Cost optimization of tannery wastewater treatment by electrocoagulation process with iron electrode under various DC voltage and electricity consumption

Muchlis1*, A A Sari1, Widyarani1, E Sutarlan1, E B Nursanto2, N Fasa2

1 Research Unit for Clean Technology, LIPI, Bandung 40135, Indonesia
2 Department of Chemical Engineering, Universitas Pertamina, Kebayoran Lama, Jakarta 12220, Indonesia

muchlis1577@gmail.com

Abstract. Electrocoagulation (EC) is an electrochemical technique in wastewater treatment that generates coagulant species in situ by electro dissolution of the sacrificial electrode. This work aimed to optimize the operating cost of tannery wastewater treatment by EC with iron electrodes under various DC voltages and electricity consumption. The experiment was conducted in a 400 mL batch electrochemical reactor using three iron electrode plates under a mono polar configuration and parallel distances of 26 mm. Several variations of voltage (8; 12; and 16 volt) and electricity consumption (1.7; 2.6; 3.4; and 4.3 kWh/m3) were applied. The reactor performance was evaluated based on the sedimentation curve using Imhoff cone. Simultaneously, the operating cost was analysed based on the electrode mass consumption and electricity consumption under variation in iron electrode price and electricity rates. The result showed that the optimum operating condition was obtained at the electrical voltage of 12 VDC and the electricity consumption of 2.55 kWh/m3. This condition had a current density of 1.7 A/m2, the electrode consumption rate of 0.31 kg/m3, and the operating cost of 0.45 – 0.55 USD/m3.

1. Introduction
The tannery industry has significant economic impacts in developing countries through employment and export earnings, but in parallel, it has great potential adverse impacts on the environment [1,2]. Due to the conversion of rawhide into leather requires a large amount of water and several chemical operations, there is a lot of highly polluting wastewater produced from this industry. Tannery wastewater has characteristics with a massive presence of various organic and inorganic substances with high salinity levels, ammonia and organic nitrogenous pollutants, and other toxic pollutants, including sulfide and residues chromium metal salt [3,4]. Also, tannery wastewaters are characterized as highly colored, turbid with foul-smelling of acidic and alkaline liquor. Without proper treatment, tannery wastewater may endanger water body health and create a risk for human health through food chains [5,6].

Various wastewater treatment techniques can be applied to tannery wastewater. After preliminary treatment to remove large particles, various wastewater treatment options can be used to treat tannery wastewater such as adsorption, chemical precipitation, electrocoagulation, biological processes, advanced oxidation processes, ion exchange, and also emerging technologies, namely membrane filtration [7-9]. Among those processes, the electrocoagulation (EC) process has many advantages since
it is easy in operation with small footprint and simple equipment. EC also has capability to treat a large quantity of wastewater without extensive chemical treatment and less generated sludge [10]. EC is an electrochemical technique in wastewater treatment that generates coagulant species in situ by electro dissolution of the sacrificial electrode. The EC process destabilizes the colloid surface charge in the wastewater and traps pollutants in flocs that can be easily separated by sedimentation. Typically, iron (Fe) can be used as electrodes as it is low cost, readily available, and good performance [11].

Previous studies in EC mainly deal with the effects of the operating parameters, such as the applied current density, initial pH of the solution, initial concentration, and contact time to the removal efficiencies of specific pollutants [12-14]. On the contrary, there are rarely published studies about the cost optimization of wastewater treatment by EC, especially for tannery wastewater application. Due to the use of electricity may be expensive in many places, and the sacrificial electrode needs to be regularly replaced, the operating cost of EC needs to be optimized for cost-effective wastewater treatment. This present study aimed to examine the optimum operating cost of tannery wastewater treatment by EC with iron electrodes under various DC voltages and electricity consumption according to sedimentation performance assessment.

