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Integrated Electrocoagulation-Flotation Process: A Comparative Study for Employing Fe/Al Electrodes in Tanta Wastewater Treatment Plant Influent

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Abstract

Electrocoagulation/flotation (ECF) process is introducing electrical current into an aqueous media to destabilize dissolved or suspended contaminants. All the conventional and advanced treatment technologies aim to treat wastewater before discharging to the water systems. As an alternative to conventional methods for treating industrial and municipal waters, electrochemical methods have recently been investigated. This method minimizes using of chemicals was enhanced to pollutant removal, environmental impact and support sustainability goals, making them a compelling choice for wastewater management. ECF unit electrodes were made of iron or aluminum arranged in monopolar connection, where wastewater was pumped through it. In this work the impact of operating parameters for ECF process was investigated such as types of electrodes material, pH, retention time and current density for the best removal of liquid waste pollutants as biochemical oxygen demand (BOD), Total suspended solids (TSS) and chemical oxygen demand (COD). Tanta's wastewater treatment plant provided wastewater samples. The results demonstrated that using Al electrodes which arranged in monopolar connection series to reduce the operation cost, the efficiencies of removal of BOD, TSS and COD were 96 %, 98% and 97% on the other hand using Fe electrodes, results were 93 %, 94 %, and 95 % respectively, the optimizing parameters were (initial pH =7.5, electrode distance= 20 mm, time of retention = 8 min., and current density = 3.5 mA/cm^2). The experimental findings revealed that the effluent wastewater was odorless, clear and suitable for reuse.

Keywords: Electro-coagulation/flotation ; Current density; Fe and Al electrodes; COD; BOD; Energy Consumption.

1. Intoduction

Due to the climate change and all over the world governments strive to reduce the emission of gases, fresh water availability only 1% and salty water for the seas and oceans more than 97% on the earth [1]. Worsley, the 1% of fresh water now decreased as result of continuous contaminants from human activities and industrial process especially in the developing countries [2]. There are important techniques for waste water treatment.

Firstly, **Electrochemical Methods:** Utilize electrical currents to induce chemical reactions, breaking down pollutants into less harmful substances. This method often involves processes like electrocoagulation, electrooxidation and electroreduction.

Secondly, **Conventional Techniques:** Typically include biological treatment (like activated sludge), chemical precipitation, and physical methods (like filtration). These methods often rely on biological activity or chemical reactions using additives to treat wastewater.

Magnetic Treatment by the magnetic field has a significant effect on the physical and chemical properties of water as well as potable or saline solutions [3].

Electrochemical wastewater treatment methods offer several advantages over conventional techniques, making them increasingly favorable in modern environmental management. Unlike traditional methods that often rely on chemical additives or extensive physical processes, electrochemical treatments utilize electrical currents to facilitate the breakdown of pollutants, resulting in a more efficient and effective removal of contaminants.

Electro-coagulation flotation method use for minimizing waste production in wastewater treatment because of vertical electrodes setup, in which, the hydrogen gas bubbles produced at the cathode electrodes then, at that point, causing the

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impurities loating to the surface, in which higher removal proficiency would be achieved [4]., including heavy metals, organic compounds , remove pathogens and contaminants in colloidal inorganic forms from a variety of waste waters, industrial effluents as food, tannery, mechanical workshop (soluble oil) polymerization, and wastewater textile industries [5].

Electro-coagulation is one of elective innovations for some kinds of wastewaters other than the Conventional Techniques Often rely heavily on chemical additives, which can contribute to environmental pollution and health risks. Electro coagulation method had benefits than traditional innovations as coagulation which eliminates the need for chemical coagulants and flocculants, leading to a more environmentally friendly process.

A great deal of studies revealed the high proficiency of electrocoagulation for treating domestic and industrial wastewater [6, 7].

Upsides for involving electrocoagulation strategy in wastewater treating are less maintenance, operations cost and profoundly effectiveness for eliminating various kinds of contaminants [8, 9].

In contrast with the regular techniques the industrial wastewater treating by electrocoagulation-flotation process has more prominent capacity to eliminate the COD, BOD and TSS [10, 11].

Electrochemical water treatment are green methods not harmful to the ecosystem have gained popularity in recent years. Electro-coagulation one of best technologies for treating wastewater. ECF cycle has various benefits, including simplicity of operations, short treatment times, low production of sludge, and free chemicals additions [12, 13].

To reduce costs using onsite sustainable/renewable-energy sources with energy-storage systems as backup power for ECF processes. These sources include solar photovoltaic [14].

