Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

Treatment of ultrafiltration-treated reverse osmosis landfill leachate concentrate using aluminum and iron electrocoagulation and the electro-assisted Fenton process: a comparative study

ARTICLES doi:10.4136/ambi-agua.3190

Received: 31 May 2026; Accepted: 10 Sep. 2026

Kátia Rodrigues de Souza; Marianna Ribeiro de Souza Schliesing; Lucas Marinho de Souza; Leonardo Zanon; Ronei de Almeida*

Faculdade de Engenharia. Universidade do Estado do Rio de Janeiro (UERJ), Rua São Francisco Xavier, n° 524, CEP: 20550-013, Rio de Janeiro, RJ, Brazil. E-mail: katiarodriguesuerj21@gmail.com, mariannaribsouza@gmail.com, lucasmarinho2004@hotmail.com, leo.zanon97@gmail.com
*Corresponding author. E-mail: ronei.almeida@eng.uerj.br

Editor-in-Chief: Nelson Wellausen Dias

ABSTRACT

This study investigates the application of electrocoagulation (EC), using aluminum (Al) and iron (Fe) electrodes and the electro-assisted Fenton (EAF) process to treat ultrafiltration-treated concentrate leachate from the reverse osmosis (RO) process. Treatability tests were conducted using a laboratory-scale apparatus. Electrolysis time was monitored to determine the ideal residence time. Treatment performance was assessed based on true color, absorbance at 254 nm (Abs254), and dissolved organic carbon (DOC). The Abs254/DOC ratio, termed specific ultraviolet absorbance (SUVA), was monitored to assess changes in the aromaticity of wastewater organic matter. A preliminary cost estimate was prepared to compare the operating costs of Al/Fe-EC and EAF. Iron electrodes showed better performance than aluminium electrodes in terms of pollutant removal efficiency and treatment time. Treatability performance of electrochemical methods, based on color, Abs254, and DOC removal, was determined as follows: EAF > Fe-EC > Al-EC. Considering benchmarking of performance indicators for treatment costs, i.e., USD g^{-1} DOC removed, the results were reported as follows: 32.28 USD g^{-1} DOC (Al-EC), 14.74 USD g^{-1} DOC (Fe-EC), and 29.27 USD g^{-1} DOC (EAF). Although Fe-EC was more cost-effective than EAF, the electro-assisted Fenton process achieved higher removal efficiencies across true color, Abs254, and DOC parameters. In addition, EAF was the only process capable of reducing SUVA, indicating a decrease in the recalcitrance of the treated effluent (from 6.5±0.3 to 3.4±0.2 L mg^{-1} m^{-1}).

Keywords: advanced oxidation processes, landfill leachate concentrate, operating costs, recalcitrant organic matter, reverse osmosis concentrate.

Eletrocoagulação com eletrodos de alumínio e ferro e processo Fenton eletroassistido para o tratamento de concentrado de osmose inversa após ultrafiltração: um estudo comparativo

