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# Comparative Analysis of Aluminum and Iron Electrode Performance in Electrocoagulation for Industrial Wastewater Treatment

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**ABSTRACT**
This study presents a comparative analysis of electrocoagulation for industrial wastewater treatment, evaluating the performance of aluminum (Al) and iron (Fe) electrodes. The research combines a systematic literature review with experimental trials on a pilot-scale system. Experimental data for Al electrodes revealed inconsistent performance, showing a significant COD reduction at high pollutant concentrations but a paradoxical increase at low concentrations. This increase is attributed to the formation of soluble organic complexes. Conversely, experimental trials with Fe electrodes demonstrated consistent COD reduction across a range of influent concentrations. Fe electrodes successfully reduced COD by 1010 mg/L (from 2660 mg/L) and 790 mg/L (from 3220 mg/L) on two separate days, confirming their superior stability. These findings validate the theoretical advantages of Fe over Al electrodes and underscore the importance of selecting electrodes based on wastewater characteristics. The study concludes that Fe electrodes provide a more reliable and stable solution for treating fluctuating industrial wastewater.

**KEYWORDS:** electrocoagulation; wastewater treatment; aluminum; iron; COD



## 1. INTRODUCTION

Industrial wastewater poses a significant challenge due to its variable and often high pollutant load, thus requiring reliable treatment technologies. In an electrocoagulation (EC) system, the choice of electrode material is critical because it determines the treatment's effectiveness, operational stability, and the characteristics of the resulting sludge. Aluminium (Al) and iron (Fe) are the most common electrode materials due to their availability and low cost. However, their performance varies significantly, which is a major factor in treating industrial wastewater with its inherent fluctuations in pollutant concentration.

Al electrodes are particularly effective at treating wastewater with high pollutant concentrations, but their performance can be inconsistent. At low COD concentrations, the $Al^{3+}$ ions released from the electrode may not find enough pollutants to bind to, instead forming soluble organic complexes. This can paradoxically increase the COD and turbidity of the effluent, making the treatment ineffective or even detrimental.

Additionally, the flocs produced by Al electrodes are often lighter and more difficult to settle, which poses challenges for the subsequent sludge separation process. In contrast, Fe electrodes demonstrate more stable performance across a wider range of pollutant concentrations and are less prone to forming soluble complexes. This consistency makes them a more reliable and stable option for treating wastewater with fluctuating COD loads. The flocs produced by Fe electrodes are typically heavier and settle more easily, which simplifies the solid waste management process.

While previous research has discussed the mechanisms behind COD removal and sludge characteristics, direct comparisons with concrete experimental data for fluctuating wastewater conditions remain limited. This study aims to fill that gap by providing a data-driven basis for selecting the most suitable electrode material for industrial wastewater treatment. A comprehensive review highlighted that while EC is a promising technology, its full potential is often limited by a lack of understanding of optimal operational conditions for specific wastewater types and electrode materials [1].

The aim of this study is to directly compare the performance of Al and Fe electrodes for treating industrial wastewater with fluctuating COD concentrations, thereby providing a practical, data-driven basis for electrode selection.

## 2. METHOD

This study employed a dual methodology consisting of a systematic literature review and a comparative experimental analysis. This study utilized a pilot-scale electrocoagulation unit to conduct comparative trials on aluminium (Al) and iron (Fe) electrodes. The unit was configured with a portable plastic tank measuring 70 cm (length) x 40 cm (width). Inside the tank, five pairs of parallel plate electrodes were installed, each measuring 15 cm (width) with an immersed height of approximately 20 cm. The total volume of wastewater treated in each trial was 15 liters. Separate experiments were conducted for each electrode material, ensuring that all operational parameters remained constant for a fair comparison. For both the Al and Fe electrode trials, the treatment conditions were standardized. A constant direct current of 50 A was applied for a duration of 60 minutes. The water temperature during the process was maintained at 70°C. Wastewater samples were collected over several days to capture a wide range of Chemical Oxygen Demand (COD) concentrations. The effectiveness of each electrode type was determined by measuring the influent and effluent COD levels, with the percentage of COD reduction calculated to provide a data-driven basis for comparison.