The electro-coagulation cycle contains in-situ production of coagulant by anode electrode dissolution, generally Fe or Al. This presents metal particles that are powerful in the destabilizing of suspended contaminants. Likewise, in the slightly basic pH range, production of hydroxide species polymerizes into $Al_n(OH)_{3n}$ that can capture the contamination's. At last, the partition of these pollutants happens by flotation or settling. It is feasible to exploit the H_2 gas produced at the cathode for the last option reason concerning unsettling. EC standards can be tracked down in electrochemical advancements applications for treating waste waters [15].

The coagulant produced by EC delivered "in situ” as show in (**figure 1**). It includes three progressive steps.

1- Dissolution of the anode electrodes.

2-Destabilizing the impurities, breaking of emulsions and particulates suspension.

3-Forming the floc by aggregation of destabilized stage.

The anode reaction produces iron or aluminum hydroxide in the form of an aqueous gelatin suspension known as flocs, which use electrostatic attraction and coagulation to remove pollutants from wastewater by sedimentation as in (Eq. 1,2).

The reduction of metal ions (Eq. 4) and $H_{2(g)}$ is produced at cathode electrodes as in (Eq. 3) will treat the dissolved organics by flotation [16, 17].

At anode:

$$M_{(s)} \rightarrow M^{n+}(aq.) + n\ e^- \quad (1)$$

$$2\ H_2O \rightarrow 4\ H^+_{(g)} + O_{2(g)} + 4\ e^- \quad (2)$$

At cathode:

$$2\ H_2O_{(l)} + 2e \rightarrow H_{2(g)} + 2\ OH^-_{(aq.)} \quad (3)$$

$$M^{n+}_{(aq.)} + n\ e^- \rightarrow M_{(s)} \quad (4)$$

Overall reaction

$$M_{(s)} + 2\ H_2O_{(l)} \rightarrow M(OH)_{n\,(s)} + H_{2(g)} \quad (5)$$

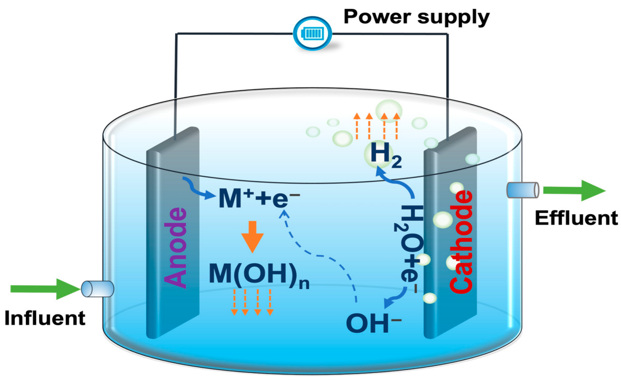

Figure 1. Electrochemical Cell diagrammatic.

The most common passivation control method employs the polarity reversal electro-coagulation (PR-EC) technique, which alternates the direction of a direct current on a regular basis and is also known as an alternating pulsed current [18].

Several studies are represented for organic and inorganic pollutants removal by using electro-coagulation techniques. However, electro-coagulation used for highly organic contamination [19].

Electro-coagulation wastewater treatment presents a promising alternative to conventional methods. While the technology is still developing, it offers advantages in terms of pollutant removal and environmental impact.

The extent of this study is to evaluate the cost and technical ECF process for liquid waste treatment. the results of the newly designed lab scale reactor for electro-coagulation-flotation process in terms of its efficiencies and integration for treating liquid waste was represented. ECF technology is better than biological, physical and chemical methods in small size and no need for large scale area, low in production of sludge, easier in operation and highly water recovery by investigating the of the impacts of different operational parameters as current density, initial pH, working time, electrode gaps and electrode material types on the TSS, BOD and COD removal efficiency to achieve the treatment of liquid waste efficiently and reduce the energy consumption. Also considering of the zero liquid discharge (ZLD).

2. Experimental

2.1. Setup of experiments

For six months batches were collected from the inlet of Tanta wastewater treatment plant, Tanta, Egypt. The samples were bottled in plastic container and preserved taken to laboratory for analysis. All samples were analyzed their water parameters as PH, Conductivity, Total Dissolved Solids (TDS), Total Suspended (TSS) Solids, Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) according to Standard Methods for the Examination of water and wastewater, 22editions. The samples were collected after each batch analyzed after filtration through (0.45 µm) filter paper before and after the Electro-coagulation/flotation process.

At this work using batch process which comprising of Electrochemical cell (EC), magnetic stirrer at 100 rpm, Direct current DC power supply from (0 to 10 A) and pH meter at room temperature (25 °C ±2).

EC is constructed of acryl glass. The feed enters the cell through the bottom-located pipe and drains out through the top.

Operating parameter for this work show in (**figure 2**) two up and down pipes are closed and worked in a batch scale. Al and Fe electrodes were used with 2.5 mm in thick, and arranged in monopolar connection. Electrode width W = 100 mm and electrode length

L = 150 mm the active surface area of electrodes which immersed in to the electrolyte was 100 cm^2.