RESUMO

Este estudo investiga a aplicação da eletrocoagulação (EC) com eletrodos de alumínio (Al) e ferro (Fe), bem como o processo Fenton eletroassistido (FEA), no tratamento do concentrado proveniente de um sistema de ultrafiltração, utilizado para reduzir o volume do concentrado gerado no tratamento de lixiviado por osmose inversa (OI). Ensaios de tratabilidade foram conduzidos em um aparato de escala laboratorial. O tempo de eletrólise foi monitorado para determinar o tempo de residência ideal. O desempenho do tratamento foi avaliado com base na remoção de cor verdadeira, na absorbância a 254 nm (Abs254) e no carbono orgânico dissolvido (COD). A razão Abs254/COD, denominada absorbância ultravioleta específica (SUVA), foi monitorada para avaliar alterações na aromaticidade da matéria orgânica presente no efluente. Uma estimativa preliminar de custos foi elaborada para comparar os custos operacionais dos processos Al-EC, Fe-EC e FEA. Eletrodos de ferro apresentaram melhor desempenho do que eletrodos de alumínio em termos de eficiência de remoção de poluentes e tempo de tratamento. O desempenho dos métodos eletroquímicos avaliados quanto à tratabilidade, considerando a remoção de cor verdadeira, Abs254 e COD, seguiu a seguinte ordem de eficiência: EAF > Fe-EC > Al-EC. Considerando o custo de tratamento, expresso em USD g^{-1} de COD removido, os resultados obtidos foram: 32,28 USD g^{-1} de COD para Al-EC, 14,74 USD g^{-1} de COD para Fe-EC e 29,27 USD g^{-1} de COD para FEA. Embora o EC com eletrodos de ferro tenha apresentado melhor relação custo-benefício em comparação ao processo Fenton eletroassistido, o processo FEA alcançou maiores eficiências de remoção de cor, Abs254 e COD. Além disso, o FEA foi o único processo capaz de reduzir os valores de SUVA, indicando diminuição da recalcitrância do efluente tratado (de 6,5±0,3 para 3,4±0,2 L mg^{-1} m^{-1}).

Palavras-chave: concentrado de osmose inversa, custos operacionais, lixiviado de aterro concentrado, matéria orgânica recalcitrante, processos oxidativos avançados.

1. INTRODUCTION

The degradation of the waste organic fraction produces landfill leachate in disposal facilities, a contaminated wastewater that poses ecological, environmental, and human health risks due to its refractory organic matter, high ammonia concentrations, and high salinity (Aquino *et al.*, 2025; Fang *et al.*, 2021).

Landfill leachate can be treated using various methods, including physical, chemical, and biological treatments, as well as landfill recirculation and/or its combination with sewage in municipal wastewater treatment plants (Costa *et al.*, 2019). Over the last decade, in response to increasingly stringent wastewater-disposal standards, reverse osmosis (RO) has been implemented in many medium- and large-sized engineered landfills (de Almeida *et al.*, 2023). In 2018, the RO treatment capacity in China reached 60,000 m^3 day^{-1} (Chen *et al.*, 2021). This process has been adopted as a standalone treatment or in combination with physicochemical and/or biological methods for leachate purification (Zhang *et al.*, 2020).

However, RO produces a residual matrix termed “membrane concentrate” or “concentrated leachate” – a highly polluted stream containing salts and organics at challenging concentrations (e.g., 8.14 – 66.9 g L^{-1} total dissolved solids and 0.4 – 49.5 g L^{-1} chemical oxygen demand) (Gripa *et al.*, 2023; Keyikoglu *et al.*, 2021). The concentrate can comprise, on average, 30–50% of the incoming leachate, making it urgent to develop sustainable strategies for its management (Calabrò *et al.*, 2018; Keyikoglu *et al.*, 2021).

In this context, electrocoagulation (EC) re-emerges as a promising method for concentrate treatment. This electrochemical process is based on the *in situ* production of a coagulant using sacrificial metal electrodes. The coagulant promotes the destabilization of colloidal particles, aggregation/flocculation of suspended solids, and/or precipitation of water contaminants (Yusmaini *et al.*, 2026). This technique has a simple operation, low footprint, the ability to degrade refractory organic matter, that is, the fraction of organic matter that is resistant to degradation by conventional treatment processes and therefore tends to persist in the treated effluent, and high tolerance to high salinity (Bassa *et al.*, 2026; Lima *et al.*, 2017; Tang *et al.*, 2024). Indeed, electron mobility in EC is facilitated by high-salinity wastewater, thereby reducing energy consumption and the need for a supporting electrolyte, which may favor the treatment of concentrates by EC technology (Tang *et al.*, 2024).

