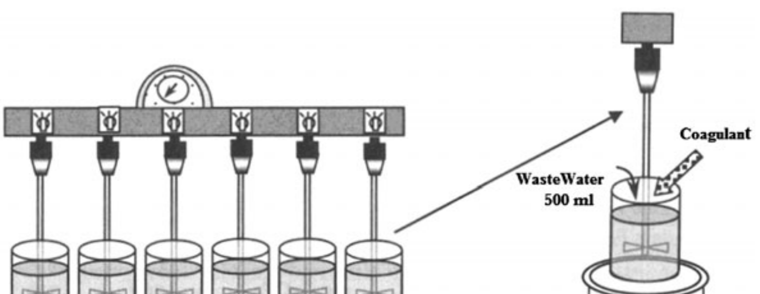


Fig. 2. Schematic diagram of CC process experimental setup.

treated. Unit prices, *a* and *b*, given for the Turkish Market, September 2012, are as follows: electrical energy price 0.06 US $/kWh, electrode material price 1.80 US$/kg for aluminum, and 0.6 US$/kg for iron.

Calculation of energy consumption is expressed as (Eq. (5.)):

$$\text{Energy}_{\text{consumption}} = \frac{(V \times I \times t)}{v} \tag{6}$$

where $\text{Energy}_{\text{consumption}}$ is energy consumption (kWh/m^3), V is voltage (Volt), I is current (Ampere), t is EC time (s), and v is volume of the treated wastewater (m^3), respectively. According to Faradays law, electrode material consumption and charge loading are calculated in the following equations:

$$\frac{\text{Faraday}}{m^3} = \frac{(I \times t)}{(F \times v)} \tag{7}$$

$$\text{Electrode}_{\text{consumption}} = \frac{(I \times t \times M_{\text{w}})}{(z \times F \times v)} \tag{8}$$

where F is Faraday's constant (96,485 C/mol), M_{w} is the molar mass of aluminum and iron (26.98 g/mol for Al and 56 g/mol), and z is the number of electron transfer (z_{Al}:3, z_{Fe}:2), respectively.

3. Results and discussion

This study is mainly focused on the EC of SWW. The efficiency of pollutants removal from wastewaters by EC process depends on several operating parameters, such as the type of electrode material, initial pH, current density, and electrolysis time. In addition to the removal efficiencies of COD, oil-grease, and turbidity as criteria to assess the EC process performance, electrodes, and energy consumptions per cubic meter of wastewater have also been taken into consideration. Both aluminum and iron electrodes are used in the same runs for comparative purpose. Moreover, EC and CC processes were compared for treatment performances.

3.1. *Effect of initial pH on EC process*

pH is an important parameter effecting removal efficiency in the EC process [17,33,46]. To determine the effect of initial pH on the treatment of SWW by EC process, the experiments were conducted at 80 A/m^2 current density and 20 min EC time. For this purpose, initial pH values were adjusted between 3 and 8. According to initial pH values during to EC process, the two electrode materials showed that there were changes between initial and final pH values. As shown in Fig. 3(a) and (b), the final pH values increase was based on the initial pH values. Some investigators have reported that a pH increase occurs during EC when the initial pH is low [24,47]. This can be attributed to OH$^-$ ion accumulation in aqueous solution during the process. In acidic condition, the increase of pH was attributed to hydrogen evolution at cathodes [24,48].

As seen in Fig. 3(a) and (b), the effect of initial pH on COD removal efficiency was given for both the electrodes comparatively. For iron electrodes, high COD removal efficiencies were obtained at pH range 4–6. At pH 6, the highest COD removal efficiency was found to be 72.8%. For aluminum electrode, the highest COD removal efficiency at pH 4 was obtained as 73.5%. Meanwhile, when the experiments at the conditions original SWW pH $\approx$ 7 value were carried out, COD removal efficiency was obtained as 66.5% for iron electrode, and 57.1% for aluminum electrode, respectively.

On the other hand, the highest oil-grease removal efficiencies were obtained at pH:6 for both electrodes (Fig. 3(a) and (b)). These rates were found to be 85.1% for the iron and 88.7% for the aluminum electrode, respectively. Oil-grease removal efficiencies were decreased at lower acidic and higher basic pH values. However, this decrease was not as evident as in the COD removal rate. The minimum removal efficiencies for aluminum and iron electrodes were obtained as 81.4% at pH 3 and 81% at pH 7. Finally, higher oil-grease removal efficiencies of both electrodes materials by EC process were obtained. According to Kobya et al. [33], the removal of oil-grease colloids from wastewater is accomplished according to various complicated mechanisms; in addition to adsorption on or entrapping in metal hydroxides flocks, destabilization by electrical field and electrogenerated Al or Fe salts may also occur and enhance the removal efficiency of EC [33].

The effect of initial pH on the turbidity removal efficiencies is presented in Fig. 3(a) and (b) for iron and aluminum electrodes. The highest turbidity removal efficiency at pH 6 was found to be 87.8%. It is seen that turbidity removal efficiency under and above values of pH 6 was decreased. For aluminum electrode, the highest turbidity removal efficiency was obtained as 96.7% at pH 7.

