

Benefits of Electrocoagulation in Treatment of Wastewater: Removal of Fe and Mn metals, oil and grease and COD: three case studies

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Abstract

In this work, the benefits of electrocoagulation were analyzed through three case studies. The effluents we have studied were from different industrial sectors. The effluent from the San Rafael-Minsur S.A Mine was the final tailings of the tin concentration process. Using iron anode, a current density of 22.35 A/m² and 45 minutes of process, it was possible to remove Fe (99.17%), Mn (99.97%), TSS (99.35%) and other metals such as Cu, Zn and Cd were Removed in more than 99%, while the removal of Pb was very varied, the pH remained in a range of 6.6 to 8. The effluent from the Conchán Oil Refinery was immediately taken out of the API separator without any previous treatment, the results show that in 30 minutes at 50 A/m² using Al anodes, 98% NTU, 60% of oils and fats and 32.27% phenol, were removed with an energy consumption of 3.04 \$/m³, while the pH remained in a range between 8 to 9. The effluent from the treatment ponds of the waste disposal plant (Befesa-Perú) was processed using iron anodes with a time of 30 minutes and 110 A/m², reaching a removal of 95.6% NTU and 45.14% COD, with an energy consumption of 3.30 kwh /m³ at a cost of 0.29 \$ /m³, while the pH remained in a range of 8 to 8.3.

Keywords: Electrocoagulation, Fe/Al electrodes, COD, Mine San Rafael-Minsur S.A Perú, Conchán Oil Refinería, Befesa Perú.

INTRODUCTION

Electrocoagulation (EC) as primary treatment has been successfully applied in the removal of different contaminants from industrial effluents, such as removal and transformation of polycyclic aromatic hydrocarbons [1], treatment of paint manufacturing wastewater [2], treatment of textile wastewater [3]; [4], removal of organic pollutants in industrial wastewater [5], removal of aluminum and boron from an oil drilling mud

effluent [6], removal of phosphate [7], removal of heavy metals [8]; [9]; [10]; [11], hardness, COD and turbidity removals [12], arsenic removal from drinking water [13]. EC is a process involving many chemical and physical phenomena that use consumable electrodes Fe or Al to supply ions into the wastewater [14]; [15]; [16]; [12]. During electrolysis in wastewater treatment, the sacrificial Fe or Al anode is oxidized generating corresponding metal ions, which immediately hydrolyze to polymeric iron or aluminum hydroxide.

These polymeric hydroxides are excellent coagulating agents [14]; [17]; [18]; [19] and, the small bubbles of oxygen hydrogen released from the anode and cathode can help to float the flocculated particles out of the wastewater [20]; [14]. In the EC process, the destabilization mechanism of the contaminants, particulate suspension, and breaking of emulsions may be summarized as follows. **(A)** compression of the diffuse double layer around the charged species by the interactions of ions generated by oxidation of the sacrificial anode (Eqs.1, 2, 5 and 8) [14]; [21]; [22]; [23]; [24], with the simultaneous formation of hydroxyl ions and hydrogen gas at the cathode (Eq. 3, 4, 6, 7, 8, 9 and 10) [12]; [25]: formation of coagulants. **(B)** charge neutralization of the ionic species present in [15] wastewater by counter ions produced by the electrochemical dissolution of the sacrificial anode. The two proposed mechanisms for the iron electrode are indicated by equations 1 to 7.

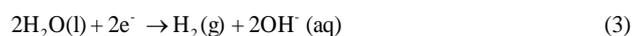
Ferric ions generated by electrochemical oxidation of Fe electrode may form monomeric and polymeric hydroxyl metallic complexes depending on the pH of the aqueous medium, which has strong affinity or dispersed particles as well as counter ions to cause coagulation [17]; [26]; [27]. For Fe anode some metallic complexes are: Fe(OH)₃, Fe(OH)₂, Fe(OH)²⁺, Fe(OH)₂⁺, Fe(H₂O)₄(OH)²⁺, Fe(H₂O)₅(OH)²⁺, Fe₂(H₂O)₆(OH)₄²⁺, Fe(OH)₄⁻, Fe(H₂O)₆³⁺, Fe₂(H₂O)₈(OH)₂⁴⁺, which finally transform into Fe(OH)₂(s) and Fe(OH)₃(s). [19]. The proposed mechanism for aluminum is indicated by equations 8 to 9.

Mechanism (I): Fe at alkaline medium

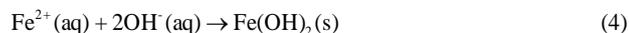
Anodic process:



Cathodic process:



In solution:



Mechanism (II): Fe at acid medium

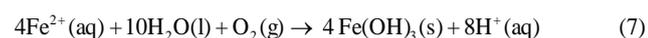
Anodic process:



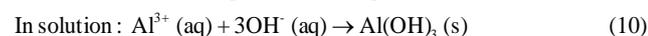
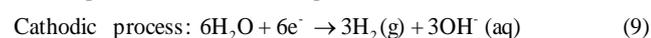
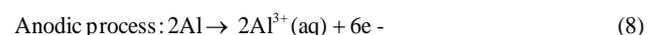
Cathodic process:



In solution:



Mechanism Al:



$\text{Al}^{3+}(\text{aq})$ and $\text{OH}^-(\text{aq})$ ions generated by electrode reactions (8) and (9) react to form various monomeric species, such as $\text{Al(OH)}^{2+}(\text{aq})$, $\text{Al(OH)}_2^+(\text{aq})$, $\text{Al}_2(\text{OH})_2^{4+}(\text{aq})$, $\text{Al(OH)}_4^-(\text{aq})$, and polymeric species such as $\text{Al}_6(\text{OH})_{15}^{3+}(\text{aq})$, $\text{Al}_7(\text{OH})_{17}^{4+}(\text{aq})$, $\text{Al}_8(\text{OH})_{20}^{4+}(\text{aq})$, $\text{Al}_3(\text{OH})_4^{5+}(\text{aq})$, $\text{Al}_{13}(\text{OH})_{34}^{5+}(\text{aq})$, and $\text{Al}_{13}\text{O}_4(\text{OH})_{24}^{7+}(\text{aq})$ which finally transform into $\text{Al(OH)}_3(\text{s})$ according to complex precipitation kinetics [28]; [7]. 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 [14].

