EQUILIBRIUM JOURNAL OF CHEMICAL ENGINEERING
*Homepage:*https://jurnal.uns.ac.id/equilibrium

Performance of Fe-Graphite Electrodes for COD Removal from POME during a 30-min Electro-Fenton Treatment

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DOI: *https://dx.doi.org/10.20961/equilibrium.v10i1.122378*

Article History
Received: 26-06-2026, Accepted: 05-08-2026, Published: 06-08-2026

Keywords:
Chemical Oxygen Demand (COD), Current Intensity, Electro-Fenton, Organic Degradation, Palm Oil Mill Effluent (POME).

ABSTRACT. Palm oil mill effluent (POME) contains a high organic load and requires treatment before discharge. This study evaluated chemical oxygen demand (COD) removal and organic degradation in POME using an electro-Fenton system equipped with an iron anode and a graphite cathode. POME had an initial COD concentration of 86,382.74 mg/L and a pH of 4.15. Experiments were conducted for 30 min at 300 rpm, with an interelectrode distance of 3 cm and an H_2O_2/COD ratio of 0.425. The applied current was varied from 0.10 to 0.70 A, while other conditions were maintained constant. COD removal increased as the current was raised to 0.55 A, achieving the highest removal efficiency of 45.93%. However, increasing the current to 0.70 A decreased the removal efficiency, presumably because of competing reactions, including hydrogen evolution and H_2O_2 decomposition. Kinetic analysis demonstrated that the Behnajady-Modirshahla-Ghanbary (BMG) model provided the best fit to the COD degradation data at 0.55 A, with an R^2 value of 0.9977. This result confirms the suitability of the BMG model for representing COD degradation under these conditions. Unlike previous POME studies that primarily investigated chemically supplied Fenton reagents or electrochemical oxidation using non-sacrificial anodes, this study integrates a sacrificial iron anode–graphite cathode system with short-term current evaluation and comparative COD kinetic modeling. Overall, the findings indicate that electro-Fenton treatment can partially reduce the organic load of high-strength POME within 30 min.

1. INTRODUCTION

The palm oil industry plays a significant role in Indonesia's economy; however, it also generates large volumes of liquid waste known as Palm Oil Mill Effluent (POME). This wastewater is characterized by a high organic content, with Chemical Oxygen Demand (COD) levels reported to reach approximately 90,000 mg/L [1]. Moreover, POME typically exhibits acidic properties and contains complex organic compounds that are resistant to degradation, creating potential environmental risks when discharged without adequate treatment [2].

Among the available treatment technologies, biological processes such as anaerobic digestion have been extensively implemented due to their relatively low operational costs [9]. Despite this advantage, biological treatment often requires long hydraulic retention times and may not effectively remove recalcitrant organic compounds, resulting in limited COD reduction under certain conditions [11]. These challenges have encouraged the exploration of alternative treatment methods capable of providing faster and more efficient pollutant removal.

Advanced Oxidation Processes (AOPs) have gained considerable attention as an alternative approach for treating wastewater with high organic loads. The effectiveness of AOPs is primarily attributed to the generation of hydroxyl radicals (•OH), which possess strong oxidizing properties and are capable of transforming complex organic molecules into simpler compounds that are more readily degraded [3]. Consequently, AOP-based technologies are increasingly considered promising options for overcoming the limitations associated with conventional treatment processes.

One of the most widely investigated advanced oxidation processes (AOPs) technologies is the electro-Fenton process. In this system, hydrogen peroxide (H_2O_2) is generated in situ through oxygen reduction reactions occurring at the cathode surface [5]. The generated H_2O_2 subsequently reacts with iron(II) ions (Fe^{2+}) to produce

hydroxyl radicals (•OH), which act as the primary oxidizing species responsible for pollutant degradation [4]. Furthermore, the sacrificial iron anode continuously releases Fe^{2+} ions into the reaction medium, thereby sustaining the Fenton reaction and enhancing the overall treatment efficiency [6].

Previous studies on POME treatment using Fenton-based processes have mainly focused on optimizing operating parameters and maximizing COD removal. For example, investigated hydroxyl radical production and COD reduction using an electro-Fenton system applied to diluted POME [22]. Other studies employed externally supplied iron salts and H_2O_2 to treat POME that had undergone preliminary treatment [1]. Although these studies demonstrated the potential of Fenton-based oxidation for POME treatment, their results do not fully describe the degradation behavior of raw, high-strength POME treated with a sacrificial iron anode. Moreover, limited attention has been given to the effect of applied current on short-term COD degradation and its kinetic characteristics in an iron-graphite electro-Fenton system.