2. Methodology

2.1. Tannery wastewater
A batch of 20 L tannery wastewater sample was collected from the equalization tank in the wastewater treatment facility and used for all purposes in this research. Tannery wastewater was collected from a leather tanning industry in Subang Regency, Indonesia.

2.2. Experimental setup
The EC was operated in a rectangular Plexiglas reactor without stirring, using three parallel iron electrodes spaced by 26 mm and dipped in the wastewater. The surface area in contact with the wastewater was 55mm × 34mm on each plate side. A Potentiostatic mode of digital DC power supply (0-30 VDC, 0-10 A) was used to supply a constant voltage. The three iron electrodes were connected so that the central electrode functioned as a cathode (active surface 37.4 cm²), while the other two functioned as the anode (active surface = 74.8 cm²).

![Figure 1. Schematic diagram of the electrocoagulation cell.](image)

2.3. Experimental procedure
For each experiment, 400 ml tannery wastewater was used in the first step of the electro dissolution process. At the beginning and end of each experiment, the electrodes were cleaned with rust remover, soapy water and deionized water. Afterwards, the cleaned electrodes were dried with a towel paper and weighted using a calibrated analytical balance (Metler Toledo ME204) to obtain the mass loss of the electrodes. Each experiment was run twice using the same electrodes. After the electro dissolution process, the wastewater was agitated with a magnetic stirrer for 5 minutes at 150 rpm. Subsequently, the wastewater was placed in Imhoff cone for settling rate observation, where the heights of sludge blanket were measured every 5 minutes for 30 minutes.
2.4. Experimental design

The experiments were conducted under three levels of voltage (8; 12 and 16 VDC) and four levels of electricity consumption (1.70; 2.55; 3.40; 4.25 kWh/m$^3$). The design of the experiment is shown in Table 1. The variation of energy consumption level was selected based on a preliminary experiment (unpublished results). The duration of electro dissolution was calculated based on the energy level, DC voltage, and electric current as shown in equation (1).

$$t = \frac{E}{V I} \times 1440$$  \hspace{1cm} (1)

Where, $t$ = duration of electro dissolution (s); $V$ = voltage (VDC); $I$ = electricity current (A); $E$ = energy consumption (kWh/m$^3$); 1440 = conversion factor from kWh.m$^{-3}$ to W.s/(0.4 L)

2.5. Operating cost

To simplify, the operating cost was calculated based on the consumption of electricity and sacrificial electrode. For each experiment, the average electrode mass loss from the two runs was used in the calculation. Because the electricity rate and iron price vary, the calculated operating costs were simulated around current prices.

3. Results and discussion

3.1. Electrode mass consumption

![Figure 2. Electrode consumption of various voltage and energy consumption.](image)

(a) Run-1.  
(b) Run-2.
After the EC process, the surface of the anode plates showed surface damage by corrosion. While during electrocoagulation using iron electrodes, dark solutions were released from the surface of anode plates. This phenomenon is called electro-dissolution, where the main reaction is the generation of iron ions and the hydrolysis of iron ions into coagulant iron hydroxides and polyhydroxides [15]. To study the profile of iron electrode consumption during the EC process, the electrode mass loss in each run of the experiment was evaluated as a function of DC voltage and energy consumption levels (figure 2).

Figure 2 shows that higher energy consumption resulted in higher electrode consumption. For the same energy consumption, higher voltage resulted in lower electrode mass loss. The highest electrode consumption was the experiment with operating conditions 8VDC – E4 (4.25 kWh/m³). In contrast, the lowest electrode consumption was the experiment with operating conditions 16VDC – E1 (1.7 kWh/m³). Even though a higher current density resulted in a higher electrode dissolution, as reported in the literature [13, 14, 17], the current density was not a determining factor when the comparison was conducted under the same energy consumption.