(C) Floc formation: the floc formed as a result of coagulation creates a sludge blanket that entraps and bridges colloidal particles that are still remaining in the aqueous medium [14]. Water is also electrolyzed in a parallel reaction, producing small bubbles of oxygen (Eq.2) at the anode and hydrogen (Eqs. 3, 6 and 9) at the cathode. These bubbles attract the flocculated particles and float the flocculated pollutants to the surface through natural buoyancy [14]; [19]. The hydroxides, oxyhydroxides and polymeric hydroxides are usually more effective coagulants than those used in chemical dosing, they are able to destabilize colloidal suspensions and emulsions, to adsorb, neutralize or precipitate dissolved polluting species, and finally to form flocs that can be removed either by settling/filtration or flotation [29].

The experiments were conducted at room temperature and, using the Eqs (11, 12 and 13) were calculated the pollutant removal efficiency, electrical energy consumption and electrical energy consumption per volume unit. Where C_o is the initial pollutant concentration and C_t is the concentration after of a EC process time, E is the electrical energy in kwh, V the cell voltage(V), I the current (A) and t is the time of EC process per hour, V_w wastewater volume (m^3), E_{cw} is electrical energy

consumption in kwh.m^{-3} . The removal efficiency (RE %), energy consumption (E , kwh) and energy consumption per unit of volume treated (E_{cw} , kwh/m^3) after EC were calculated using the following equations.

$$RE(\%) = 100x \frac{C_o - C_t}{C_o} \quad (11)$$

$$E = 0.001V.It \quad (12)$$

$$E_{cw} = E / V_w \quad (13)$$

The objective of this work is to analyze the efficiency of removal of contaminants by electrocoagulation by working with effluents from three different industrial sectors, through batch processes. The efficiency of EC in removing Fe and Mn from wastewater of the tin production mining Minsur S.A plant, removing oil and fat from wastewater of the Conchán Refinery that is a state-owned and privately owned company engaged in the transportation, refining, distribution and marketing of fuels and other petroleum products, and removing of DQO from wastewater from the treatment ponds of the final waste disposal Befesa-Peru plant were investigated. The initial characteristics of each effluent were analyzed initial pH, concentration of the contaminants as well as the effect of the variation of the current density and treatment time and electrode materials on the removal efficiency of the pollutants to determine the best conditions of removal in each case.

MATERIALS AND METHODS

Case study I: Removal of iron and manganese from the effluent from the San Rafael mining unit: Procedure in batch mode.



Figure 1. Thickener 80F (Minsur S.A).

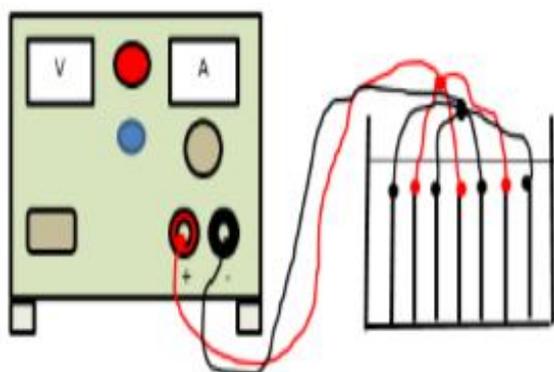


Figure 2. Experimental set up by batch.

The San Rafael Mine is located in the district of Antauta, Province of Melgar, Region of Puno, Perú to 4500 m.a.s.l. San Rafael is the world's third largest tin producer currently producing 12% of the world's tin. Among the main pollutants found in concentrator plant effluents are: cadmium, copper, lead, manganese, iron, suspended solids, and other metals. These pollutants are harmful to health and the environment, which is why the Peruvian state regulates the values of effluents from the mining sector.

The study effluent comes from the final tail of the process of concentration of tin, which is decanted in the thickener of 80 feet in diameter (figure 1), to finally be sent to the river Antauta. The effluent analysis was performed in duplicate, table 1 shows its physico-chemical characteristics. The reactor was made of plexiglass with a capacity of 5 L, with seven Fe electrodes arranged vertically with a spacing of 0.03 m and dimensions of 0.224 m x 0.133 m (figure 2). The reactor worked with four cathodes (0.238 m²) and three anodes

(0.179 m²). The analyzes were carried out in the Minsur S.A laboratory for pH measurement (Potentiometer Thermo Scientific, Orion Versastar Meter SN V00180), turbidity (Portable Turbidity Meter TPW / TPI HF SCIENTIFIC) and spectrophotometer (Agilent, AA 240 FS / MY14120002), the emissions used for Fe and Mn were 372 nm and 403.1 nm respectively.

Table 1. Characteristics of the effluent from the overflow of the thickener 80F

Physical parameters	Value	Detection	Ministry of the environment (MINAM) DS 010-2010
pH	6.620	-	6 - 9
Conductivity (μS/cm)	913.00	0.010	-
TSS(ppm)	547.00	5.000	50
Temperature (°C)	22.400	-	-
Total metals (ppm)	-	-	-
Dissolved metals (Fe, ppm)	0.543	-	2
Fe (ppm)	25.049	0.03	-
Mn (ppm)	8.341	0.005	-
Cu (ppm)	0.111	0.01	0.5
Pb (ppm)	0.030	0.01	0.2
Zn (ppm)	0.128	0.01	1.5
Cd (ppm)	<0.005	0.005	0.05
Cr (ppm)	-	0.01	0.1
Hg (ppm)	-	0.02	0.002
As (ppm)	-	0.01	0.1

Case study II: Removal of oils and grease of effluent from API separator Conchán Oil Refinery