### 2.1 Literature Review

Industrial wastewater treatment is a significant challenge due to its variable characteristics and high pollutant loads, requiring reliable technology to ensure compliance with environmental standards [2]. Electrocoagulation (EC) has emerged as an efficient method for wastewater treatment, using an electric current to destabilize contaminants and form flocs for easy removal [3]. Compared to conventional chemical treatment methods, EC offers advantages such as smaller sludge footprint, competitive operational costs, and high removal efficiency for various pollutants, including heavy metals like arsenic [4] and contaminants from metal plating wastewater [5, 6]. The effectiveness of the EC process is highly dependent on the choice of electrode material, with aluminum (Al) and iron (Fe) being the most used due to their availability and low cost [7]. However, the performance characteristics of these two materials vary significantly.

Al electrodes are known for their ability to treat wastewater with high pollutant concentrations. However, studies show that the performance of Al electrodes tends to be inconsistent, especially at low COD concentrations. Under these conditions, the released $Al^{3+}$ ions may fail to find enough pollutants to bind to, instead forming soluble organic complexes [7]. This phenomenon can paradoxically increase the COD and turbidity of the effluent, making the treatment process ineffective and even detrimental. Furthermore, Al electrodes are known to produce lighter flocs that are often difficult to settle, posing a challenge in the subsequent sludge separation process [1]. In contrast to Al electrodes, Fe electrodes exhibit more stable performance across various pollutant concentration ranges. Scientific literature supports the idea that Fe electrodes are less prone to forming soluble complexes, thus being able to more effectively precipitate pollutants [7]. This consistent performance makes them a more stable and reliable option for treating wastewater with high COD fluctuations. Another operational advantage is that Fe electrodes tend to produce heavier and more easily settled flocs, which greatly facilitate sludge separation and solid waste management processes [1].

Although EC is a promising technology, its full potential is often limited by a lack of understanding of optimal operational conditions for specific wastewater types and electrode materials [1]. Existing research has discussed the mechanisms behind COD removal and sludge characteristics, but direct comparisons with concrete experimental data for fluctuating wastewater conditions remain limited. Therefore, the objective of this study is to directly compare the performance of Al and Fe electrodes for treating industrial wastewater with fluctuating COD concentrations, thereby providing a practical, data-driven basis for better electrode selection.

### 2.2 Experimental

The experimental component was carried out using a pilot-scale electrocoagulation unit. Two separate trials were conducted using distinct electrode materials: one with Al electrodes and another with Fe electrodes.

- Wastewater Samples: Wastewater samples were collected over several days to capture a wide range of COD concentrations.
- Electrode Configurations: The first set of experiments used Al plates as electrodes, while the second set used Fe plates.

- Data Collection: For each trial, the influent and effluent COD were measured to determine the COD reduction. The percentage of COD reduction was calculated using the following formula:

$$\text{COD Reduction (\%)} = \frac{COD_{inlet} - COD_{outlet}}{COD_{inlet}} \times 100\% \quad (1)$$

## 3. RESULT AND DISCUSSION

### 3.1 Performance of Aluminum (Al) Electrodes

The trial process using Al with a small-scale electrocoagulant was conducted on July 2, 3, 7, 8, 9, and 11, 2025. Experimental data for the Al electrodes revealed a highly inconsistent performance, which was heavily dependent on the initial COD concentration. The Al electrodes were effective in reducing high COD values but proved to be ineffective at low COD concentrations. This is shown in Table 1.