Likewise, the electro-assisted Fenton (EAF), a modified Fenton-based method, has attracted increasing attention. In EAF, hydrogen peroxide (H_2O_2) is externally added, while the electrochemical system enhances the catalytic iron cycle responsible for the generation of hydroxyl radicals (•OH) (Liu *et al.*, 2025). In this process, •OH radicals are produced through the Fenton reaction, while the electrochemical system sustains the catalytic cycle of ferrous ions. This is achieved through the use of a sacrificial iron electrode as the iron source, while the ferric ions generated during the Fenton reaction are electrochemically reduced at the cathode, regenerating Fe^{2+} and maintaining the catalytic cycle ($Fe^{3+} + e^- \rightarrow Fe^{2+}$) (Bokare and Choi, 2014). Among its advantages, EAF does not require the addition of ferrous salts and generates minimal sludge compared with the conventional Fenton process.

In light of the above, this study investigates the effects of EC (using aluminum and iron electrodes) and EAF on the treatment of a UF-treated RO concentrate. Thus, samples for this study were obtained from UF-treated reverse osmosis concentrate; UF permeate was subjected to treatability analyses. The idea behind this approach was to use an electrochemical technique to degrade organics and remove color from the UF permeate. In addition, a preliminary cost estimate was elaborated to compare the operating costs of Al-EC, Fe-EC, and EAF.

To the best of our knowledge, this is the first technoeconomic evaluation of UF-treated concentrates in the literature. Our findings aim to propose management options for membrane concentrate and to improve the operational feasibility of the landfill leachate treatment chain.

2. MATERIAL AND METHODS

2.1. ROC and UF-treated samples

The ROC of this study came from a sanitary landfill located in the municipality of Seropédica, Rio de Janeiro State (22°44′37″ S, 43°42′27″ W). ROC samples were collected from 2021 to 2022. Results are presented as mean ± standard deviation (n = 3), where n represents the number of independent samples/experimental replicates. The following parameters were measured for their characterization: pH, chemical oxygen demand (COD), dissolved organic carbon (DOC), ammonia nitrogen (NH_3-N), absorbance at 254 nm (Abs254), chloride (Cl^-), sulfate (SO_4^{2-}), and conductivity.

The UF-treated sample was produced by feeding ROC into a bench-scale UF system (PAM Membranas Seletivas, Brazil). UF was performed using a second-hand hollow-fiber polyvinylidene fluoride (PVDF) membrane (filtration area of 0.100 m^2; packing density of 1333.2 m^2 m^{-3}) provided by PAM Membranas Seletivas, Brazil. The filtration system was operated in concentration mode; the concentrate stream was recycled back to the feed tank, and the permeate was collected. In practical applications, the UF process would be used to reduce concentrate volume. The UF experimental unit was operated in dead-end filtration mode at an operating pressure of 2–3 bar. The volume reduction factor (VRF), i.e., the recovery in batch mode, was not defined because the objective was to obtain a sufficient volume of UF permeate for subsequent electrochemical tests. The operational conditions and performance of the UF

process are not systematically discussed in this study, as the primary focus is on evaluating electrochemical treatments.

UF permeate samples were collected and characterized for pH, true color, DOC, Abs254, and conductivity. UF-treated samples were stored at 4ºC for electrolysis treatability tests.

2.2. Experimental apparatus

2.2.1. Electrocoagulation (EC): Al and Fe electrodes

Electrocoagulation (EC) tests were conducted using a laboratory-scale apparatus. The electrochemical reactor was cylindrical. In each trial, pairs of aluminum (Al) and iron (Fe) plate electrodes measuring 15 cm × 3 cm × 2 mm (length × width × thickness) were connected in parallel, with a fixed inter-electrode distance of 30 mm. The electrode pairs, with one electrode serving as the anode and the other as the cathode, were connected to a DC power supply (Yaxun; Model: 1502dd+; 0 – 2 A; 0 – 15 V) operating in constant-potential mode. The voltage applied to the system was 6.0 Volts (V), and the electric current varied from 500 to 550 milliamperes (mA). Figure 1 presents a schematic representation of the experimental apparatus.