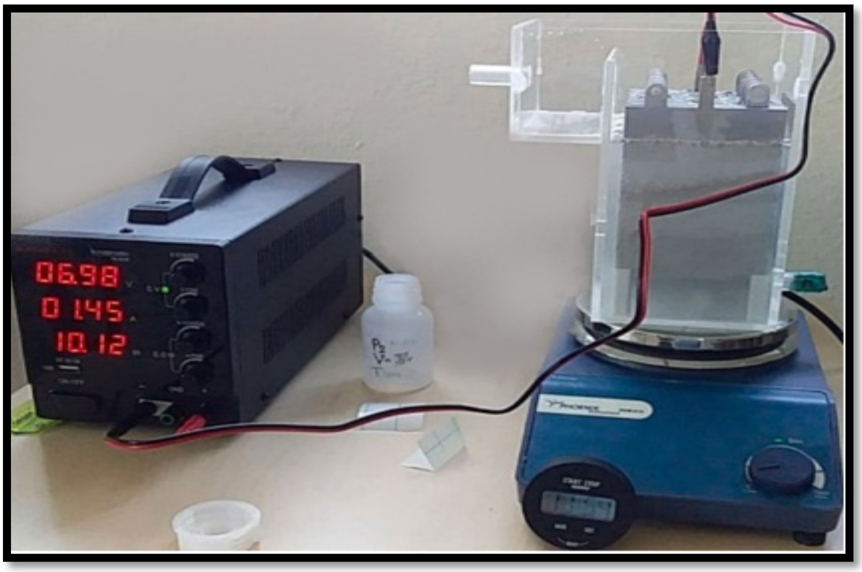

Figure 2. Electrochemical Cell.

In the Experimental the Current density was used 1 to 4 mA/cm^{2}for operating Time 2 to 8 min at Initial pH 4.5 to 10.5 pH

2.2. Calculations

% Removal efficiency = $\frac{C_o - C}{C_o} \times 100$ (Eq. 6)

Where:

C_o is initial and C is final concentration. Operational cost (OC) for 1 m^3 treated liquid waste.

OC = (Energy + electrodes) consumption cost Energy consumption (Ec) calculated from

$$Ec\ (kwh) = \frac{V \times I \times t}{V \times 1000} \quad \text{(Eq. 7)}$$

Where V = voltage in volt, I = current in A, t = electrolysis time in h and v = volume treated in m^3

Electrodes consumption for 1 m^3 treated water theoretically calculated by Faraday's law (Eq. 8).

$$m = \frac{I \times t \times M_{wt}}{Z \times F \times V} \quad \text{(Eq. 8)}$$

Where m = electrode consumption in (g\m^3), I = the current in (A), M_{wt}= molecular weight of the metal of electrode in (g\mol), z = no of involved electrons and F = faradays constant = 96,485 in (C\mol).

The actual calculation for electrodes consumption calculated by difference in electrodes masses before and after treating a given volume in a given time.

3. Results and discussion

In an ECF the electrodes associated with an outside DC source. The amount of electricity that passes through the electrolytic solution determines how much metal is dissolved or deposited [20]. In this work Al and Fe Electrode materials: aluminum alloy 5056 of series 5000, high purity Al sheet Al = 99.9 % and carbon steel in which the main elements are iron (Fe) = 98.95 were used for treating inlet samples for wastewater treatment plant in Tanta with the characteristics listed in table (1).

Table 1. Characteristics of raw wastewater samples.

Items		***Results Range***
Temp.	° C	29:30
pH	-	7: 7.8
Conductivity	µS\cm	1930:1950
TDS	ppm	922:927
TSS	ppm	230:250
COD	ppm	500:520
BOD	ppm	250:280

3.1. Current density effect (mA\cm^2)

In EC technology, Current density (CD), defined as the amount of current passing through a unit area of an electrode.CD has the most significant working parameters [21].

CD identifies the advancement of hydrogen gas at cathode and the coagulant measurement at the anode.

In this work, there were 6 electrodes altogether, 3 electrodes as anode and 3 electrodes as cathode. Which arranged in monopolar connection the anode dissolution speed and the formation of hydrogen are both controlled by the applied current [22].

At 8 minutes, an electrode distance of 2 cm, and initial pH7.5, the efficiencies of removal of Biochemical oxygen demand, chemical oxygen demand, and total suspended solids were examined in relation to the variation of this parameter between 1 and 4 mA\cm^2. CD of 3.5 mA/cm^2 result in most extreme removal for all COD, BOD, and TSS utilizing. (**Figures 3 and 4)** show that as the current density rises, more metal cations dissolve from the anode, resulting in the formation of H_2 bubbles. Be that as it may, Highest CD the more size of the hydrogen bubbles which quicker elimination of contamination by flotation [22,23].In**(figure 3**) aluminium electrodes show higher removal efficiency than iron electrodes in **(figure 4**) at the same current because more aluminium ions are released into the solution, leading to the formation of a larger quantity of aluminium hydroxide coagulant. The increased coagulant concentration can result in improved contaminant removal, especially for larger or more complex particles.