In contrast, the present study treated raw POME with an initial COD concentration of 86,382.74 mg/L using a iron anode and a graphite cathode during a 30-min electro-Fenton treatment. Applied currents ranging from 0.10 to 0.70 A were evaluated, and the COD degradation data were analyzed using first-order, second-order, and Behnajady-Modirshahla-Ghanbary (BMG) kinetic models [15]. The novelty of this work lies in combining a short-duration evaluation of the applied-current effect with kinetic interpretation using the BMG parameters, namely the initial normalized degradation rate (1/m) and theoretical maximum degradation capacity (1/b) [21]. Therefore, this study aimed to determine the optimum applied current and identify the kinetic model that most appropriately describes COD degradation in high-strength POME.

2. MATERIALS AND METHODS

2.1 Research Design

This study employed a quantitative experimental design by applying the Electro-Fenton (EF) process as a pre-treatment method for Palm Oil Mill Effluent (POME). The research focused on evaluating the effect of varying electric current intensities (0.1; 0.25; 0.4; 0.55; and 0.7 A) during a 30-minute operating period using iron–graphite electrodes. The selection of the electro-Fenton process was based on its ability to produce highly reactive hydroxyl radicals (•OH) in situ, thereby facilitating the breakdown of complex organic compounds into simpler species that are more readily degraded [5].

2.2 Research Object

The wastewater investigated in this study was raw Palm Oil Mill Effluent (POME) obtained from a palm oil mill in Jambi, Indonesia. Preliminary characterization showed an initial COD concentration of 86,382.74 mg/L and a pH of 4.15, indicating the high organic load and acidic characteristics of untreated POME [9]. No pretreatment was applied before the electro-Fenton experiments to preserve the original characteristics of the wastewater. All experiments were conducted using an iron anode and a graphite cathode.

Therefore, this study aimed to evaluate the effect of applied current, ranging from 0.10 to 0.70 A, on COD degradation in raw POME during a 30-min electro-Fenton treatment under fixed operating conditions. The study also aimed to identify the most favorable current within the investigated range and determine the kinetic model that most appropriately describes COD degradation

2.3 Research Procedure

2.3.1 Initial Analysis of POME Wastewater

The study commenced with the collection of 50 L of raw Palm Oil Mill Effluent (POME) from the effluent pond of PT Asia Sawit Lestari for use throughout the experimental study. From the collected wastewater, a 5-L sample was transferred into a sealed container and transported to PT Jambi Lestari Internasional (Environmental Consultant and Laboratory) for initial physicochemical characterization. The sealed container was used to minimize external contamination and possible biological and chemical changes during transportation. The initial pH was measured using a calibrated pH meter and was found to be 4.15, confirming the acidic characteristics of untreated POME.

The initial wastewater characterization included Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), oil and grease, sulfate (SO_4^{2-}), and total iron (Fe). These parameters were measured to provide baseline information on the organic load, suspended matter, and chemical composition of the raw POME before treatment. However, BOD_5, TSS, oil and grease, sulfate, and total Fe were

analyzed only to characterize the initial wastewater matrix, whereas electro-Fenton treatment performance was evaluated exclusively based on changes in COD concentration. The initial characterization procedure is summarized in Figure 1.

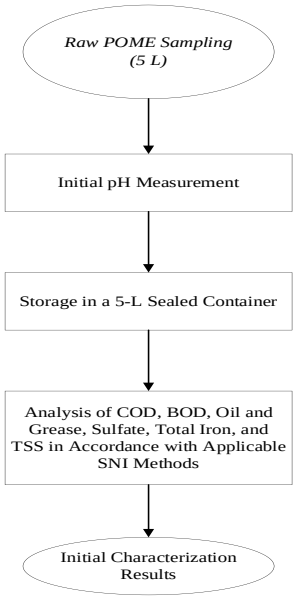


Figure 1. Flowchart of the Initial Characterization of Raw POME

The initial characterization results are presented in Table 1. The concentrations of COD, BOD, and TSS were determined to describe the organic load and suspended-solids content of the raw POME. Oil and grease, sulfate, and total Fe were also analyzed to provide a more comprehensive description of the initial wastewater matrix. These supporting parameters were measured only during the initial characterization and were not analyzed after treatment; therefore, their removal efficiencies were not evaluated. The performance of the electro-Fenton treatment was assessed exclusively based on COD degradation, in accordance with the primary objective of this study.