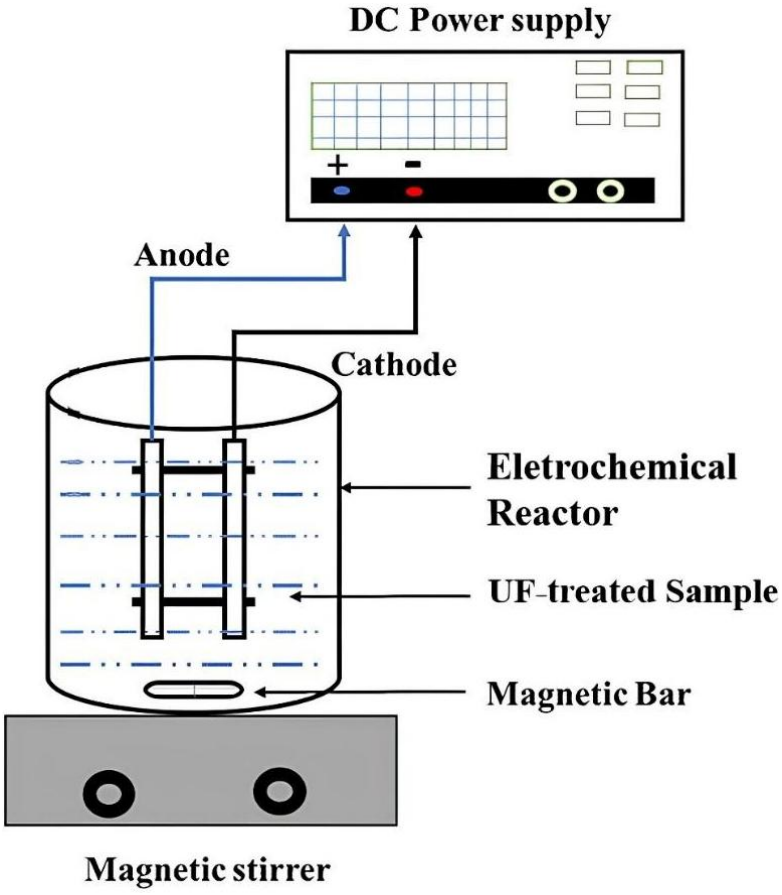

Figure 1. EC/ EAF apparatus used in the experimental investigation. UF = ultrafiltration.

The EC tests were performed in triplicate. For the Al and Fe electrodes used in the experiment, samples were subjected to electrolysis times of 10, 20, 30, 40, and 50 minutes. The pH of the samples was adjusted to pH ≈ 3 with 98% H_2SO_4 prior to Fe-EC tests. Aluminum EC tests were performed at the samples' natural pH. For the Fe-based treatment, the samples were acidified to pH ≈ 3 to provide acidic conditions favorable for iron dissolution and, particularly in electro-assisted Fenton treatment, hydroxyl-radical generation. In contrast, Al-EC was performed at the natural sample pH (≈9), where $Al(OH)_3$ formation and coagulation are

favored; therefore, no pH adjustment was applied. The iron electrodes were weighed after 50 minutes of electrolysis to determine the mass of iron consumed in the EC process.

From this, two physicochemical parameters were monitored: hydrogen potential (pH) and electrical conductivity. To determine treatment performance, true color, DOC, and Abs254 were analyzed. The Abs254/DOC ratio, known as specific ultraviolet absorbance (SUVA), was used as an indicator of the aromaticity of dissolved organic matter, while true color was evaluated as an independent parameter reflecting the samples' optical properties.

2.2.2. Electro-assisted Fenton (EAF)

The electrochemical apparatus of the electro-assisted Fenton (EAF) was identical to that used in EC with Al and Fe electrodes (Figure 1). One pair of iron electrodes (15 cm × 3 cm × 2 mm), consisting of one anode and one cathode, was used in the EAF process.

As mentioned earlier, the iron electrodes were weighed after EC to determine the mass of iron in this process, and the results served as the basis for determining the amount of hydrogen peroxide (H_2O_2) in the EAF. Before all runs, organic impurities and oxide layer on electrode surfaces were removed by dipping for 4 min in a HCl solution (35%).