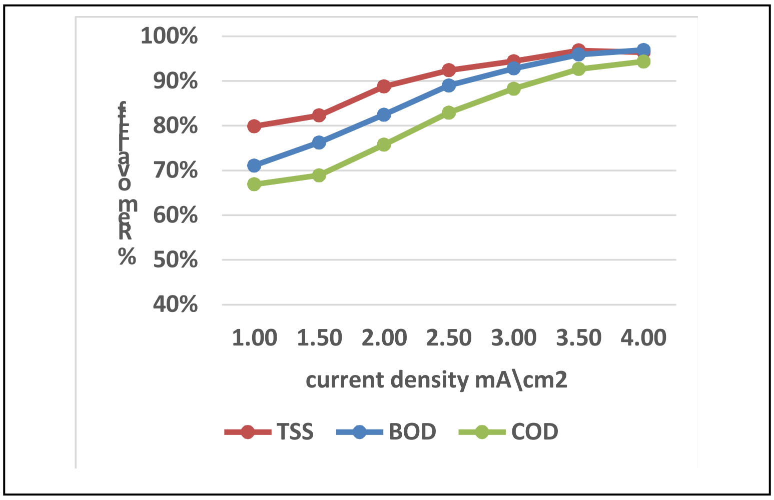

Figure 3. CD effect on TSS, BOD and COD removal efficiency by using AL electrodes.

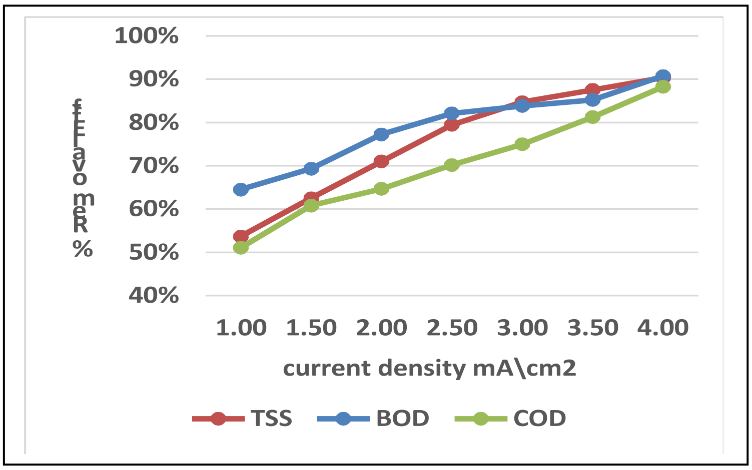

Figure 4. CD effect on TSS, BOD and COD removal efficiency by using Fe electrodes.

3.1.2. Initial pH value

It has been demonstrated that process of electro-coagulation is highly pH-dependent. The experiments were carried out with an electrode distance of two centimetre, a current density of 3.5 mA/cm^2, and an initial pH of 4 to 12 after 5 min. As displayed **Figures 5 and 6)** TSS, BOD and COD eliminations efficiencies were viewed as the best close to slightly basic pH = 8.5 involving the two sorts of electrodes as they were for Fe electrodes 96 %, 94 % and 95 % however the most elevated one was by involving aluminum electrodes at pH = 7.5 as it accomplishes 98 % 96 and 97 % individually. The pH value increased as the EC process's operating time increased. This is because of the accumulation of OH^- ions in aqueous solutions. Operating at lower pH and higher pH than the optimum operating condition of pH value was resulting in decreasing of the removal efficiencies of contaminants. It is observed that the performance of pollutants removal efficiency for using Al electrodes was wider pH range than Fe electrodes. The soluble Al and Fe hydroxide compounds as Fe(OH)3 at pH value between 5.5-8.5 [24] and the formation of Al(OH)3 at pH value between 4-10 [25].Al electrodes was better than Iron electrodes at pH7.5 [26]; rather the final pH has greater effect in the removal efficiency of waste water contaminants [27].

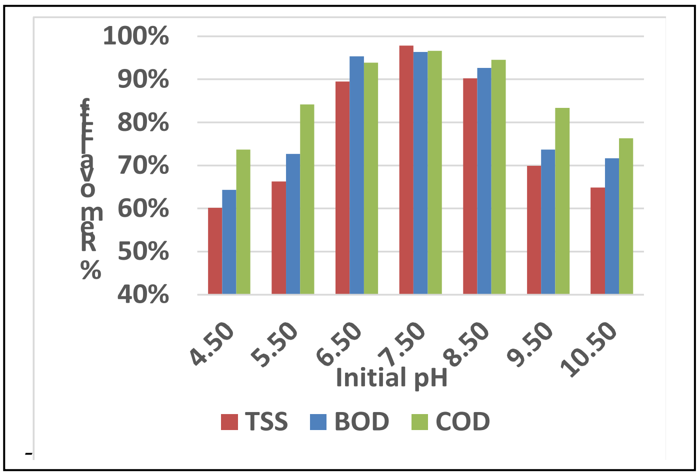

Figure 5. Initial pH effect on TSS, BOD and COD removing efficiencies by using Al electrodes.