Table 1. Physico-Chemical Characteristics Of POME

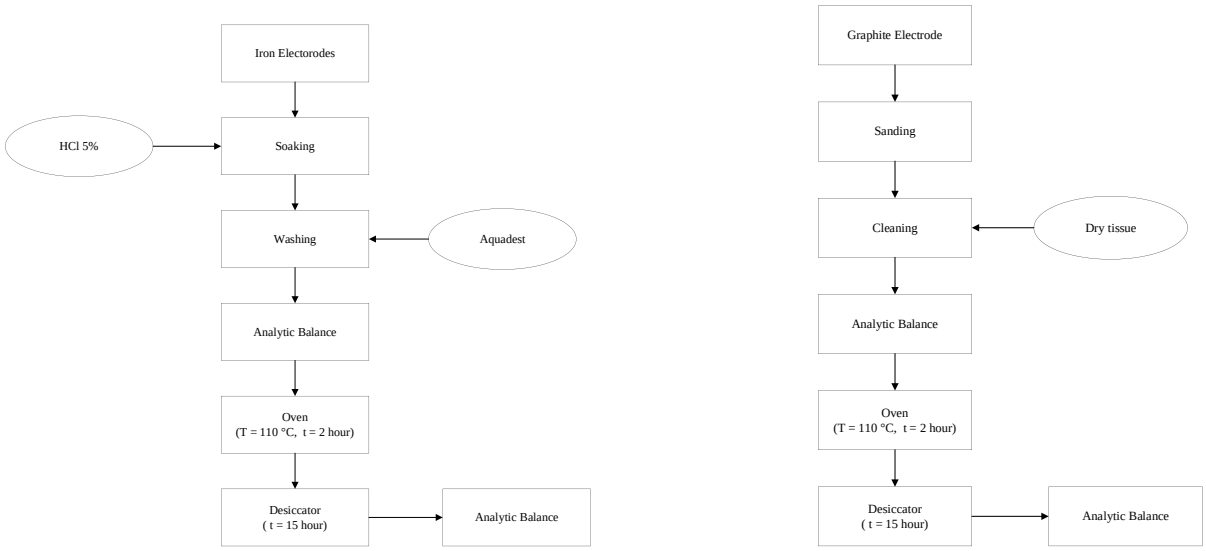
Parameter	Initial value	Unit	Analytical method
pH	4.15	–	Calibrated pH meter
Chemical Oxygen Demand (COD)	86,382.74	mg/L	IKML JLI-12 (spectrophotometric method)
Biochemical Oxygen Demand (BOD)	29,071.36	mg/L	SNI 6989.72:2009
Total Suspended Solids (TSS)	26,160.00	mg/L	APHA 2540 D (2017)
Oil and grease	962.06	mg/L	SNI 6989.10:2011
Sulfate (SO_4^{2-})	5,106.10	mg/L	SNI 6989.20:2019
Total iron (Fe)	13.01	mg/L	SNI 6989.84:2019

2.3.2 Electrode Preparation

Preparation of the iron (Fe) electrode was carried out using an iron plate with dimensions of 22 cm × 2 cm × 0.2 cm. The use of iron as a sacrificial anode was adopted from previous Electro-Fenton studies, where Fe^{2+} ions generated from the electrode surface contributed to hydroxyl radical production [15]. Prior to use, the iron plate was immersed in a 5% HCl solution for 30 min to remove surface oxides and other adhering impurities. A comparable acid-cleaning procedure, followed by rinsing with deionized water, has previously been applied to iron electrodes used in electrochemical wastewater treatment [16]. The electrode was subsequently rinsed thoroughly with distilled water to remove residual acid and detached contaminants. After washing, it was dried in an oven at 110 °C for 2 h and cooled in a desiccator for 15 min. Once it had reached room temperature, the cleaned

and dried electrode was weighed using an analytical balance to determine its initial mass before the electro-Fenton experiment.