As seen clearly in Fig. 3(a) and (b), the removal efficiencies of the pollutants decreased in lower and higher pH values. It can be explained that the extent of hydrolysis of M^{3+} depends on the pH. The hydrolysis and polymerization of M^{3+} at a pH range of 5–9 forms mononuclear and/or polynuclear metal com-

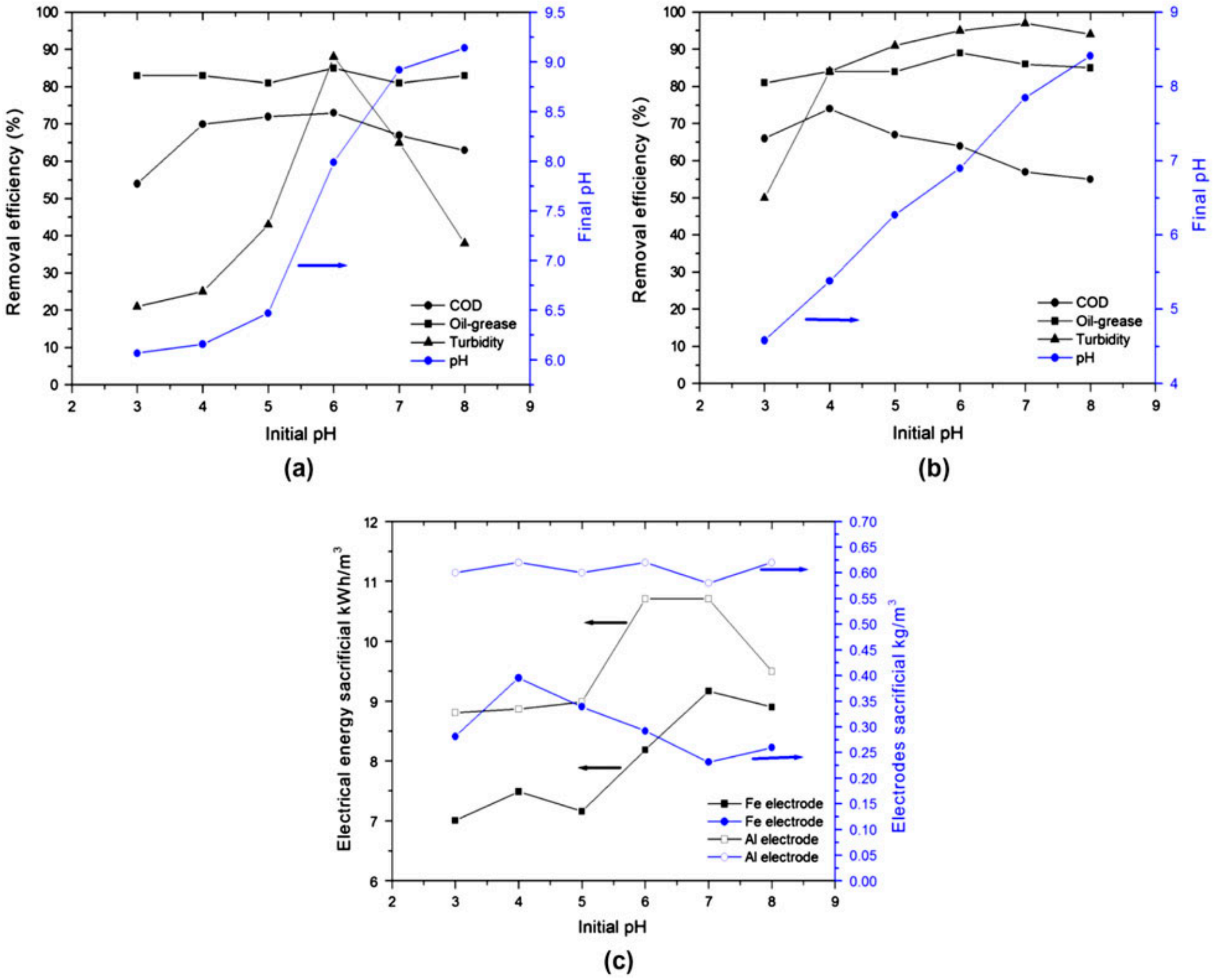


Fig. 3. (a) Effect of initial pH on COD, oil-grease, and turbidity removal for iron electrodes. (b) Effect of initial pH on COD, oil-grease, and turbidity removal for aluminum electrodes. (c) Effect of initial pH on electrical energy and electrode consumptions for iron and aluminum electrodes.

plexes, e.g. $M(OH)_3$, $M(OH)^{2-}$, $M_2(OH)^{4+}$, and $M_{17}(OH)_{32}{}^{7+}$, that are effective coagulants for the pollutants [49]. For both electrodes, in terms of COD, oil-grease, and turbidity, the optimum pH values appeared between 4 and 6. The optimum pH for aluminum and iron electrodes was obtained as pH 4 and pH 6, respectively.

The electric energy consumption was calculated for pH 3–8 as 7.01–89.0 kWh/m^3 for iron and 8.81–9.50 kWh/m^3 for aluminum electrode (Fig. 3(c)). For both electrodes, the electric energy consumption increased with the pH 5–7. It was also observed that aluminum electrode was higher than that of iron electrode. The values of electrode consumptions for iron electrode were 2.14 times higher that of aluminum electrode at pH 3. At acidic pH, the removal of COD for iron electrode was lower than that of aluminum electrode.