An H_2O_2/Fe(II) ratio of 4 was used in EAF, based on the optimal condition reported by Torres *et al.* (2025). Thus, in this work, the EAF was evaluated by adding approximately 50 mmol L^{-1} H_2O_2 for the Fenton reaction. Treatability tests with H_2O_2 were also performed to assess the direct oxidation of the UF-treated sample by hydrogen peroxide.

Proquimios Chemicals LTDA (Brazil) and Vetec (Brazil) provided peroxide hydrogen (30%) and pentahydrated sodium thiosulfate ($Na_2S_2O_3 \cdot 5H_2O$), P.A. The advanced electrochemical treatment was performed at pH ≈ 3, 3.6 V, and 500–550 mA. H_2SO_4 (98%) was used for pH adjustment, and H_2O_2 (30%) was used for electro-oxidation, both added dropwise.

Samples were taken every 10 minutes up to 50 minutes. $Na_2S_2O_3 \cdot 5H_2O$ 32 mmol L^{-1} was added to stop the oxidation reactions. Sodium thiosulfate pentahydrate was used to quench residual H_2O_2 and thereby stop further oxidation reactions before analysis, ensuring that the analytical results reflected the treatment conditions at the end of the electro-oxidation experiment.

The removal efficiency (RE) for the measured parameters in Al/Fe-EC and EAF treatability tests was calculated using Equation 1.

$$RE\ (\%) = \left(1 - \frac{C}{C_0}\right) x\ 100\% \quad (1)$$

Where C_0 is the initial concentration (or measured value) of the water quality parameter, and C is its final concentration (or measured value) after treatment.

2.3. Preliminary cost estimation

A preliminary cost estimation was prepared to compare Al/Fe-EC and EAF operations for treating UF-treated effluent. In this analysis, energy demand, electrode consumption, and chemical consumption for treatment were considered (Illi *et al.*, 2025; Torres *et al.*, 2025; Visconcin *et al.*, 2024; Zevallos *et al.*, 2025).

Energy consumption (kWh m^{-3}) was determined based on applied current, cell voltage, electrolysis time, and volume of treated effluent, according to Equation 2.

$$Energy\ (kWh\ m^{-3}) = U\ x\ I\ x\ \left({}^{t}/_{v}\right) x\ 10^{-3} \quad (2)$$

Where U is the cell voltage (volts, V), I is the current intensity (amperes, A), t is the electrolysis time (hours, h), and *v* is the effluent volume (cubic meters, m^3).

Electrode consumption was determined by measuring the mass loss of electrodes before and after the treatability test ($C_{electrode}$, in kg m^{-3}).

For Fe-EC, the cost of pH adjustment using sulfuric acid was considered, whereas for EAF, both pH adjustment and hydrogen peroxide consumption are included in the operating costs (OpEx). The OpEx was estimated using Equation 3.

$$OpEX\ (USD\ m^{-3}) = \alpha\ x\ C_{energy} + b\ x\ C_{electrode} + c\ x\ C_{chemical} \quad (3)$$

Where $C_{chemical}$ is the total chemical consumption per m^3 of treated effluent. The parameters a, b, and c represent energy (USD kWh^{-1}), electrode material (USD kg^{-1}), and chemical prices (USD m^{-3}). All prices were based on Brazilian market prices or reagent tariffs, in US dollars (USD).

2.4. Analytical procedures

Analytical procedures followed Standard Methods for the Examination of Water and Wastewater (APHA; AWWA; WEF, 2017).

The pH measurement was performed using a QUIMIS pH meter (model Q400AS) in accordance with Method 4500-H^+ B. The Abs254 was measured using a Shimadzu UV-1800 spectrophotometer, as described in Method 5910-B. The true color and chemical oxygen demand were determined according to Methods 2120-C and 5220-D, using a Hach DR2800 portable spectrophotometer. Ammonia nitrogen (Method 4500-NH_3 E) was performed with a portable multiparameter model Orion StarTM Thermo pH/ISE. The conductivity was determined using a DIGIMED conductivity meter (model DM31), according to Method 2510-B. Chloride (Cl^-) and sulfate (SO_4^{2-}) determinations were performed using methods 4500-Cl B and 4500-SO_4^{2-} D, also in accordance with the Standard Methods. Dissolved organic carbon (DOC) (method 5310 C) was determined by the TOC Analyzer model Shimadzu (TOC-V).