A graphite rod measuring 22 cm in length and 0.6 cm in diameter was used as the cathode. Before use, the graphite surface was mechanically polished with fine-grit sandpaper to remove adhering impurities and obtain a clean, uniform surface. Mechanical polishing with sandpaper followed by rinsing with distilled water has previously been employed in the preparation of graphite-rod electrodes [17]. Loose particles remaining after polishing were removed, and the electrode was thoroughly rinsed with distilled water. The graphite rod was then dried in an oven at 110 °C for 2 h and cooled to room temperature in a desiccator to minimize moisture uptake. After cooling, the electrode was weighed using an analytical balance to determine its initial mass before treatment. A schematic representation of the electrode preparation procedure is presented in Figure 2.

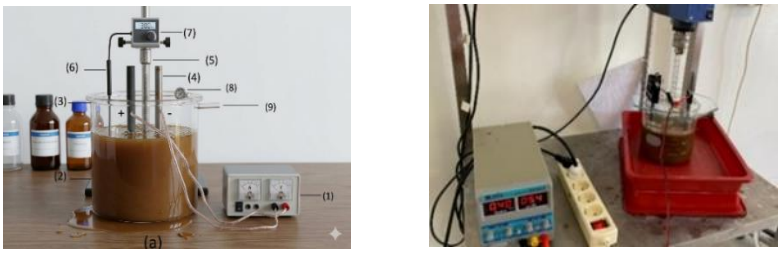


(a) (b)

Figure 2. (a) Flowchart of Iron (Fe) Electrode Preparation, (b) Flowchart of Graphite Electrode Preparation

2.3.3 Preparation of the Electro-Fenton Experimental Setup

The preparation of the Electro-Fenton experimental setup was initiated by preparing a 2000 mL beaker glass as the reactor vessel where the reaction took place. Iron (Fe) plates and a graphite rod were then prepared to serve as the anode and cathode, respectively. Subsequently, clamps were prepared to support and hold the electrode materials in position. The clamps were designed with two sides to securely maintain the anode and cathode at the desired distance throughout the experimental process.



Components:
(1) = Coddy 3005DT DC power supply
(2) = 2-L glass beaker
(3) = Iron anode
(4) = Graphite Cathode
(5) = T-shaped glass stirrer
(6) = Thermometer
(7) = Mechanical Stirrer
(8) = Sampling Port
(9) = Foam Outlet
Supporting Equipment: pH meter, wooden support frame, and plastic container

Figure 3. (a) AI-generated schematic illustration of the electro-Fenton reactor used for POME treatment, (b) photograph of the experimental electro-Fenton setup

Furthermore, a DC power supply was prepared as the electrical energy source for the Electro-Fenton system. A mechanical stirrer equipped with a T-shaped glass stirring rod was also installed to ensure homogeneous mixing of the wastewater during the treatment process. The experimental setup used for the pre-treatment process is illustrated in Figure 3.

After the entire experimental setup had been assembled, the next step was the preparation of the materials by introducing 1000 mL of Palm Oil Mill Effluent (POME) into the beaker glass. Subsequently, the power supply was switched on, and the mechanical stirrer was adjusted to an appropriate speed to ensure that the mixture remained homogeneous throughout the process. The graphite cathode and iron (Fe) anode were arranged facing each other inside the reactor with an inter-electrode distance of 3 cm. Electrode positioning was maintained using wooden clamps to ensure stable operating conditions during the reaction. This spacing was selected in accordance with Electro-Fenton reactor configurations reported in previous studies [15].

Following reactor preparation, 77 mL of 35% hydrogen peroxide (H_2O_2) was added to the system. The Electro-Fenton process was then conducted for 30 min to evaluate the degradation performance under the specified operating conditions. During the 30-min electro-Fenton treatment, samples were collected at 5-min intervals, specifically at 5, 10, 15, 20, 25, and 30 min. This interval was selected to provide sufficient temporal resolution for monitoring changes during treatment, particularly during the rapid initial oxidation stage and the subsequent transition toward slower degradation [15]. The pH of each sample was measured to monitor changes in the reaction medium, while the actual current was recorded directly from the DC power supply to verify the stability of the applied current. COD analyses were conducted only on the samples collected at 5, 15, and 30 min. These sampling points were selected to represent the early, intermediate, and final stages of the 30-min treatment, respectively. The flowchart of the Electro-Fenton process is presented in Figure 4.