Conchán Oil Refinery (PETROPERU S.A), is characterized by its great operational flexibility to process light crude (35 API) and coarse (19 API) and is known for the manufacture of asphalts. As a result of its processes each year it generates and treats more than 25 000 m³ of high turbidity effluent contaminated with oils and greases and others that are finally disposed at sea. This effluent generated during the process

reaches the API separator (named because its design was patented by the American Petroleum Institute) (Figure 3), was treated by EC. The reactor was constructed with plexiglass 0.18 m length, 0.10 m wide and 0.20 m deep (figure 4). The electrodes, two anodes and two cathodes were of aluminum and arranged vertically and spaced from each other 0.03 m. The treated effluent volume was 3 L and the total area exposed to the current flow was 0.095 m². During the process, voltage and

temperature measurements were made. After the electrochemical process, the effluent was filtered to separate the sludge formed and preserved adequately at low temperature for later analysis in an external accredited laboratory. The batch process is shown in Figure 10. Some parameters of maximum permissible limits (MPL) of liquid effluents of the sector Hydrocarbons in Perú are listed in Table 2.



Figure 3. API Separator Conchán oil

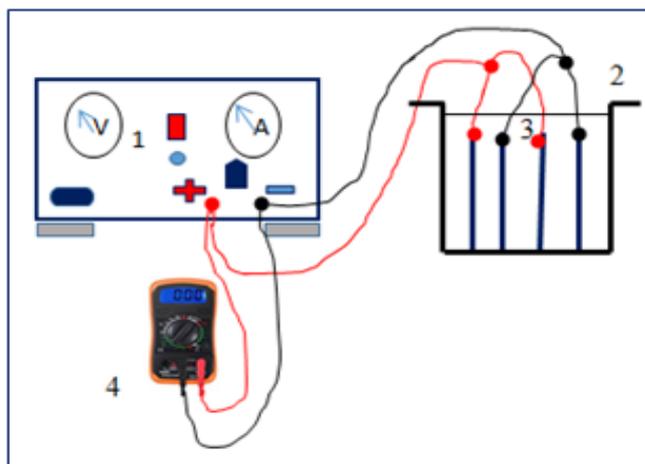


Figure 4. (1) DC power supply, (2) electrolysis Refinery cell (3) electrodes and (4) multimeter

Table 2. Characteristics of effluent and Peruvian norm (MPL)

Physical parameters of effluent	Ministry of the environment (MINAM), MPL: DS(DS N° 037-2008-PCM)		
Oiland grease(ppm)	31.30	Total petroleum hydrocarbons (TPH)	20
Phenols (ppm)	21.77	Oil and grease(ppm)	20
Chlorides (ppm)	2118.00	Fenoles FCC(ppm)	0.50
Turbidity(NTU)	136.00	DQO(ppm)	250
pH	7.0 9.0	pH	6 a 9

Case study III: Decrease of COD of the effluent from the industrial waste management pond - Befesa Perú.

The treated industrial effluent comes from the treatment ponds of the waste disposal plant (Befesa Perú, figure 5). The pond has a total area of 10,000 m² and a total capacity to receive 250,000 m³ of industrial waste. Its main pollutant is the chemical oxygen demand (COD). Experiments were performed with Fe electrodes. The reactor (figure 6) of 0.004 m³ of

working capacity was constructed with plexiglass, and the dimensions of the electrodes were (0.134mx0.134 mx0.0016m), using five vertical electrodes, three cathodes (0.054 m²) and two anodes (0.036 m²) with a separation of 0.03 m. The analyzes were carried out in the laboratory of Befesa, for the measurement of the pH (pH meter HI9025 Hanna Instruments), turbidity (Portable Turbidimeter TPW/TPI HF SCIENTIFIC) and COD (Spectroquant Nova 60 photometer).



Figure 5. Storage pond N°3 of wastewater

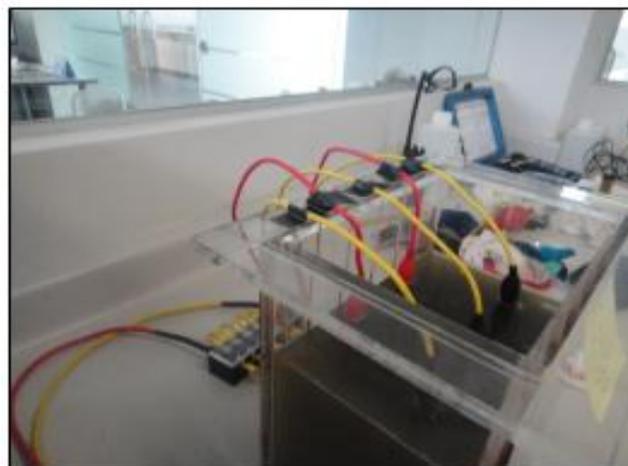


Figure 6. Batch reactor (Befesa Perú Laboratory).

RESULTS AND DISCUSSION

In any EC process, the applied current density is a determining factor in the level of removal of pollutants from wastewater. Not necessarily at higher current density greater removal is obtained, there are other factors to be taken into account that can seriously affect the process, such as the loss of electrical energy due to the heating of the effluent, passivation phenomena of the electrodes, consumption of electrodes, unit cost of treatment among others. A wide review of applications of electrocoagulation technology can be reviewed in [27]; [30]; [31].

San Rafael mine- Minsur S.A.

The figure 7 shows the stabilization of the voltage at different current densities during the process. The best response was 7 V with 22.35 A/m² achieved in 45 min. The effluent pH after electrocoagulation treatment would increase for acidic influent but decrease for alkaline influent [30]; [31] at 22.35 A/m² the pH was maintained in a range of 6.6 to 7.9 as shown in figure 8, and the color of the formed precipitate varied between greenish-black, due to the formation of ferrous and ferric hydroxide explained by the Eqs. 4 and 7, a similar situation is reported by [32]; [33].