**Table 1.** Results of Al electrode testing

| Date | COD Inlet (mg/L) | COD Outlet (mg/L) | Reduction (mg/L) | Percentage Reduction (%) |
|---|---|---|---|---|
| 2 Juli | 1644 | 1130 | 514 | 31,26% |
| 3 Juli | 519 | 807 | -288 | -55,5% (Increase) |
| 7 Juli | 734 | 1171 | -437 | -59,5% (Increase) |
| 8 Juli | 4530 | 2650 | 1880 | 41,5% |
| 9 Juli | 6200 | 2630 | 3570 | 57,6% |
| 11 Juli | 2230 | 3070 | -840 | -37,7% (Increase) |

**Figure 1.** Electrocoagulation process using Al electrodes

On dates with low influent COD, the Al electrodes caused a COD increase, as evidenced by the negative percentage values. This phenomenon is supported by scientific literature explaining that at low COD conditions, the $Al^{3+}$ ions tend to form soluble organic complexes instead of precipitating flocs. This directly increases the COD and turbidity of the effluent, rendering the treatment process ineffective and even detrimental.

### 3.2 Performance of Iron (FE) Electrodes and Comparative Analysis

The trial process using Fe with a small-scale electrocoagulant was conducted on July 20, 21, 29, and 30, 2025. In contrast to the inconsistent performance of Al electrodes, trials with Fe electrodes demonstrated consistently positive results across a range of influent COD concentrations. The Fe electrodes successfully reduced COD on all trial dates (Table 2). The stable performance of Fe electrodes is consistent with findings from various international journals that state Fe electrodes are less prone to forming soluble complexes and are capable of effectively precipitating pollutants across various concentrations Query successful Fe electrodes are more reliable than Al electrodes because they form more stable and effective compounds for contaminant removal. When an electric current is applied, Fe electrodes release iron ions ($Fe^{n+}$) that hydrolyse in water to form iron hydroxides, such as ferric hydroxide ($Fe(OH)_3$). This compound is known to be highly stable and insoluble, which allows it to effectively bind with pollutants and form heavy, dense flocs. These heavy flocs sink quickly, making the subsequent sludge separation process much easier [16].

Conversely, Al electrodes release aluminium ions ($Al^{3+}$). While these ions are effective at high pollutant concentrations, they tend to form soluble organic complexes rather than insoluble precipitates when the pollutant load is low. This phenomenon is a key reason for the inconsistent performance of Al electrodes, as it can paradoxically increase the COD and turbidity of the treated effluent. The flocs produced by Al are also lighter and more difficult to settle, which complicates solid waste management. Therefore, the stable, non-complex-forming nature of iron hydroxides provides a more reliable chemical mechanism for treating fluctuating industrial wastewater compared to the inconsistent behaviour of aluminium complexes [9].

**Figure 2.** Electrocoagulation process using Fe electrodes

**Table 2.** Results of Fe electrode testing

| Date | COD Inlet (mg/L) | COD Outlet (mg/L) | Reduction (mg/L) | Percentage Reduction (%) |
|---|---|---|---|---|
| 20 Juli | 2660 | 1650 | 1010 | 37,97% |
| 21 Juli | 2340 | 1870 | 470 | 20,09% |
| 29 Juli | 2200 | 1880 | 320 | 14,55% |
| 30 Juli | 3220 | 2430 | 790 | 24,53% |

The graph presents a comparison of the performance between Aluminum (Al) electrodes and Iron (Fe) electrodes in the electrocoagulation process to reduce the Chemical Oxygen Demand (COD) of wastewater.