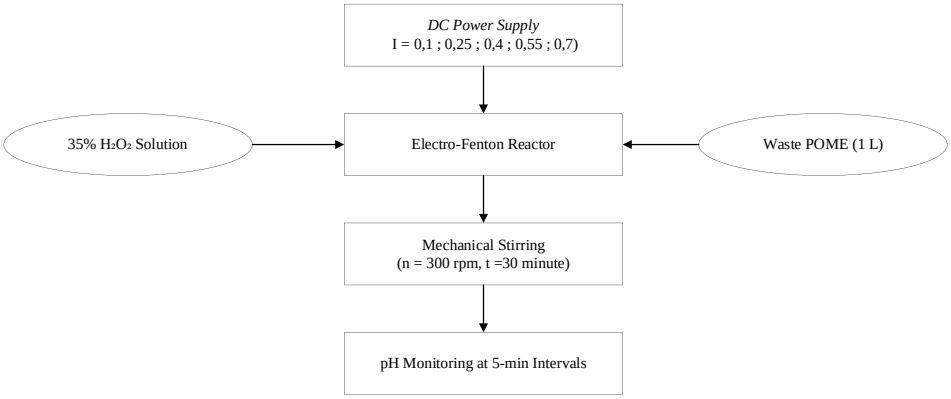


Figure 4. Flow diagram of the electro-Fenton treatment of raw POME

2.4 Data Analysis

2.4.1 Chemical Oxygen Demand (COD) Analysis

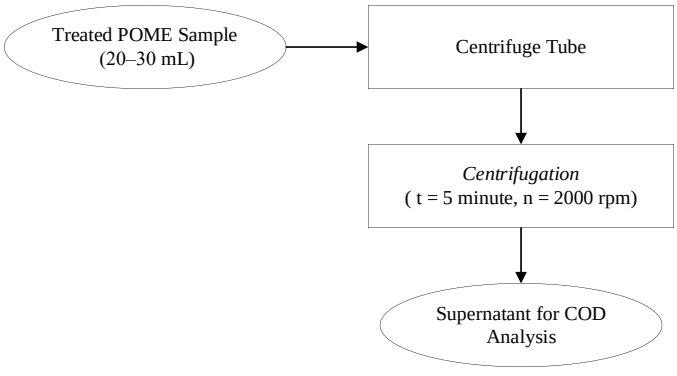


Figure 5. Flowchart of sample preparation for COD analysis

The determination of Chemical Oxygen Demand (COD) concentration was conducted in accordance with SNI 6989.15:2019 using the dichromate spectrophotometric method. Prior to analysis, the POME samples treated by the Electro-Fenton process were centrifuged at 2000 rpm for 5 minutes to separate the precipitated solids from the liquid phase. The resulting supernatant was subsequently used for COD analysis. COD values were determined from absorbance measurements obtained using a spectrophotometer at a specific wavelength and converted based on a standard calibration curve [12]. The flowchart of the centrifugation procedure is presented in Figure 5.

2.4.2 COD Degradation Efficiency Calculation

The COD degradation efficiency was calculated to evaluate the performance of the Electro-Fenton process in reducing the concentration of organic compounds. The percentage of COD removal was calculated using Equation (1):

$$COD\ Removal = \frac{C_0 - C_t}{C_0} \times 100\%$$

where:

- D = COD removal efficiency (%)
- C_0 = initial COD concentration (mg/L)
- C_t = COD concentration at observation time *t* (mg/L)

2.4.3 Reaction Kinetic Model Analysis

Kinetic evaluation of COD degradation was performed using first-order, second-order, and Behnajady-Modirshahla-Ghanbary (BMG) models. The inclusion of the BMG model was motivated by its successful use in previous studies to describe the complex degradation behavior observed in Electro-Fenton systems [15]. In addition, the Behnajady-Modirshahla-Ghanbary (BMG) model was employed to describe the two-stage reaction mechanism that frequently occurs in advanced oxidation processes [8].

The first-order kinetic model was applied to describe the variation of COD concentration with reaction time, as presented in Equation (2):

$$\ln\left(\frac{C_0}{C_t}\right) = k_1 t$$

To further evaluate the degradation behavior, the experimental data were also fitted to a second-order kinetic model, as described in Equation (3):

$$\frac{1}{C_t} - \frac{1}{C_0} = k_2 t$$

In addition to the conventional kinetic models, the Behnajady-Modirshahla-Ghanbary (BMG) model was applied to describe the degradation profile, as presented in Equation (4):

$$\frac{t}{1 - (C_t - C_0)} = m + bt$$

Linear regression was applied to determine the kinetic parameters and evaluate the applicability of each model. The coefficient of determination (R^2) was used as the primary criterion for assessing model performance. The model with the highest R^2 value was considered to provide the most accurate representation of COD degradation during the Electro-Fenton process.