The lower solubility of Fe(OH)₂ is reaching with a pH between 11.0 and 11.5, and the Fe(OH)₃ reach the minimum solubility in the range of 7.0 to 8.0 [33]. The determination of heavy metals in industrial effluents is an obligatory and regulated control, in Perú by the Ministry of the Environment. The presence of heavy metals in water and wastewater are causing serious environmental and health problems because of their solubility in water. Although organic contaminants can be biodegradable [8], inorganic pollutants cannot be biodegradable [34]; [31] and they can enter to the food chain and accumulate in living organisms [8].

During the EC process, 99.2% of iron removal was achieved in the first fifteen minutes of the EC process with a current density of 22.3 A/m² and at the highest applied current density the

removal was 88.6%. With respect to Manganese with the three current densities applied, the same level of removal of 99.7% was achieved at fifteen and forty-five minutes as shown in figures 9 and 10.

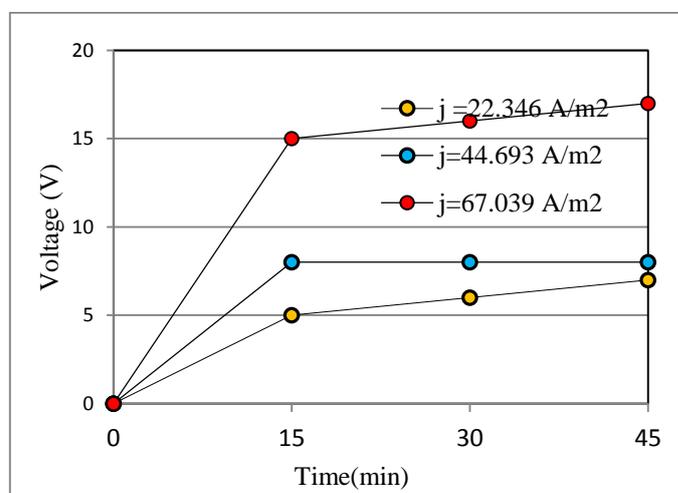


Figure 7. Effect of current density on voltage

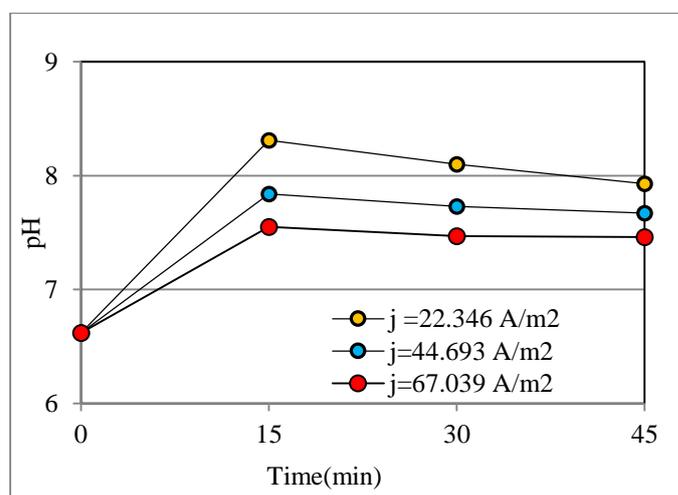


Figure 8. Effect of current density on pH.

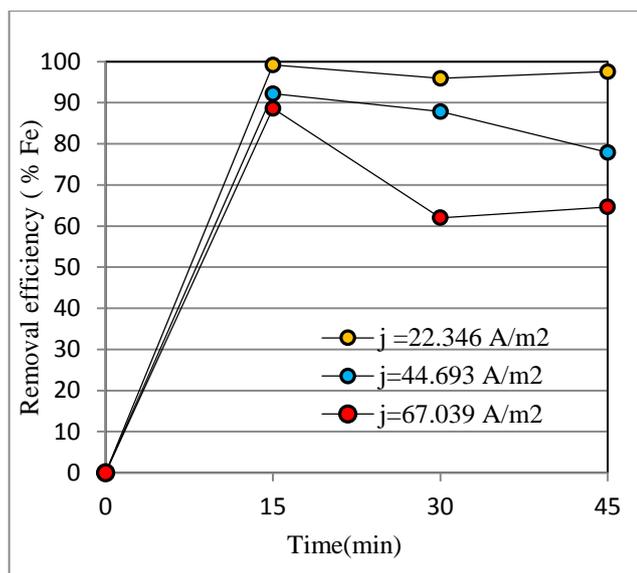


Figure 9. Effect of current density on Fe removal efficiency.

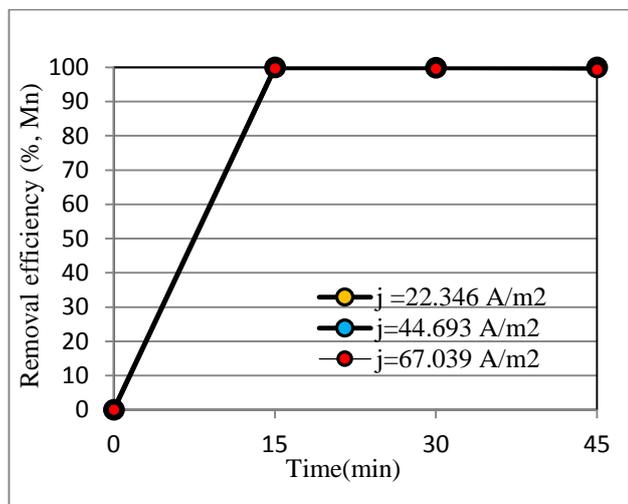


Figure 10. Effect of current density on Mn removal efficiency.

Total Suspended Solids (TSS) is the term used to refer to the solid particles suspended in water, and is considered aqueous pollutant. Depending on the origin of the effluent it may contain both inorganic and organic material. Figure 11 shows the percentage of removal of TSS, in the first fifteen minutes on average a removal of 98% is reached, when the applied current density is 22.35 A/m² the percentage of removal remains in time, while with 66.04 A/m² the removal of TSS drops to 91.6% at forty-five minutes. Electrical Conductivity is a measure of the ionic activity and determines its capacity to transmit current. Figure 11 shows the variation of conductivity with time, in the first fifteen minutes the average removal was 7.0%. According to the three current densities used, this property is more affected by the higher density of applied current at thirty minutes the percentage of removal was of 13.6% reaching 15.2% at forty-five minutes, while at the lowest current densities the removal levels for the same times are practically equal of 6.3% and 10.7% respectively. Table 3 shows that the

removal of Cu, Zn and Cd was 99.9% and, the removal of Pb shows a random behavior with low levels.