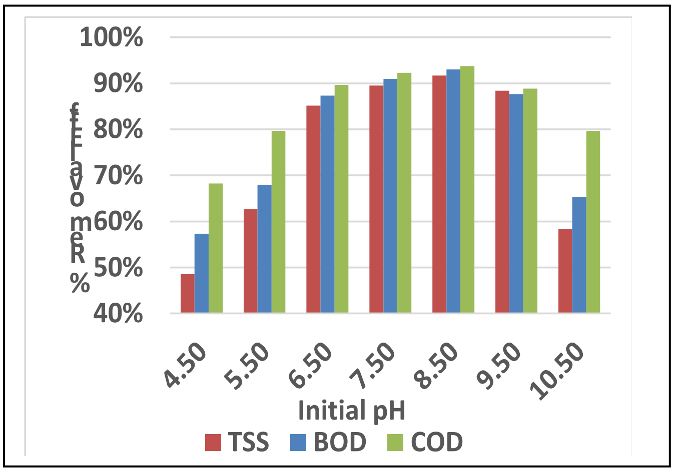

Figure 6. Initial pH effect on TSS, BOD and COD removing efficiencies by using Fe electrodes.

3.1.3. Effect of electrodes materials

The ongoing treatment heart is electrode get together. The most common materials for electro-coagulation electrodes are iron and aluminum [28]. As per **(Figure 7)**, the aluminum cathode's trial removal efficiencies for Complete TSS, COD and BOD were 98 %, 97 % and 96 %, while the Fe electrode elimination efficiencies for the previously mentioned water quality boundaries (TSS, COD and BOD) were 94 %, 95 % and 93 % separately.

The electrodes materials were studied in arrange of monopolar connection, CD = 3.5 mA\cm^2, electrode spacing 20 mm, initial pH = 7.5 and solution conductivity 1750 µS\cm Removal efficiencies was observed for using iron electrodes lower than Al plate electrodes [29]. The iron electrode-treated effluent becomes yellow within the few min of treatment. This may be come of ferric and ferrous particles.

Fe^{2+} is the particles made in situ of electrolysis of Fe anode ferrous are weak in coagulation because of its law positive charge. It dissolves readily in neutral or acidic conditions and is easily oxidized into Fe^{3+} by water's dissolved oxygen [30]. Aluminum generates aluminum hydroxides during electro-coagulation, which are more effective at adsorbing and precipitating pollutants compared to iron hydroxides. This leads to better coagulation and pollutant removal efficiency.The emanating that was treated with an aluminium electrode seemed white interestingly and stayed white in the interim; no settling of sludge, just white froth was created as the electrode was dissolved and trivalent aluminium (Al^{+3}) was delivered.Aluminum-based electro-coagulation can work effectively over a wider pH range (typically pH 4-9), whereas iron tends to work optimally in a narrower pH range, limiting its versatility in varying wastewater conditions.In contrast to iron-based systems, which frequently create more voluminous and challenging-to-dewater sludge, aluminium-based electro-coagulation systems typically produce sludge that is easier to manage and has a lower volume.

Aluminum has better corrosion resistance and slower oxidation rates compared to iron, which leads to more stable performance over time. Iron can undergo oxidation, forming passivating layers that reduce its effectiveness during the process.

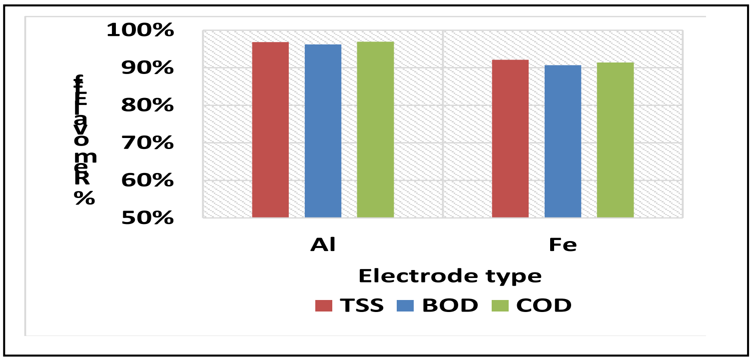

Figure 7. Effect of electrode type on TSS, BOD and COD removal efficiency.