As a result, the total electrode consumption depends on electrodes material as well as pH of the medium. At the same current density, both acidic and basic pH values, electrodissolution of iron electrodes is higher than aluminum.

3.2. Effect of current density on the EC process

Current density is another important parameter on pollutant removal efficiency in EC process. Current density influences the metal hydroxide concentration formed and controls the reaction rate during the process. Especially, it is known that the current density determines the coagulant dosage, and bubble production, and hence, affects the growth of flocs [33,50].

Fig. 4(a) and (b) shows the effect of current density on COD, oil-grease, and turbidity removal efficiencies with operating time constant at 20 min and pH 6 for iron electrode, pH 4 for aluminum electrode. The current density varied from 20 to 140 A/m^2 in the EC process. The highest COD removal efficiency at 100 A/m^2 current density was obtained as 76.7% for iron electrode, and 78.3% for aluminum.

In another performance criteria, oil-grease, and turbidity removal efficiencies were 92.9 and 97.2% for iron electrode, at 100 A/m^2 current density. The oil-grease removal by aluminum electrode was 94.7% at 100 A/m^2. Accordingly, turbidity removal efficiency was 90.2% at this current density. It can be concluded that the EC process is an effective method especially for the removal of oil-grease. During the EC process, as a result of the reactions, H_2 gas revealed on the cathode helped the pollutants rise to the surface of water caused by the reactions and they are collected. Moreover, the metal hydroxide forms evolving from the reactions make the suspended solids settle and this situation helps in the removal of turbidity. For these reasons, the removal efficiencies will increase as the current density increases. This phenomenon was observed from the experimental results as higher removal efficiencies are reached at higher current densities. However, from the economical point of view, it would be disadvantageous due to high operational costs.

On the other hand, according to the Faraday Law (Eq. (2)), in terms of electrode material consumption, current density increment will increase the amount of metal ions etched from the corresponding electrode. As a result of this fact, an increment in electrode material consumption for both electrode types was observed. The relationship between current density and electrode material consumption was linear for iron electrodes while it was nonlinear in case of aluminum electrodes due to chemical attack by H^+ (Fig. 4(c)). The electrode consumption was calculated for current density 20–140 140 A/m^2 as 0.152–1.084 kg Fe/m^3 for iron and 0.088–0.698 kg Fe/m^3 for aluminum electrodes, respectively.

The total operation cost increased with increasing current density and operating time in the EC process because energy and electrode consumptions were related to these parameters. OC at 20–140 A/m^2 changed from 0.101 to 1.639 \$/m^3 for iron electrode and from 0.197 to 2.757 \$/m^3 for aluminum electrode. The OC for removal efficiencies of COD, oil-grease, and turbidity at the optimum conditions (pH 6, 100 A/m^2 and 20 min for Fe and and pH 4, 100 A/m^2 and 20 min for Al) were calculated as 0.872 \$/m^3 for iron electrode and as 1.645 \$/m^3 for aluminum electrode, respectively.

3.3. *Effect of operation time on the EC process*

Operation time is an important parameter which is influential on the EC process. As the formation and amount of metal hydroxides, which play an important role in the removal of pollutants, is time dependent, operation time is an effective parameter on COD, oil-grease, and turbidity removal efficiencies. In order to determine the effect of operation time on the efficiencies of COD, oil-grease, and turbidity removal by EC process, the experiments at optimum conditions (i.e. for iron electrode: current density is 100 A/m^2 and optimum pH is 6; for aluminum electrode: current density is 100 A/m^2 and optimum pH is 4) were carried out. Effect of operation time on performance of EC process was investigated between 2.5 and 60 min.

For the EC process, if sufficient operation time is not provided due to dissolved electrode material and coagulants that is produced by the ions, it will yield a hard-to-filter sludge. In our experiments, the sludge formed in 2.5 to 10 min of EC process was difficult to filter and time consuming. Also in these time ranges, there were some disadvantageous results in particular, low removal efficiencies and filtering problems. These problems may come into existence due to insufficient formation of metal hydroxides at low-operating times.

As seen in Fig. 5(a) and (b), the removal efficiencies of COD increased in 2.5–60 min from 17.46 to 76.7% for iron electrode and from 47.6 to 78.3% for aluminum electrode. The removal efficiencies for COD did not change much after operating time of 20 min for both electrodes. This may be cathode reduction and formation of new electrocoagulant flocks.

Oil-grease removal efficiency as another performance parameter was also investigated in the process of EC. The highest oil-grease removal efficiency was obtained in 30 min as 94.9% with iron electrode. By the way, in 20 min of operation, this efficiency was 92.8%. This efficiency improvement for the cost of 10 min may be negligible. A similar situation was observed with aluminum electrodes. In 30 min of operation time, the removal efficiency was 94.9%, while it was 94.7% in 20 min. Therefore, by taking operational costs into consideration, 20 min of EC time is ideal for oil-grease removal.