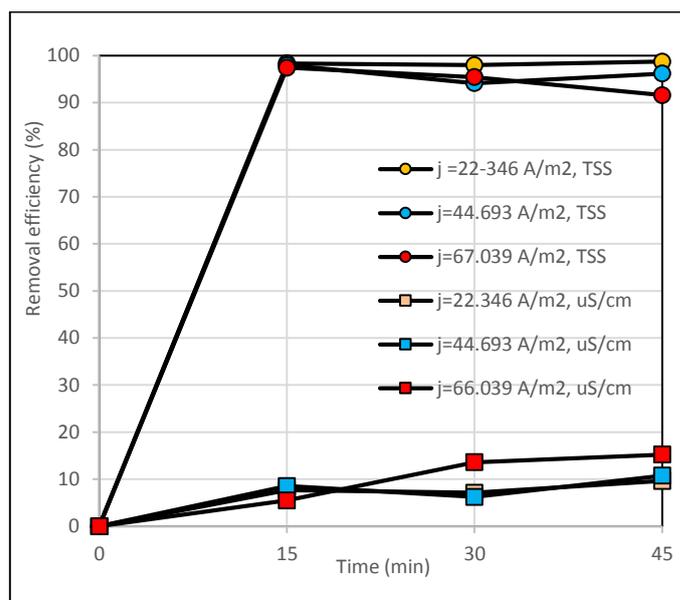


Figure 11. Effect of current density on removal of TSS and conductivity (µS/cm).

Table 3. Removal efficiency (%) of other metal contaminants.

j (A/m ²)	22.4			44.8			67.1			
	Time(min)	15	30	45	15	30	45	15	30	45
Fe dissolved	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90
Cu	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90
Pb	2.50	21.67	5.00	16.67	5.83	0.83	5.83	41.67	7.50	
Zn	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90
Cd	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90

Conchán Oil Refinery

Since ionic conductivity is crucial for electrochemical processes [27], the conductivity of the solution is an important factor that affects the efficiency and power consumption of EC, the higher the conductivity, the lower the power consumption of EC due to the increased pollutant removal efficiency [31] and when the electrolytic conductivity is low, the current efficiency will decrease [14]. The conductivity of the solution is enhanced by adding anions in the form of salts such as NaCl, we did not apply any type of salt, because the aqueous medium allowed us to apply a wide range of current.

Figure 12 shows the result of the percentage of removal of oils and fats that can be reached at different current densities in 30 min. Based on these results, the best response was 58.68% with 50 A / m². At 100 and 150 A / m² there is a small decrease in performance with respect to 50 A / m² of -1.6% and -1.81% respectively, probably due to passivation effects of the electrodes. Electrode passivation, specifically of aluminum electrodes, has been widely observed and recognized as

detrimental to reactor performance. This formation of an inhibiting layer, usually an oxide on the electrode surface, will prevent metal dissolution and electron transfer, thereby limiting coagulant addition to the solution [14]. Figure 12 also shows the percentage removal of turbidity in 30 min.

The initial turbidity of the API separator effluent was 136 NTU. The lowest level of removal of 65.12% occurred with 50 A / m² and the highest removal of 98.56% at 150 A / m². The current density is expected to exhibit a strong effect on EC, especially on the kinetics of turbidity removal: higher the current, shorter the treatment [35]. The removal of organic matter, particularly in the colloidal form, is adsorption/entrapment on freshly produced metal hydroxide flocs. This mechanism is also responsible for the removal of the suspended solids corresponding to turbidity from the industry effluents [12].

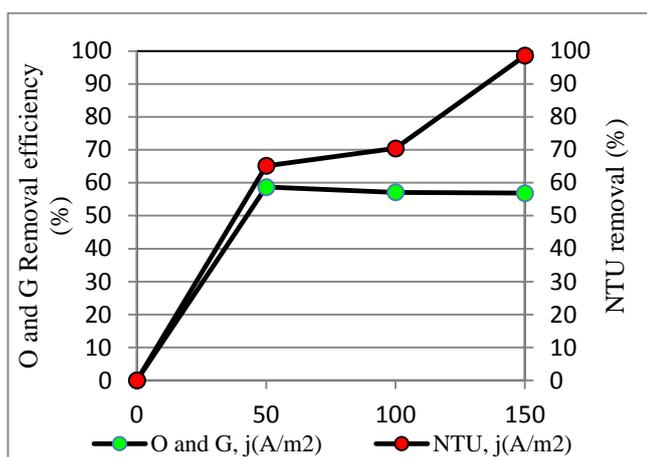


Figure 12. Effect of current density on removal of oil and grease and turbidity (NTU), 30 min.

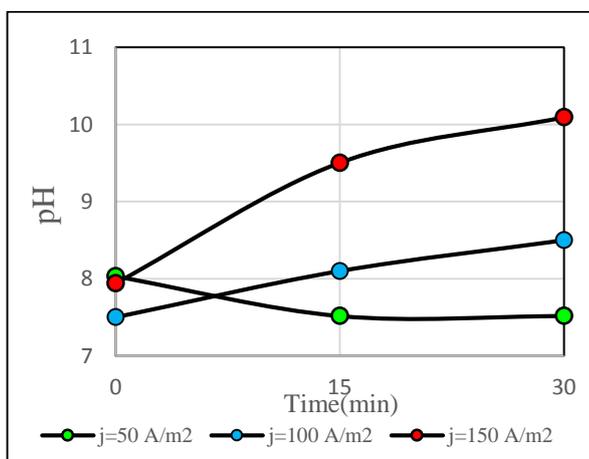


Figure 13. Effect of current density on pH

The pH of the solution plays an important role in the EC process. The pH of the reaction solution changes during the electrocoagulation process [12]. The polymerization degree increases with increasing pH. The hydrolyzed cations neutralize, with their positive charges, the negative potential of

the double layer surrounding the colloidal particles [36]. Figure 13 shows the variation of the pH over time at different current densities. At 50 A/m² the pH decreases, while at higher current densities the pH increases, due to the higher production of OH⁻ as a consequence of the water electrolysis given by the Eq (3).