3.1.4.Time of retention

ECF retention time very important it has a fundamental significance also, impact on the efficiency of ECF process. At a constant distance of two centimeters and a constant current density of 3.5 mA/cm^2, initial pH = 7.5 and monopolar connection of electrodes the effect of time was examined in this experiment. **(Figure 8)** and **(Figure 9)** delineates the effect of contact time on the removal of contaminants utilizing two Al and Fe electrodes at neutral pH. If the contact time for electrolysis more than optimum time, the contaminants removal efficiency will not be good as result of insufficient floc density production [31]. EC includes two phases which are destabilization and aggregation. The first stage is typically short, while the second stage tends to be fairly lengthy. Results show that the effectiveness begin to be critical for some contaminates at the treatment time of 5 min. however the most extreme efficiency was gotten at operating time of 8 min. for the pollutants studied, the elimination efficiency is significantly improved with treatment duration. It is assumed that the rate of hydroxyl and metal ion production on the electrodes increases with time, especially above 6 minutes.
Aluminium Electrode at Extended operation improves the elimination of pollutants. The production of sludge rises but stays below that of iron Electrode which improve the initial removal of pollutants but may lead to increased sludge, rust-induced electrode passivization, and the possible production of secondary pollutants such as iron oxides.

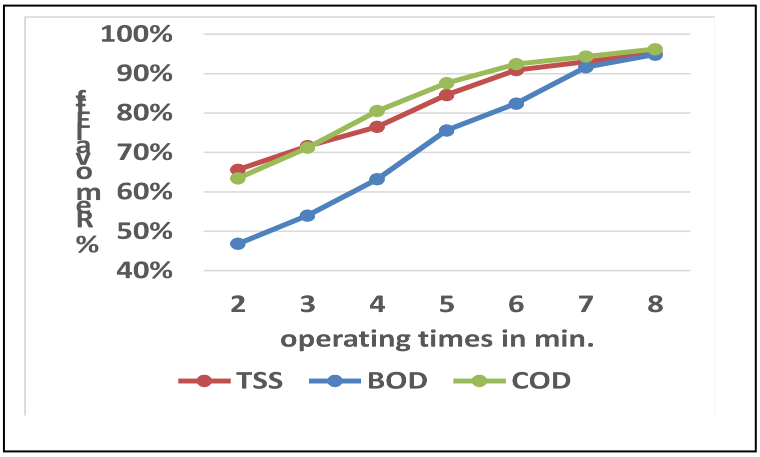

Figure 8. Effect of operating time on TSS, BOD and COD removal efficiency by using Al electrodes.

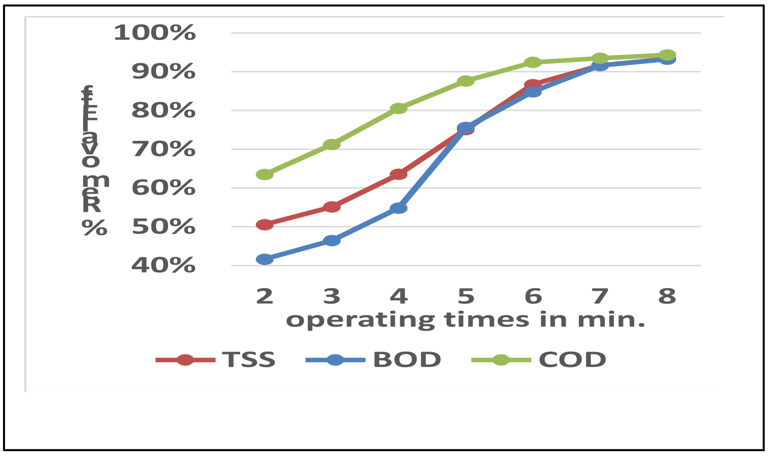

Figure 9. Effect of operating time on TSS, BOD and COD removal efficiency by using Fe electrodes.

3.1.5. Spacing between electrodes

Studying the impact of inter-distance between the electrodes on the electro-coagulation techniques for the removal of pollutants from sewage, Disparate spaces between the electrodes were reasonable. Because of Bukhari [28] ascend in the spacing between anode and cathode electrodes will reduce the expense of treatment however could reduce also the process performance. Separating the electrodes by distance of 20 to 40 mm was intended to study the impact on efficiencies of pollutant removal in domestic sewage for TSS, BOD and COD by using EC containing Al and Fe electrodes and applying CD = 3.5 mA\cm^2, initial pH = 7.5, electrodes was connected in monopolar arrange and conductivity of electrolyte solution was 1930 µS\cm retention time of 8 min. Materials of the electrode impacted the proficiency of sewage treatment conduct as results of their mechanism. The results represented in **(figure 10 and 11)** show that the higher removal efficiencies were 99 %, 97 % and 98 % respectively obtained by using Al electrodes for TSS, COD and BOD but for using Fe as electrodes it was 94 %, 92 % and 93 % at 20 mm spacing between electrodes.