3 RESULTS AND DISCUSSION

Table 2. COD Concentrations During Electro-Fenton Treatment

Applied Current (A)	Initial COD (mg/L)	COD at 5 Min (mg/L)	COD at 15 Min (mg/L)	COD at 30 Min (mg/L)
0.10		78,625.4	77,073.9	74,857.5
0.25		94,583.4	82,171.6	76,852.3
0.40	86,382.74	72,641.1	76,187.3	65,327.0
0.55		55,353.2	47,374.2	46,709.3
0.70		66,546.0	55,574.9	55,131.6

The effectiveness of the Electro-Fenton (EF) process was examined through changes in Chemical Oxygen Demand (COD) at reaction times of 5, 15, and 30 min under various current intensities. As shown in Table 2, COD concentrations generally decreased over the 30-min treatment period, although temporary fluctuations were observed at several applied-current levels. These variations indicate that COD degradation did not proceed uniformly under all investigated conditions. The observed reduction indicates the continuous occurrence of oxidation reactions within the EF system, resulting in the gradual degradation of organic matter contained in the POME wastewater.

Table 2 shows a general decline in COD concentration as the reaction time increased, demonstrating the capability of the Electro-Fenton process to reduce the organic load present in POME wastewater. The decrease in COD can be attributed to the formation of hydroxyl radicals (•OH) generated through the reaction between Fe^{2+} ions and hydrogen peroxide (H_2O_2). Owing to their high oxidation potential, these radicals are able to attack complex organic structures and convert them into simpler compounds. Under the lowest current intensity (0.10 A), the reduction in COD occurred at a relatively slow rate, indicating limited production of reactive oxidizing species.

At an applied current of 0.25 A, the COD concentration during the first 5 min was measured at 94,583.40 mg/L. This value was higher than the initial COD concentration of 86,382.74 mg/L, representing a measured increase of 8,200.66 mg/L or 9.49%. The reactor conditions during the initial treatment stage are presented in Figure 6. This increase does not necessarily indicate an additional organic load but may represent an apparent increase caused by positive interference from residual H_2O_2 in the dichromate-based COD analysis. Demonstrated that residual H_2O_2 can react with dichromate and consequently increase the measured COD value [18], also reported that H_2O_2 may cause COD overestimation in a photo-Fenton system [19]. Quantified residual H_2O_2 and corrected the COD results to minimize similar interference in a peroxide-assisted electrochemical process [20]. Therefore, the increase in measured COD was most likely associated with residual H_2O_2 interference during COD analysis, potentially accompanied by sampling variability arising from the heterogeneous characteristics of POME. This phenomenon is illustrated in Figure 6.

Figure 6. Visual observations of the POME reactor during electro-Fenton treatment at an applied current of 0.25 A: (a) initial reactor condition before treatment, (b) foam and bubble formation following H_2O_2 addition, and (c) reactor condition after 5 min of treatment

Within the investigated range, increasing the reaction time and applied current generally improved COD removal efficiency. Similarly identified electrolysis time and applied current as important operating variables affecting electro-Fenton treatment performance [12]. A higher applied current can accelerate electron-transfer reactions and promote the electrochemical production of Fenton reagents, thereby increasing hydroxyl radical (•OH) formation and enhancing the oxidation of organic compounds [3]. In addition, a longer treatment duration provides more time for interactions between oxidizing species and organic pollutants, allowing COD degradation to proceed more extensively [6].

The COD removal efficiency generally increased with treatment time, while the applied current produced different removal responses within the investigated range. However, a further increase in current did not improve treatment performance, possibly because competing electrochemical reactions reduced the effective utilization of H_2O_2 and hydroxyl radicals. The COD removal profiles under the investigated operating conditions are presented

in Figure 7.