When another important performance parameter, turbidity removal efficiency was investigated, the highest removal efficiency was 98.1% for iron electrode in 60 min. However, in 20 min this removal efficiency was 95.9%, which is very close to the highest removal efficiency. Accordingly, for aluminum

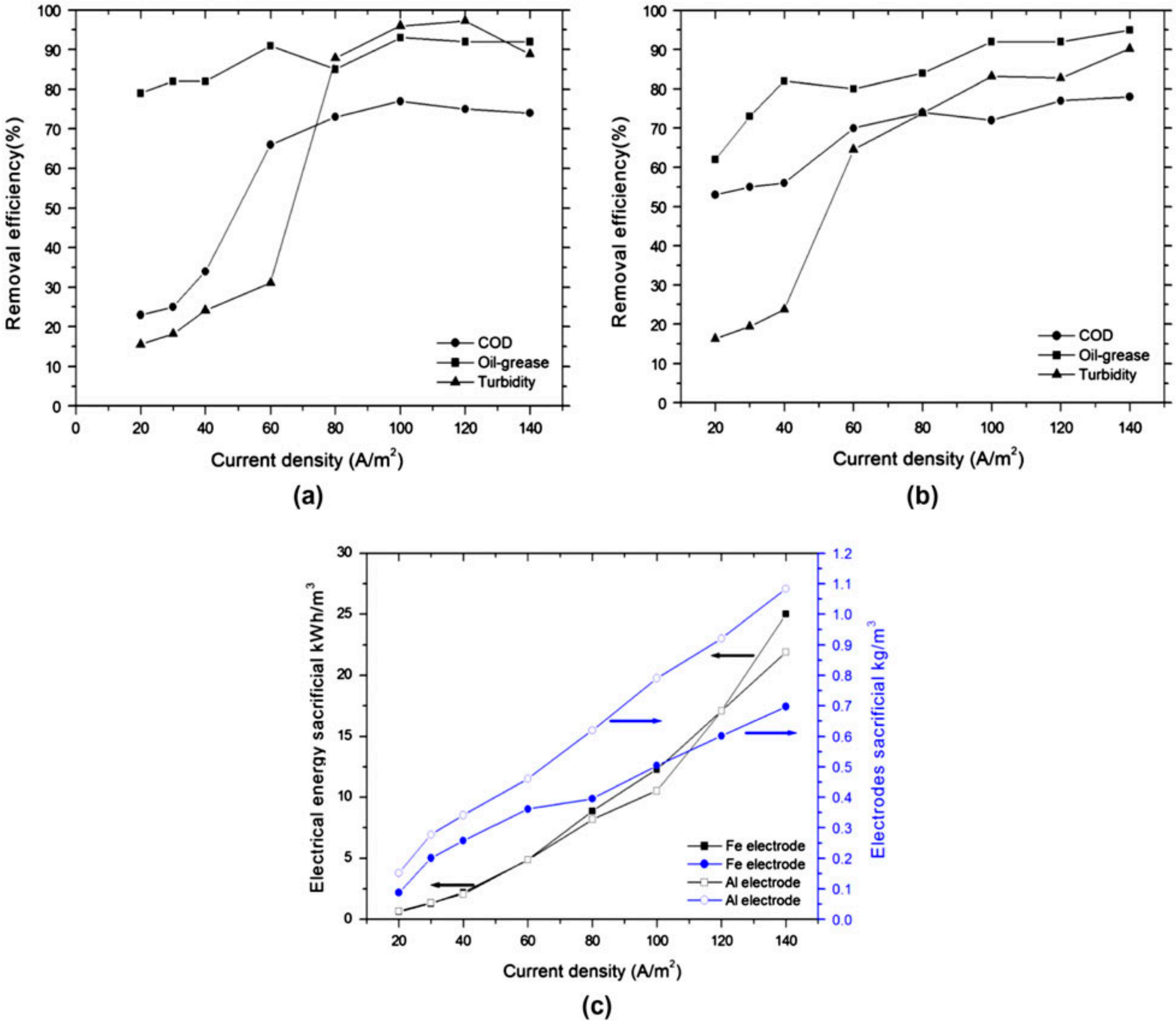


Fig. 4. (a) Effect of current density on COD, oil-grease, and turbidity removal for iron electrodes (b) Effect of current density on COD, oil-grease, and turbidity removal for aluminum electrodes. (c) Effect of current density on electrical energy and electrode consumptions for iron and aluminum electrodes.

electrode, the maximum turbidity removal efficiency was 99.6% in 60 min (also 90.2% in 20 min.).

In Table 2, the operation costs of SWW for aluminum and iron electrodes at different EC operation time were shown. It is also seen that EC operation time directly influences the consumption of both energy and electrode. They increase with the increase in the EC time (Fig. 5(c)). The EC time increasing from 2.5 to 60 min causes an increase in energy consumption from 2.85 to 78.78 kWh /m^3 and an increase in electrode consumption from 0.024 to 1.585 kg Al/m^3. For iron electrode, the EC time increasing from 2.5 to 60 min causes an increase in the energy consumption from 1.37 to 40 kWh /m^3 and an increase in the electrode consumption from 0.165 to 2.261 kg Fe/m^3. It is clear that the EC time is a very important parameter for the EC process because it affects the economic applicability in the treatment of the SWW. Table 2 shows that the operating cost changed with the increase of EC time. When the EC time was changed from 2.5–60 min, the operating cost was determined as 0.214–7.583 \$/m^3 for Al and as 0.132–3.08 \$/m^3. The optimum operating time for both electrodes in the EC process was selected as 20 min.