At small space between Aluminum electrode Increases Al^{3+} production, enhances pollutant removal efficiency, improves flotation via smaller bubbles, but may accelerate electrode passivization and increase sludge production.
While Iron electrode Boosts Fe^{2+}/Fe^{3+} generation, improves pollutant removal and flotation, but increases corrosion and sludge formation.
Wider Electrode Spacing:
Aluminum: Decreases coagulant production, reduces pollutant removal efficiency, lowers sludge volume, but increases energy consumption and reduces flotation efficiency.
Iron: Slows Fe ion generation, reduces pollutant removal efficiency, produces less sludge, but increases energy costs and decreases flotation efficiency.

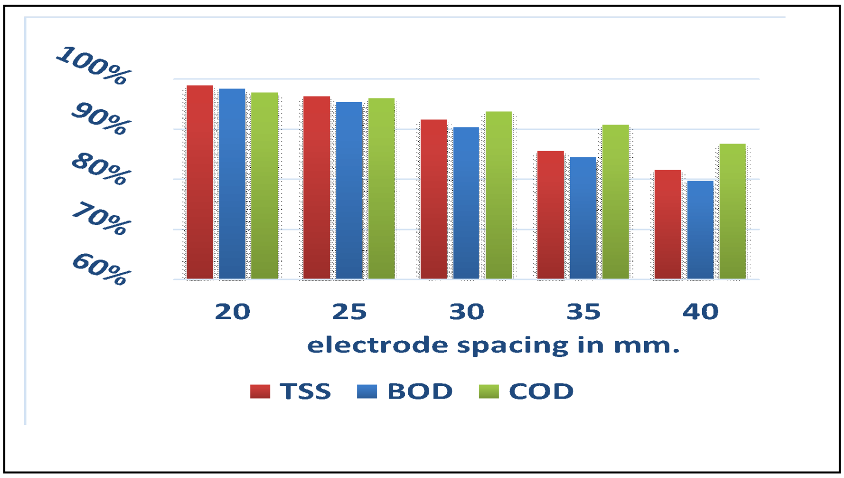

Figure 10. Effect of electrodes spacing on TSS, BOD and COD removal efficiencies by using Al electrodes.

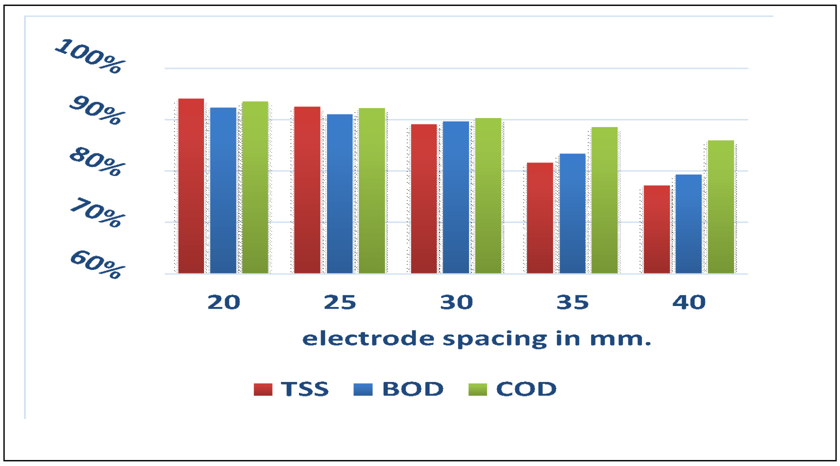

Figure 11. Effect of electrodes spacing on TSS, BOD and -COD removal efficiencies by using Fe electrodes.

3.1.6. Energy consumption and economic evaluation at optimum operating parameters

For each wastewater treatment technology must be cost-effective. Two main factors include energy cost, sacrificial electrodes. Electrical energy consumption is a crucial parameter for the EC technique that significantly affects the cost of operation.
Energy and electrodes consumption were calculated for using Al and Fe electrodes in EC process for liquid waste treatment, to evaluate the technical and economic efficiency at the optimum operating parameter's. The results in **(figure 12 and 13)** represent the electrodes consumption rate and energyconsumption as function in times. At optimum condition with conductivity solution was 1930 µS\cm and current density 3.5 mA\cm^2, initial pH = 7.5, electrodes were connected in monopolar arrange. For Al electrodes consumption was 0.0023 g\m^3 treated liquid waste and energy consumption was 0.294 kw h^{-1}\m^3. But for Fe electrodes consumption was 0.0047 g\m^3 treated liquid waste and energy consumption was 0.294 kw\m^3.The electricity commercial cost in Egypt for use is about USD 0.091 kWh−1 while the cost of commercial aluminium metal is USD 2.23 kg^{-1}.The cost of operation at these optimum conditions (pH 7, 3.5 mA cm^{-2}, and 8 min) was calculated and found to be USD 1.5 m^{-3}. Compared to similar studies, the EC unit under continuous flow conditions achieved reasonable cost-effective CSWW treatment. In a study by Potrich et al. [32] on nutrient removal from slaughterhouse wastewater using EC with aluminium electrodes, the electricity consumption was 14.1 kWh m^{-3}, sludge produced was 49.8 kg m^{-3}, and electrode material consumption of 0.15 kg m^{-3}, with a total cost around \$3.5 m^{-3}.Compared to conventional treatment methods such as chemical coagulation and biological treatment using activated sludge, the calculated operating cost was low.