3.2. Imhoff cone sedimentation curve
In this work, iron hydroxides and polyhydroxides acted as coagulation agent to form flocs from the suspended solids. The coagulation process is a method for increasing the size of solid particles into flocs by reducing inter-particle electrostatic repulsion. Then the flocs can be separated from the solution through sedimentation on the influence of gravity, depending on the type and size of the flocs produced [16]. Good separation process can be obtained when agglomerated particles in a suspension increase in size and sedimentation rate [17]. For concentrated suspensions, where zone settling occurs, the sedimentation rate can be readily observed by following the interface between the clear supernatant and sedimenting solids [18].

The sedimentation test was conducted using Imhoff cone to study the separation performance of the wastewater after treated with different voltages and energy consumptions in the EC cell. The sludge blanket volume ($V_{sb}$) was recorded as a function of time (figure 3).

![Figure 3. Settling curve performance after treatment under various voltage and electricity consumption.](image_url)
From all 12 experiments, 9 experiments showed observable settling performance in Imhoff cone within 30 minutes (figure 3). Each experiment had a specific settling curve that fitted the exponential decay model and hindered settling patterns. In hindered settling, the sedimentation rate of particle is affected by hydrodynamic interaction with other moving particles [19].

Both replication of the experiment showed the pattern of settling curves with good consistency. The best three of the settling performances were obtained at the operating conditions $12\text{VDC--E2} > 16\text{ VDC--E3} > 8\text{VDC--E1}$. In contrast, the worst settling performance was obtained at the operating conditions $8\text{VDC-E4}$. The results also showed that the optimum coagulant dosage from the iron electro-dissolution plays an essential role in the separation performance.

3.3. Operating Cost

To determine the optimum operating cost of the EC process for the typical tannery wastewater, the operating cost associated with the best three of the settling performances ($12\text{VDC--E2}$; $16 \text{VDC--E3}$; and $8\text{VDC--E1}$) were calculated. As a comparison, the operating cost of the worst settling performance ($8\text{VDC-E4}$) was also calculated as shown in table 3, figures 4 and 5.

| Operating condition | Electrode consumption (kg/m$^3$) | Electricity Consumption (kWh/m$^3$) | Operating Cost Equation (USD/m$^3$) |
|---------------------|----------------------------------|-------------------------------------|-----------------------------------|
| R1                  | 0.314                            | 2.55                                | $C_1 = (0.309 \times \text{iron price}) + (2.55 \times \text{electricity rate})$ |
| R2                  | 0.303                            | 3.40                                | $C_2 = (0.297 \times \text{iron price}) + (3.40 \times \text{electricity rate})$ |
| Average             | 0.309                            | 1.70                                | $C_3 = (0.372 \times \text{iron price}) + (1.70 \times \text{electricity rate})$ |
| R3                  | 0.359                            | 4.25                                | $C_4 = (0.678 \times \text{iron price}) + (4.25 \times \text{electricity rate})$ |

As shown in figures 4 and 5, the best three candidates of the settling performance ($12\text{VDC--E2}$; $16 \text{VDC--E3}$; and $8\text{VDC--E1}$) had operating costs that were much lower than the worst candidate ($8\text{VDC-E4}$). It means that excessive electricity and electrode consumption made the EC process ineffective and
inefficient. This result also implied that the right coagulant dosage under suitable current density and EC duration time played an essential role in the EC feasibility.

According to the simulation of operating cost and the settling curve performances, the optimum condition was obtained from experiment 12VDC-E2, with an electrical voltage of 12 VDC and the electricity consumption of 2.55 kWh/m³. At a current density of 1.7 A/m², the electrode consumption rate was 0.31 kg/m³, resulting in an operating cost of 0.45 – 0.55 USD/m³.

4. Conclusion
The level of voltage and energy consumption have significant impact on sedimentation performance and operating cost of tannery wastewater treatment by EC with iron sacrificial electrodes. In the study, the optimum condition was obtained at the electrical voltage of 12 VDC and the electricity consumption of 2.55 kWh/m³, which resulted in an electrode consumption rate of 0.31 kg/m³ and the operating cost of 0.45 – 0.55 USD/m³.

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