3.4. Effect of initial pH on CC process

The effect of initial pH in the treatment of slaughterhouse wastewater by CC process was investigated. For this purpose, experiments were conducted by

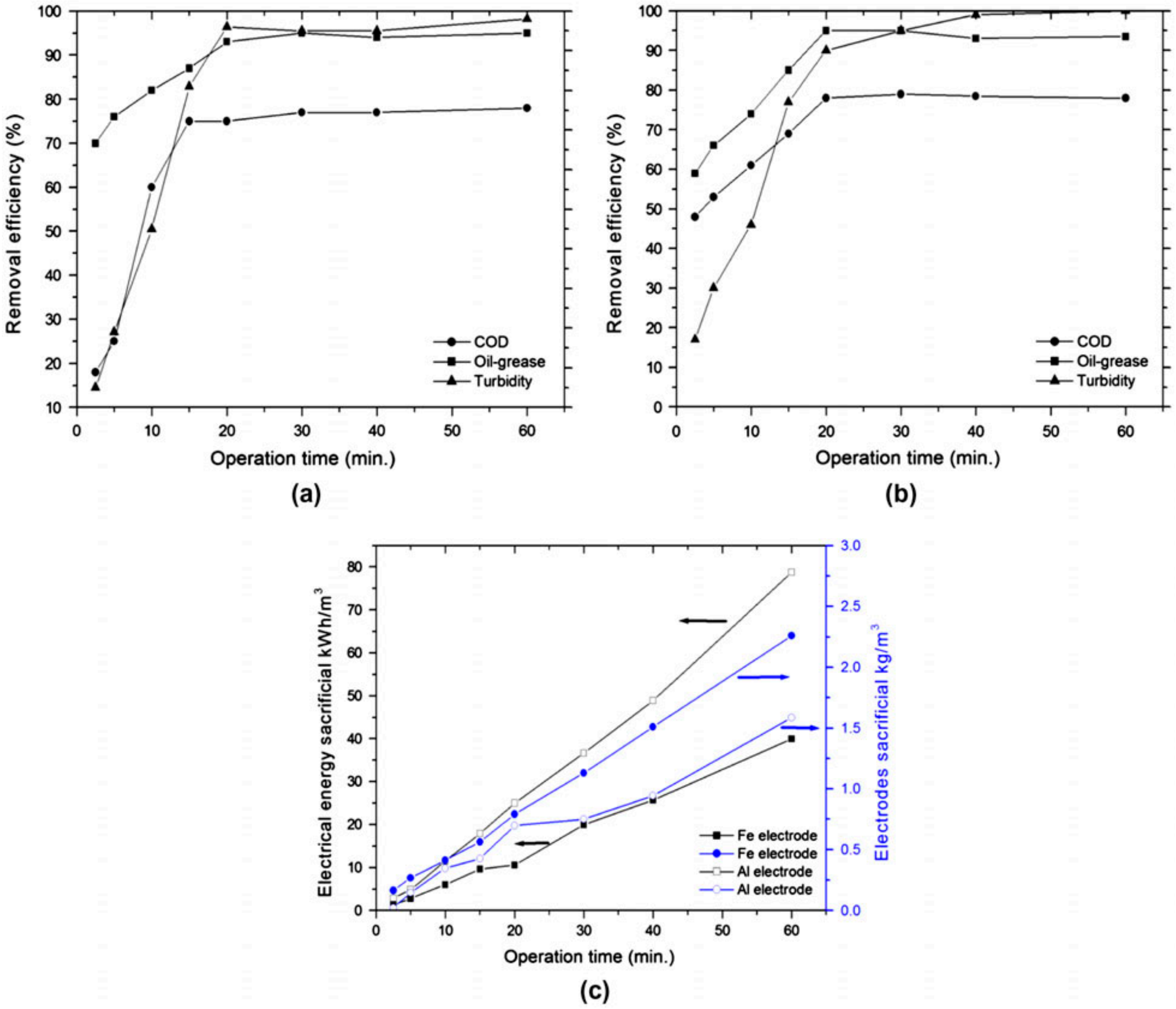


Fig. 5. (a) Effect of operation time on COD, oil-grease, and turbidity removal for iron electrodes. (b) Effect of operation time on COD, oil-grease, and turbidity removal aluminum electrodes. (c) Effect of operation time on electrical energy and electrode consumptions for iron and aluminum electrodes.

choosing some constant initial conditions. For each coagulant, constant coagulant doses of 200 mg Fe^{3+}/l and 200 mg Al^{3+}/l were taken. For speed mix 5 min at 200 rpm and for slow mix 15 min at 45 rpm mixing speeds were chosen, and also 60 min for precipitating time was accepted as constant conditions. In order to investigate the effects of initial pH, the pH values of wastewater were applied between 3 and 8 and removal efficiencies of COD, oil-grease, and turbidity for this range were examined.

Effect of pH in CC on% COD, oil-grease, and turbidity removals is given in Fig. 6(a–c).

When COD removal efficiency of $Al_2(SO_4)_3.18H_2O$ coagulant was examined, the pH increased with increasing removal efficiency. This increase turns to a decrease after a pH value of 7. It has been observed that maximum COD removal efficiency 36.4% was achieved with a pH of 7. Also, for a pH value of 7, oil-grease removal efficiency reported was 93.6%. Maximum turbidity removal of 90.5% occurs when pH is 5. As a result, the most suitable pH value, as it was also close to the pH of wastewater, was obtained as 7.