With the extension of hydrolysis of Al³⁺, multicore coordination compounds and Al(OH)₃ precipitate can be formed [14]; [36]. These processes are explained with Eqs 8, 9 and 10, which can be summarized by: Al³⁺ → Al(OH)_n³⁻ⁿ → Al₂(OH)₂⁴⁺ → Al₁₃complex → Al(OH)₃. The pH of the solution after 30 min was maintained in a range of 7.5 to 10. In the pH range of 4–9, Al(OH)₂⁺, Al(OH)₂⁺, Al(OH)₂⁴⁺, Al(OH)₃ and Al₁₃(OH)₃₂⁷⁺ are formed. The surface of these compounds has large amounts of positive charge, which can lead to adsorption electrochemistry neutralization and net catching reaction [14]. At pH > 6.5, the adsorption is the main process [35]; [37].

The removal of oils and fats is due to the flotation of the flocs formed due to their lower density than water and the gases generated during the EC process, which help to float the contaminants. Adsorption: OG + Al(OH)₃ → particles and, OG Polymeric + Al(OH)₃ → particles. The performance of electroflotation is reflected by the pollutant removal efficiency and the power consumptions. The pollutant removal efficiency is largely dependent on the size of the bubbles, it depends on water pH as well as the electrode material. The hydrogen bubbles are smallest at neutral pH. Decrease or increase of pH from 3.0 to 4.0 results in the increase of hydrogen bubbles. At pH of 6.0, the mean hydrogen bubble is 27 μm. For oxygen bubbles, their size increase with pH [30].

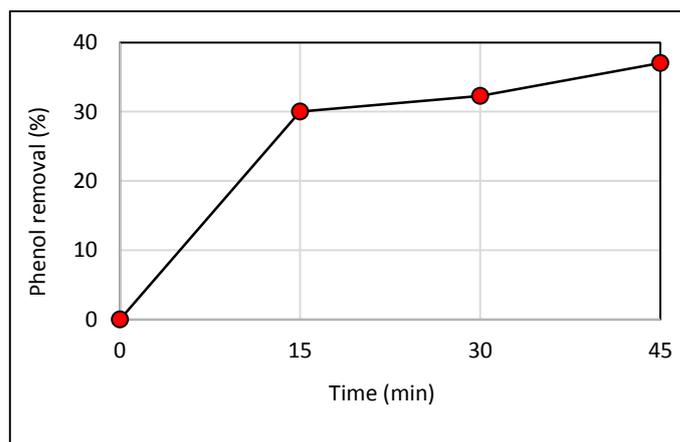


Figure 14. Effect of current density on removal of phenol at 50A/m².

One of the most prevalent forms of organic chemical pollutants in industrial wastewaters are Phenol and phenolic compounds [38]; [39]. High concentrations of phenol and phenolic compounds typically are found in aqueous effluents of oil refineries, petrochemical, ceramic, and steel plants, coal conversion processes, phenolic resin and pharmaceutical industries [38]; [40]; [41]; [42]; [39]. Since phenol and its

derivatives are toxic and harmful to living organisms even at low concentrations, they are known as noxious pollutants [42].

Organic substances such as phenol acquires its surface charge as a result of ionization, as indicated: $R-OH \rightarrow RO^- + H^+$ [43]. Natural organic matter (NOM) is found as a mixture of organic compounds in all water environments, especially surface water. In such waters, NOM contains both hydrophobic and hydrophilic compounds. Aromatic hydrocarbons form an integral part of the hydrophobic component of NOM [44]. Several factors can affect the NOM removal, the current density influences the oxidation speed of the anode, water temperature, pH, as well as NOM properties.

The pH of the solution has a direct effect on the removal of the phenol, if this increases to 7 the removal efficiency increases, if the pH is greater than 7 the removal efficiency decreases [39]. Figure 14 shows the effect of current density on the percentage of phenol removal (values are not shown at current densities of 100 and 150 A/m^2). The highest removal speed occurs during the first fifteen minutes, reaching 30.0%, which is when the pH drops to 7.5, in 30 minutes the removal is 32.3%, the experiment was extended to 45 minutes and no significant improvement in the removal of this contaminant is observed. Other research works show that by operating reactor in batch mode, using synthetic solutions with Al electrodes after 2 hrs remarkable removal 97% of phenol [45], and 100% of phenol can be achieved [46].

The graphs of the effect of the current density on the density of the treated effluent (kgm^{-3}) and on the temperature ($^{\circ}C$) are not shown, but we show the mathematical models found for each applied current density as a function of time in minutes, in both cases with $R^2 > 0.9$: $d50 = -0.0291t + 997.84$, $R^2 \approx 0.99$, $d100 = -0.1012t + 997.94$, $R^2 \approx 1$, $d150 = -0.1969t + 998.03$, $R^2 \approx 1$, and $T150 = 0.6405t + 21.536$, $R^2 \approx 1$, $T100 = 0.3714t + 21.357$, $R^2 \approx 1$, $T50 = 0.1202t + 21.554$, $R^2 \approx 1$. Table 4 shows the energy consumption per unit volume at different current densities in 30 min.