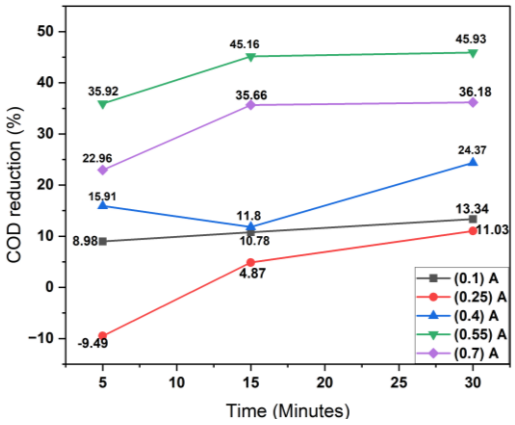


Figure 7. Effects of treatment time and applied current on COD removal efficiency

Figure 7 shows that the highest COD removal efficiencies were obtained at an applied current of 0.55 A, increasing from 35.92% after 5 min to 45.93% after 30 min. At 0.25 A, a negative removal efficiency was observed after 5 min because the measured COD concentration exceeded its initial value. The removal efficiency subsequently increased to 4.87% and 11.03% after 15 and 30 min, respectively. Increasing the applied current to 0.70 A did not further improve COD removal, indicating that 0.55 A provided the best performance within the investigated current range.

The COD removal efficiency of 45.93% obtained at 0.55 A after 30 min was comparable to the 46.1% reported for composite industrial wastewater treated for the same duration using iron–iron electrodes. A higher COD removal efficiency of 84.3% was subsequently achieved after stainless-steel electrodes and other operating conditions were evaluated and selected [4]. A recent electro-Fenton study on distillery wastewater achieved 79.5% COD removal from an initial COD concentration of 5,500–6,000 mg/L under optimized operating conditions [10]. Another study reported 86.7% COD removal from petrochemical wastewater after 60 min under optimized electro-Fenton conditions consisting of pH 5, an H_2O_2 concentration of 50 mmol/L, and a current density of 20 mA/cm² [6]. The lower removal efficiency obtained in the present study may be associated with differences in wastewater characteristics, initial pollutant load, electrode configuration, reagent concentration, and treatment duration. In particular, this study treated raw POME with a high initial COD concentration of 86,382.74 mg/L for only 30 min under fixed operating conditions. Thus, the result demonstrates partial COD degradation within a short treatment period and indicates that the investigated system is more appropriate as a pretreatment than as a standalone treatment.

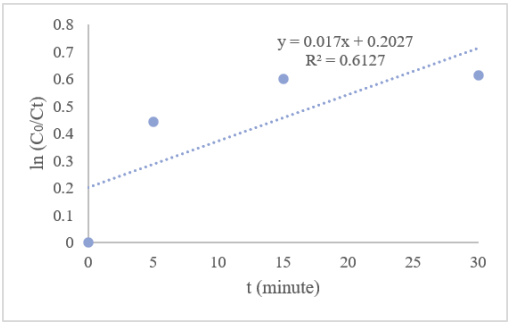


Figure 8. First-Order Kinetics Profile at a Current of 0.55 A

To evaluate the COD degradation mechanism during the Electro-Fenton process, the experimental data were analyzed using the first-order kinetic model under the optimum current intensity of 0.55 A. The first-order kinetic model is commonly employed to describe reaction systems in which the degradation rate is directly dependent on the concentration of pollutants remaining in the solution [15]. In this model, a linear relationship is obtained by plotting $\ln(C_0/C_t)$ against the reaction time.

Based on the plot of $\ln(C_0/C_t)$ versus reaction time, a coefficient of determination (R^2) value of 0.6127 was obtained. The first-order kinetic model is presented in Figure 8. The obtained (R^2) value indicates that the first-order kinetic model was not able to adequately represent the experimental data. The relatively low linearity

suggests that the COD degradation process in the Electro-Fenton system did not entirely follow a simple first-order kinetic mechanism. This behavior may be attributed to the complexity of oxidation reactions occurring in the Electro-Fenton process, including the generation of hydroxyl radicals (•OH), interactions between organic compounds and reactive species, as well as the occurrence of side reactions during treatment [5]. Therefore, the first-order kinetic model exhibited limited suitability for describing COD degradation in POME wastewater treated by the Electro-Fenton method.