In the coagulation tests with the coagulant $FeSO_4.7H_2O$, maximum COD removal 27.7% was obtained when pH was 7. Also, oil-grease removal maximum value reached 88.5% when pH was 7. When turbidity was examined, again, maximum value of 85.9% was reached when pH was 7. As a result, for all the three parameters, the maximum removal values were

Table 2
Experimental results for Al and Fe electrodes at different EC operation time

Operating time (min)	Al electrode (pH 4, 100 A/m^2)								Fe electrode (pH 6, 100 A/m^2)							
	Removal efficiency (%)			pH$_f$	Elec. energy consumption (kWh/m^3)	Electrode consumption (kg/m^3)	Operation cost ($/m^3)	($/kg COD)	Removal efficiency (%)			pH	Elec. energy consumption (kWh/m^3)	Electrode consumption (kg/m^3)	Operation cost ($/m^3)	($/kg COD)
	COD	Oil-grease	Turbidity						COD	Oil-grease	Turbidity					
2.5	47.6	59.2	17.2	4.68	2.85	0.024	0.214	0.134	17.4	75.7	5.4	7.01	1.37	0,165	0.132	0.22
5	53.1	63.0	27.9	4.85	4.93	0.146	0.559	0.315	25	86.3	18.9	6.95	2.79	0,268	0.247	0.288
10	61.1	65.7	35.7	4.85	11.51	0.346	1.313	0.641	59.8	82.4	33.8	7.36	6.05	0,412	0.487	0.237
15	68.6	66.8	76.6	4.90	17.88	0.424	1.837	0.801	74.5	85.2	81	7.92	9.64	0,562	0.749	0.292
20	78.3	94.7	90.2	5.34	25.02	0.697	2.757	0.985	76.7	92.8	95.9	8.56	10.53	0,790	0.872	0.319
30	78.9	94.8	94.8	7.79	36.66	0.749	3.55	1.373	76.7	94.9	94.6	8.92	19.95	1,131	1.537	0.584
40	68.3	81.6	99.2	8.33	48.88	0.942	4.626	2.034	77.1	89.9	92.5	8.67	25.7	1,509	1.995	0.754
60	77.9	84.5	99.6	8.63	78.78	1.585	7.583	2.917	76.7	88	98.1	8.92	40	2,261	3.08	1.17

obtained at pH values of 7. For this reason, the optimum pH range was accepted as 7 for $FeSO_4.7H_2O$.

The highest COD removal efficiency with $FeCl_3.6H_2O$ coagulant was 26.44% for both pH values 6 and 7, there were no main differences for these pH values. The highest oil-grease removal efficiency with a value of 89.9% was obtained when the pH was 6. When turbidity results were examined, the maximum removal efficiency was determined as 91.2% for a pH value of 7. When results were evaluated, the optimum pH value for this coagulant was decided to be 6. As a result, for $Al_2(SO_4)_3.18H_2O$ and $FeSO_4.7H_2O$, the optimum pH value was 7, whereas for $FeCl_3.6H_2O$, the optimum pH value was taken as 6. But for all the three coagulant materials, when COD removal efficiency was considered, it is seen that not much removal was done but high values for oil-grease and turbidity removal were reached.

3.5. Effect of coagulation dose on CC process

In CC process, one of the important parameters is the coagulant dosage. Satisfying the necessary amount of metal hydroxide effective in the removal of pollutants is only possible by the optimum coagulant amount. In CC process, in order to determine the effect of coagulant dose, tests with pH values that were determined as optimum in pH tests were conducted. The effects of coagulant dosage on COD, oil-grease, and turbidity removals in CC process were examined. The results obtained are shown graphically in Fig. 7.

When coagulant dose effects on COD removal in CC were examined, the max COD removal efficiency using $FeCl_3.6H_2O$ coagulant was obtained as 37.3%, which was reached for 100 mg Fe^{3+}/l dose. With $Al_2(SO_4)_3.18H_2O$ coagulant at 200 mg Al^{3+}/l dose, the highest COD removal efficiency was 36.9% and turbidity was 89.8%, whereas this removal efficiency