Table 4. Energy consumption and energy consumption per unit volume

J (A/m^2)	Energy consumption (kwh)	Energy consumption per unit volume (kwh/m^3)
50	0.00912	3.04
100	0.02945	9.82
150	0.05790	19.30

Befesa Perú

Chemical oxygen demand (COD) is a measure of the amount of the oxygen used in the chemical oxidation of inorganic and organic matter present in wastewater. Compounds that contribute to COD are: biodegradable organic compounds, non-biodegradable compounds and inorganic oxidizable compounds [32]. Since dairy waste streams contain high concentrations of organic matter, these effluents may cause serious problems, in terms of organic load on the local municipal sewage treatment systems [47] COD is an critical

water quality parameter because, it provides an index to assess the effect discharged wastewater will have on the receiving environment.

Higher COD levels mean a greater amount of oxidizable organic material in the sample, which will reduce dissolved oxygen (DO) levels. A reduction in DO can lead to anaerobic conditions, which is deleterious to higher aquatic life forms. During the development of this research project Befesa Perú carried out industrial waste management, wastewater used was a mixture of different industries.

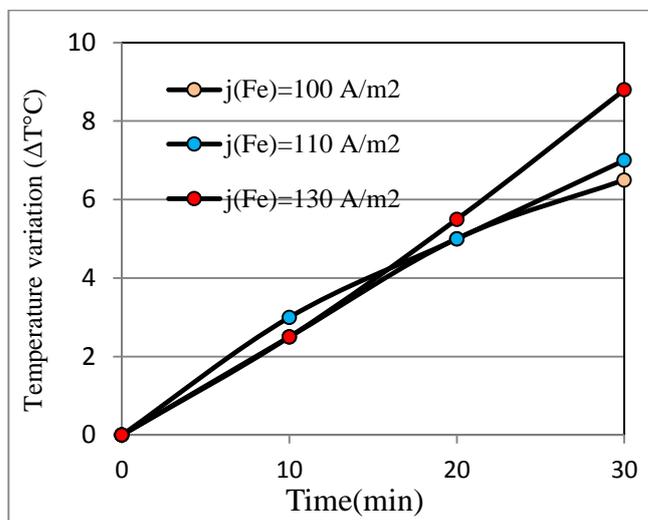


Figure 15. Effect of current density on temperature

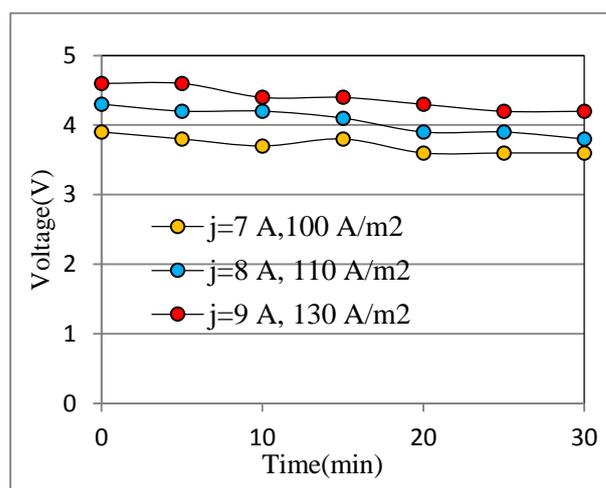


Figure 16. Effect of current density on voltage variation.

Figure 15 shows the variation of the temperature over time, with higher current density, the greater the increase in the temperature of the effluent being treated, in 30 minutes the greatest increase of $8.8^{\circ}C$ occurred with $130 A/m^2$ and the smallest increase from $6.5^{\circ}C$ to $100 A/m^2$. A linear behavior of this variation ($\Delta T, ^{\circ}C$) over time (t, min) is observed for each current density: $\Delta T_{100} = 0.2107t + 0.2679$, $R^2 = 0.996$, $\Delta T_{110} =$

$0.2339t+0.0268$, $R^2=0.997$; $\Delta T_{130} = 0.2893t+0.3036$, $R^2=0.989$.

A linear variation of the temperature over time at different current densities is reported by [48]. The increase of the temperature in the electrolytic processes is normal, the medium being a conductor has a natural resistance to the passage of the electric current, which causes that part of the electrical energy is transformed into heat, heating the effluent and decreasing the efficiency of process [49]. But this effect may be negligible when experiment is carried out at low value current density [48]. Figure 16 shows the voltage variation during the process, the highest and lowest variation in 30 minutes were given at 130 and 100 A/m² with 0.4 and 0.3 V respectively.

The electrolysis voltage is one of the most important variables [50]; [51]. It is strongly dependent on the current density, the conductivity of the water/wastewater to treat, the inter-electrode distance, and the surface state of electrodes [50]. Figure 17 shows the level of turbidity removal with time, for a process of 30 minutes at 100 and 110 A/m² turbidity is reached in 96.1 and 98.3%, while at 130 A/m² only achieved 82.9%. It is clear that current density has a marked effect on EC and the removal of turbidity and consequently on TSS.

The presence of particulate materials such as algae, clays, silts, organic particles and soluble substances in water often causes it to get turbid or colored, the quality of the treated wastewater that is discharged into fresh water bodies, leading to a problem of dispersion of pollutants [52]. Figure 18 shows the variation of pH over time. pH is an important parameter influencing the performance of the EC process [8]; [47]; [53]. At 100, 110 and 130 A / m² an increase in pH of 0.44, 0.54 and 0.68 occurs in 30 min respectively. The pH of the solution is alkaline (pH = 8), it did not vary much with the current densities applied. This result is in agreement with previously published studies [51]. On the other hand, the EC process exhibits some buffering capacity, especially in alkaline medium, which prevents large changes in pH and decreases the pollutant removal efficiency [53].

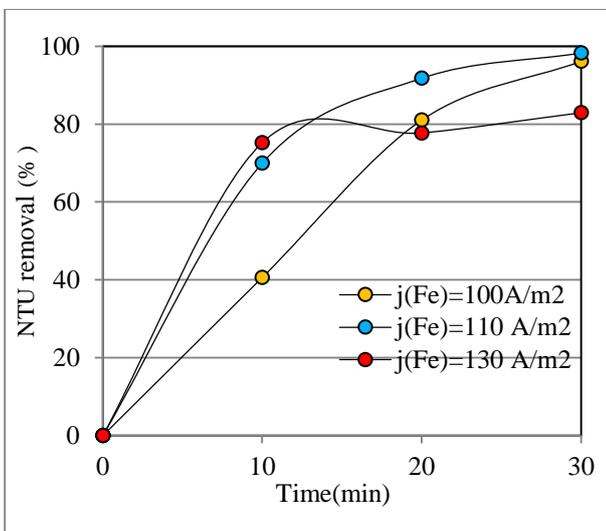


Figure 17. Effect of current density on NTU removal.