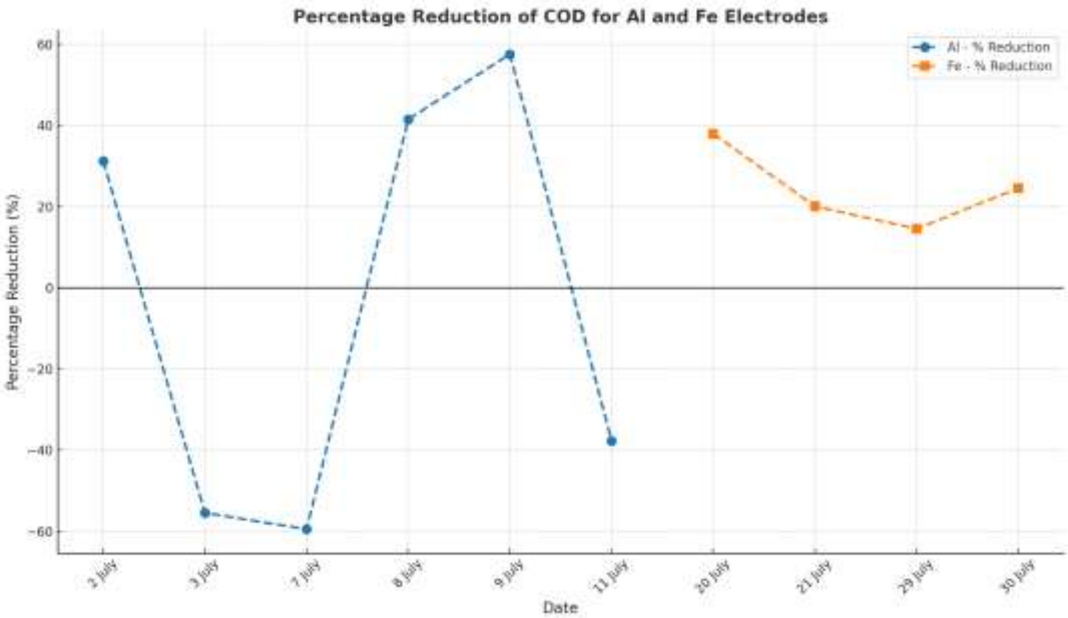


**Figure 3.** Comparison of Al and Fe electrode usage

The graph demonstrates that the performance of the Al electrode is highly unstable and not suitable for wastewater with low COD values. Effective COD reduction was observed on July 2, July 8, and July 9, where the Al electrode showed a significant decrease, reaching 57.58% on July 9. This data is consistent with findings in the literature showing that Al electrodes are very effective in treating wastewater with high pollutant concentrations [1, 7, 10].

Conversely, on July 3, July 7, and July 11, the Al electrode caused an increase in COD, as indicated by the negative percentage values. This increase was very significant, reaching -59.54% on July 7. This phenomenon is supported by scientific literature explaining that at low COD conditions, the $Al^{3+}$ ions produced tend to form soluble organic complexes rather than precipitates [11, 12, 13]. The formation of these complexes directly increases the COD level and effluent turbidity, making the treatment process ineffective and even detrimental [11, 14].

In contrast to the inconsistent performance of Al, the graph clearly shows that the Fe electrode provides stable and consistently positive results. In every trial (July 20, 21, 29, and 30), the Fe electrode successfully reduced COD, with a percentage reduction ranging from 14.55% to 37.97%. This stable performance is consistent with findings from various international journals stating that Fe electrodes are less prone to forming soluble complexes and are capable of effectively precipitating pollutants at various concentrations [1, 11, 15]. In addition to their effectiveness in COD reduction, the literature also supports that Fe electrodes produce heavier flocs that are easier to settle [11, 16, 17]. This represents a significant operational advantage as it facilitates the subsequent sludge separation process.

## 4. CONCLUSION

This study successfully compared the effectiveness of aluminum (Al) and iron (Fe) electrodes in an electrocoagulation system. Experimental data confirmed that Al electrodes are unreliable for wastewater with low COD concentrations, often causing a paradoxical increase in pollutant load. In contrast, Fe electrodes were found to be consistently effective at all tested COD levels, making them a stronger and more stable solution.

Future research on electrocoagulation using Al and Fe electrodes should prioritize the systematic optimization of operational parameters. Parameters like current density, voltage, and pH are especially important as they directly affect pollutant removal efficiency and energy demand. Current density and applied voltage (e.g., within the range of 10–40 V, with some studies reporting optimal performance around 30 V) should be systematically tested to identify the ideal balance between removal efficiency and operating cost. Likewise, maintaining the wastewater pH within the optimal range of 5–9 (preferably near neutral) can enhance COD reduction and improve floc formation. In addition, other operational factors like temperature, reaction time, electrode spacing, and electrode configuration should be integrated into an optimization framework to establish robust, cost-effective, and energy-efficient conditions for long-term application.

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