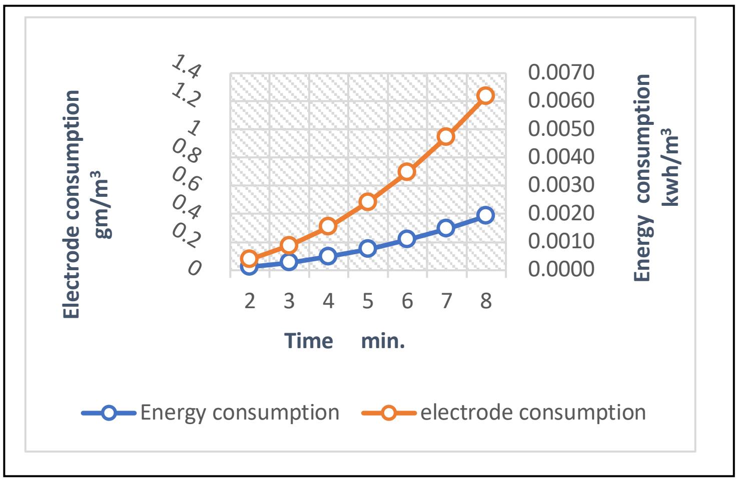

Figure 12. Electrode and energy consumption by using Fe electrodes.

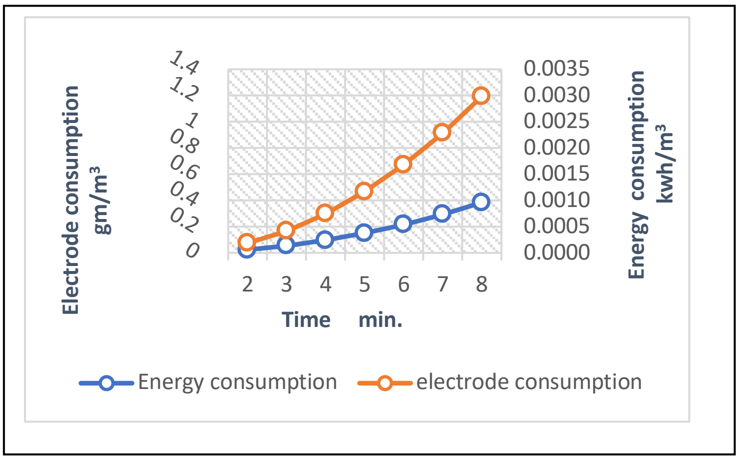

Figure 13. Electrode and energy consumption by using Al electrodes.

4. Conculsion

The following were the optimal conditions for this process: CD = 3.5 mA/cm^2, between electrode inter-distance dispersing = 20 mm, operating times = 8 minutes and initial pH =7.5. Due to their mechanisms, the various electrode materials affected the efficacy of wastewater treatment. The highest TSS removal was observed with aluminum electrodes (98 %). Fe electrodes recorded most elimination efficiency of COD (97 %) and BOD (96%). Due to their low cost and high removal efficiency, iron electrodes can also be used to treat wastewater. The applied current density has significant effect on the elimination proficiency of Electrocoagulation process. It discovered that increasing the CD between 1:3.5 mA/cm^2 improves the efficiency of the contaminants being removed. The connection of monopolar for electrode have an economic significant for lowering the operating cost. Electrodes consumption for Al was 0.0023 g\m^3 treated liquid waste and energy consumption was 0.294 kw\m3. But for Fe electrodes consumption was 0.0047 g\m^3 treated liquid waste and energy consumption was 0.294 kw\m^3. Electrochemical wastewater treatment presents a compelling solution for addressing the challenges of wastewater management. Its ability to effectively remove pollutants, reduce chemical use, and improve water quality makes it a valuable tool for promoting sustainability and environmental protection. As research and development continue, EWWT is poised to become a more widely adopted and impact technology in the field of wastewater treatment. The treated water after EC fulfills the Egypt guidelines for wastewater reuse.

Conflicts of interest

There are no conflicts to declare.

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