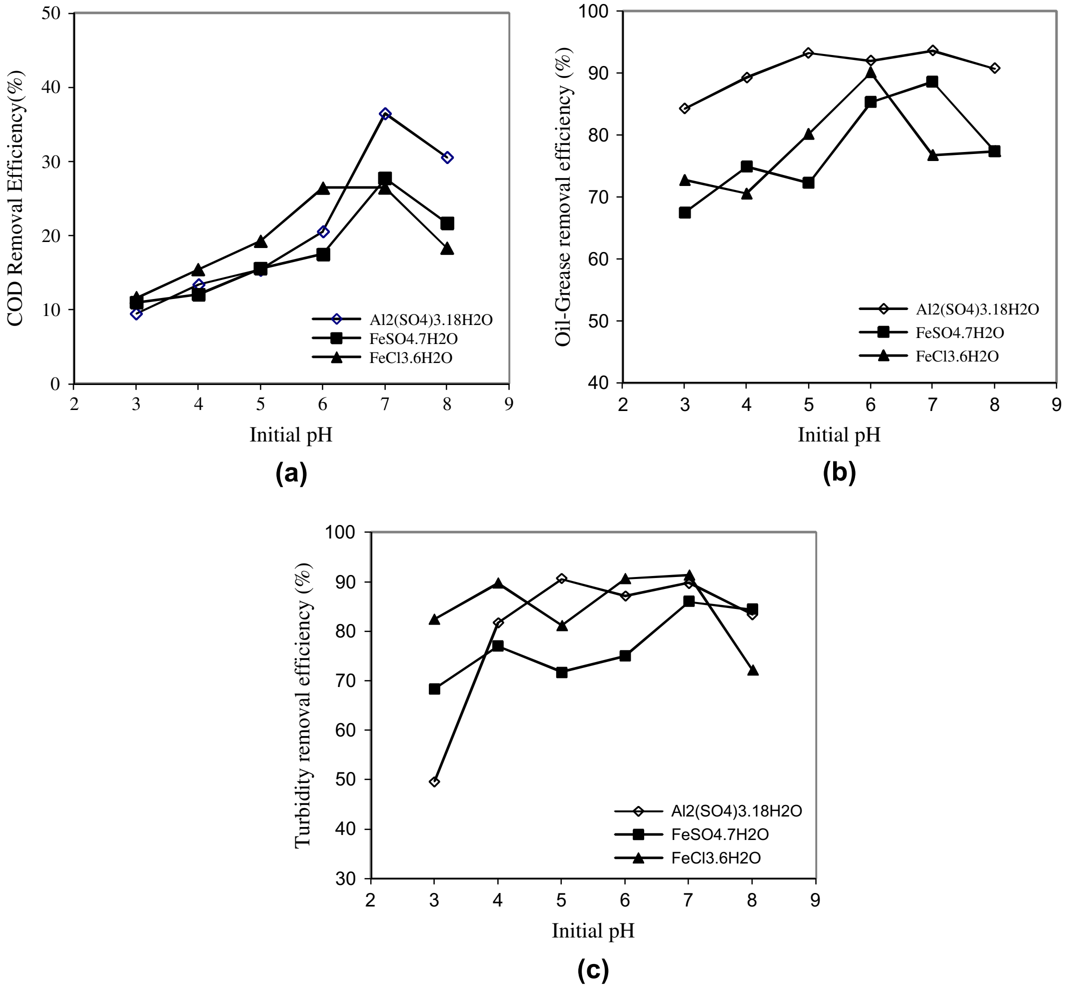
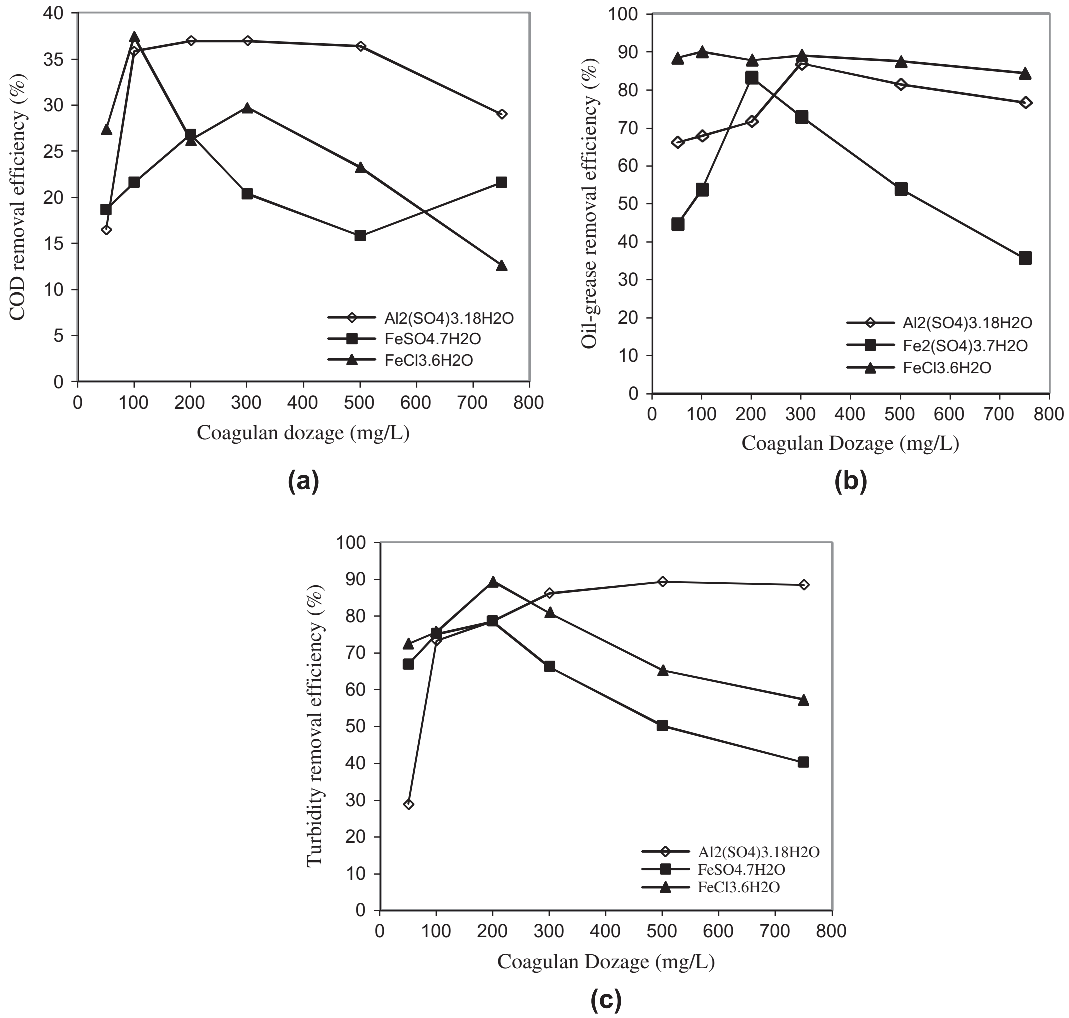