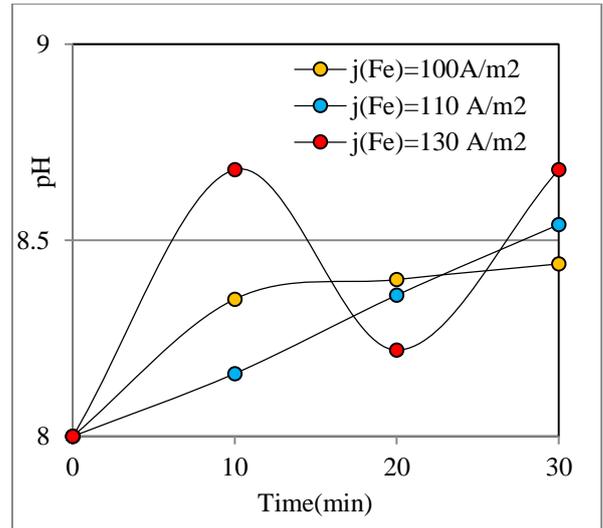


Figure 18. Effect of current density on pH.

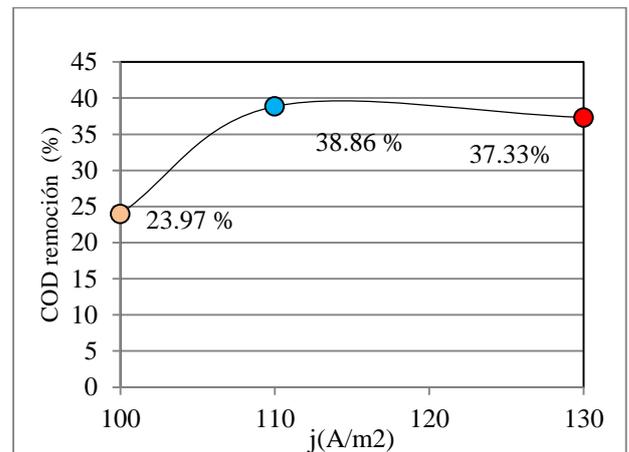


Figure 19. Effect of current density on COD removal in 30 min.

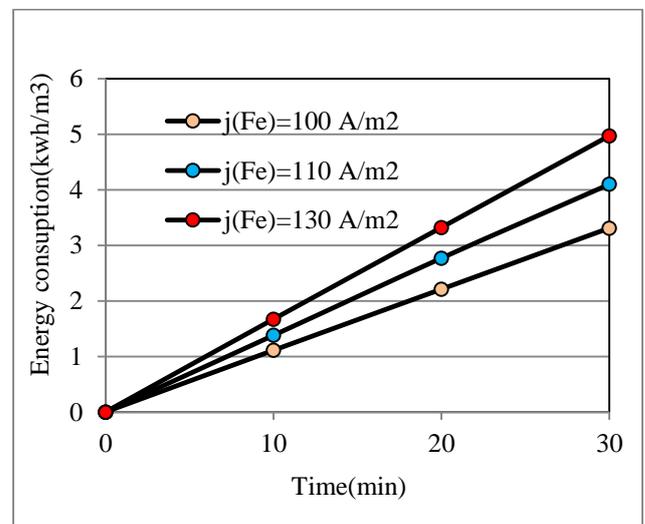


Figure 20. Effect of current density energy consumption.

Figure 19 shows the removal of the chemical oxygen demand (COD), between 100 and 110 A /m² an increasing response is observed reaching a maximum of 38.86% at 110 A/m² in 30 min, with a variation of pH [8 to 8.54]. It can be seen that the increase in current density and temperature does not favor the removal of this parameter. The reason could be due to increase in mobility and collision of ions with hydroxide polymer [54].

It is reported the removal of 61.3% of COD using iron anodes at 200 A/m² operating in a time of 25 min [55]. Figure 20 shows the energy consumption, the lowest consumption was given at 100 A/m². For any industrial process this parameter is very important, especially in electrochemical processes. Table 5 details the cost of treatment.

Table 5. Cost of treatment per cubic meter of treated effluent (\$/m³):Cost of energy in Befesa Plant (0.0875 \$ / Kwh).

I (A)	Voltage (V)	J(A/m ²)	Time (min)	Energy Kwh	Volumen (m ³)	Energy consumption consumption per unit volume (kwh/m ³)	Cost \$/m ³
7	3.7	100	30	0.0132	0.004	3.30	0.29
8	4.0	110	30	0.0164	0.004	4.09	0.36
9	4.4	130	30	0.0201	0.004	5.04	0.44

CONCLUSIONS

Electrocoagulation was evaluated as a possible technique for the reduction of pollutants from wastewater. The metals were removed with an efficiency greater than 99%, while the oils and fats and phenols reached 59 and 32% respectively. A special case was the removal of the chemical oxygen demand (COD), since the treated effluent was a mixture of effluents from various industrial sectors, reaching 39%. The levels of removal achieved with the electrocoagulation process allow us to suggest that it can be implemented as a primary process to shorten the subsequent treatment times (e.g. hydrocarbon removal) or in a final stage when the effluent has not reached the expected removal level (e.g. metals removal). EC offers several advantages over coagulation/flocculation, such as controlling the rate of coagulant formation (oxidation of the electrode) by the applied current density. Another problem that must be addressed in future research is to use two different materials simultaneously as anodes (e.g. Fe and Al) to generate two types of coagulants and analyze possible improvements in the removal of contaminants from an effluent, as well as to use FeAl alloys as anodes.

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