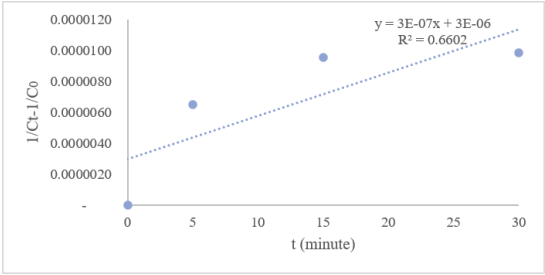


Figure 9. Second-Order Kinetic Profile at a Current of 0.55 A

In addition to the first-order model, COD degradation data were also analyzed using a second-order kinetics model at a current condition of 0.55 A. Second-order kinetics models were used to describe a reaction system whose degradation rate is influenced by the interaction between reactant species in the oxidation process [15]. In this model, a linear relationship is obtained through a plot between $(1/C_t - 1/C_0)$ to reaction time.

Based on the relationship graph $(1/C_t - 1/C_0)$ for the reaction time, a determination coefficient value (R^2) of 0.6602 is obtained The second-order kinetic modeling graph is shown in Figure 9. These values show that the second-order kinetics model has a slightly better degree of suitability than the first-order model, but is still not able to optimally describe the degradation mechanism. This indicates that the COD degradation process in the Electro-Fenton system takes place through a more complex reaction mechanism and does not rely solely on the concentration of the reactant. The formation of hydroxyl radicals (•OH), as well as side reactions, causes the oxidation process to take place dynamically during the reaction time [3]. Therefore, the second-order model is not yet fully able to represent the degradation behavior of COD in POME waste using the Electro-Fenton method.

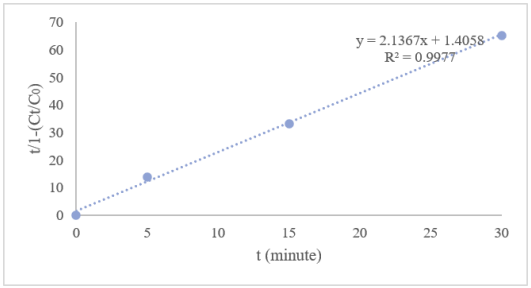


Figure 10. Kinetic Profile of BMG at 0.55 A Current

To determine the most representative kinetic model for COD degradation during the electro-Fenton process, the experimental data obtained at the optimum applied current of 0.55 A were evaluated using the Behnajady-Modirshahla-Ghanbary (BMG) model. This model describes a degradation process consisting of a rapid initial oxidation stage followed by a slower reaction stage, making it suitable for complex oxidation systems such as Advanced Oxidation Processes (AOPs). The linearized BMG equation is expressed as $t/[1-(C_t/C_0)] = m + bt$, where m represents the intercept and b represents the slope of the linear plot [15]. The BMG kinetic plot for COD degradation at 0.55 A is presented in Figure 10.

Linear regression of $t/[1-(C_t/C_0)]$ against treatment time produced the equation $t/[1-(C_t/C_0)] = 1.4058 + 2.1367t$, with $R^2 = 0.9977$. The values of m and b, obtained from the intercept and slope, were 1.4058 min and 2.1367, respectively. These parameters corresponded to an initial normalized degradation rate $(1/m)$ of 0.7114 min^{-1} and a theoretical maximum degradation capacity $(1/b)$ of 0.4680 or 46.80% [21]. The predicted maximum capacity was close to the experimental COD removal efficiency of 45.93% after 30 min. Therefore, the BMG model not only provided an excellent statistical fit but also reasonably represented the initial degradation

rate and maximum treatment capacity under the investigated conditions.

CONCLUSION

The Fe–graphite electro-Fenton system partially reduced the organic load of high-strength POME within 30 min. The optimum applied current of 0.55 A achieved the highest COD removal efficiency of 45.93%, reducing COD from 86,382.74 to 46,709.30 mg/L. Among the evaluated kinetic models, the Behnajady-Modirshahla-Ghanbary (BMG) model provided the best fit, with $R^2 = 0.9977$, an initial normalized degradation rate $(1/m)$ of 0.7114 min^{-1}, and a theoretical maximum degradation capacity $(1/b)$ of 46.80%. However, the remaining COD concentration was still considerably above the applicable discharge limit, indicating that the process is more suitable as a pretreatment than as a standalone treatment. Further studies should optimize the pH, H_2O_2 dosage, applied current, electrode configuration, and treatment duration and investigate its integration with biological or other polishing processes.

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