Fig. 6. Effect of initial pH on removals of (a) COD, (b) oil-grease, and (c) turbidity in CC.

was 93.6% for oil-grease. In the tests where $Fe_2(SO_4)_3.7H_2O$ coagulant was used, at 200 mg Fe^{3+}/l dose, for both turbidity (85.9%) and oil-grease (88.6%), high removal efficiencies were obtained. COD removal efficiency was at low values. This is because the removal of dissolved materials as a result of CC process was low.

3.6. Comparison of EC and CC processes

The comparison between EC and CC was conducted by removal of efficiencies. In the optimum operation conditions, EC is a more effective process for COD, turbidity, and oil-grease removal efficiencies than CC process. Fig. 8 shows the comparison between removal efficiencies of pollutants by EC and CC process. 78.3% COD removal efficiencies in the EC process using aluminum electrode was obtained. In case of iron electrode, COD removal efficiency was 76.7%. For CC process, when $Al_2(SO_4)_3.18H_2O$, $Fe_2(SO_4)_3.7H_2O$ and $FeCl_3.6H_2O$ coagulants were used, COD removal efficiencies was obtained as 36.4, 27.6, and 37.3%, respectively. Removal efficiencies of other pollutant parameters by EC process were also seen higher than CC process. Although optimum operation conditions were in the EC and CC process, the removal efficiencies of pollutants between each treatment process were quite different. So chemical coagulation process was not effective for treatment SWW as EC process. The fundamental physical separation process and mechanism of coagulant delivery are different for CC and EC. $M(OH)_3$ flocs resulting from EC process react with various forms of monomeric and polymeric species. Freshly formed amorphous $M(OH)_3$ (sweep flocs) have large surface areas which are beneficial for a rapid adsorption of soluble



(a)

(b)

(c)

Fig. 7. Effect of coagulant dose on (a) COD, (b) oil-grease, and (c) turbidity removal in CC.

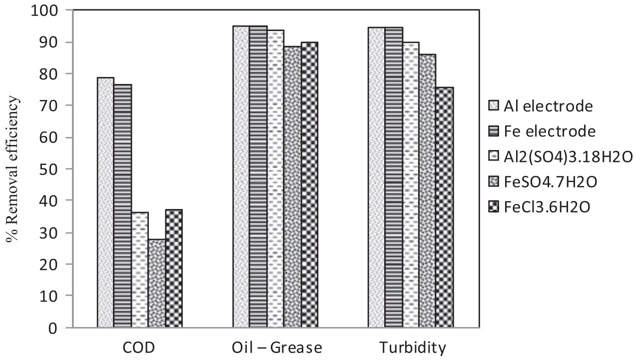


Fig. 8. Comparison of technical properties of EC and CC processes.

organic compounds and trapping of colloidal participles. As a result, EC process is more effective in the removal of pollutants than CC process.

4. Conclusions

In this study, EC is found to be an effective treatment method for SWW. In case of aluminum electrodes, the maximum COD removal efficiency (i.e. 78.3%) was achieved at optimum operational conditions as: pH 4, 100 A/m^2 current density, and 20 min EC time. Oil-grease and turbidity removal rates which are obtained under these conditions were 94.7 and 90.2%, respectively. In case of aluminum electrode, the low initial pH value is not an influential parameter because the pH value of final solution is increased approximately to pH 6, in the course of EC process. Moreover, optimum conditions for iron electrode were found to be 6, 100 A/m^2, and 20 min for pH, current density, and operation time parameters, respectively. Under these conditions, COD, oil-grease, and turbidity removal efficiencies were obtained as 76.7, 92.8, and 95.9%, respectively. From economic point of view, the energy consumption should be low for EC process, which was treated of high conductivity wastewater. Iron electrode is clearly preferable; operation costs were determined as 2.757 \$/m^3 for aluminum and 0.872 \$/m^3 for iron electrodes in the optimum operation conditions. In CC process, low COD removal efficiencies for all coagulant materials were obtained. The reason is organic pollutants in the wastewater. In dissolved organic substance removal, CC process is not an effective method. At optimum operation conditions, COD, oil-grease, and turbidity removal efficiencies were 36.4, 93.6, 89.8% for $Al_2(SO_4)_3.18H_2O$ (pH 7, 200 mg Al^{3+}/l) ,and 27.6, 88.6, 85.9% for $FeSO_4.7H_2O$ (pH 7, 200 mg Fe^{3+}/l) and 37.4, 89.9, 75.6% for $FeCl_3.6H_2O$ (pH 6, 100 mg Fe^{3+}/l), respectively. So COD, oil-grease, and turbidity removal efficiencies of the EC process were mainly evaluated in the study and the treatment of SWW using EC process may be accepted as a suitable treatment system.

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