Samples were filtered through a 0.45 µm commercial cellulose membrane prior to true color, DOC, and Abs254 analyses; although membrane-specific blank testing was not performed, its potential contribution was considered negligible, and such testing is recommended for further verification in future studies.

3. RESULTS AND DISCUSSION

3.1. ROC and UF-treated samples

The physicochemical characterization of ROC samples is shown in Table 1.

Table 1. Physicochemical characterization of ROC samples (n = 3).

Parameter	Unit	Min	Max	Mean±SD
Potential of hydrogen (pH)		8.9	9.2	9.0±0.2
True color	mg Pt-Co L^{-1}	41,040	44,545	42,510±1819
Chemical oxygen demand (COD)	mg L^{-1}	3678	11,730	7480±4050
Dissolved organic carbon (DOC)	mg L^{-1}	4556	5098	4682±280
Ammonia nitrogen (NH_3-N)	mg L^{-1}	1413	1834	1598±212
Absorbance at 254 nm (Abs254)	cm^{-1}	126	130	128±2
Conductivity	mS cm^{-1}	81.8	83.9	82.8±1.1
Chloride (Cl^-)	mg L^{-1}	4567	5938	5127±690
Sulfate (SO_4^{2-})	mg L^{-1}	4567	8150	6503±1809

SD = standard deviation.

ROC samples were alkaline and dark in color. These samples exhibited high salinity and

organic content, with a remarkable level of recalcitrant organic matter, as indicated by their high Abs254 values. Conductivity and Cl^- were measured as 82.8±1.1 mS cm^{-1} and 5127±690 mg L^{-1}. The Average COD and DOC were higher than 4000 mg L^{-1}, whereas Abs254 was reported as 128±2 cm^{-1}.

As expected, sulfate was quantified at a high level (6503±1809 mg L^{-1}). This is justified by the acidification of the incoming leachate of reverse osmosis treatment. In the RO system, the leachate pH is reduced to about 6.5 using sulfuric acid. The reduced pH of leachate is advantageous for ammonia removal and promotes salt solubility, thereby reducing scaling (Šír *et al.*, 2012; Talalaj and Biedka, 2015). In contrast, sulfate increases in the concentrate stream. A similar finding is reported in previous studies (Atik Hamoud *et al.*, 2025; Talalaj, 2015; Talalaj and Biedka, 2015).

RO concentrate was fed into a bench-scale ultrafiltration (UF) system to produce permeate samples for the electrolysis experiments. The UF permeate, i.e., the UF-treated concentrate, used in Al/ Fe-EC and EAF oxidation tests, was characterized as pH = 9.0 – 9.5 (9.2±0.2), DOC = 323 – 417 (369±41) mg L^{-1}, true color = 7825 – 8100 (7915±85) Pt-Co L^{-1}, Abs254 = 20.20 – 28.10 (25.2±3.4) cm^{-1}, and conductivity = 17 – 22 (20.4±1.5) mS cm^{-1}.

These results indicate that concentrate samples still exhibited high color, recalcitrance, and salinity after UF pretreatment. True color and conductivity were determined as 42,510±1819 mg Pt-Co L^{-1} and 82.8±1.1 mS cm^{-1}. Surprisingly, DOC content ranged from 32.3 to 41.7 mg L^{-1}, suggesting that most organic substances were in particulate form and were therefore removed during the UF process.

The SUVA of 6.5±0.3 L mg^{-1} m^{-1} indicated the predominance of aromatic organics (A SUVA value > 2 L mg^{-1} m^{-1} indicates a predominantly aromatic organic structure) (Iskander *et al.*, 2018).

3.2. Monitoring results of Al and Fe-EC and electro-assisted Fenton

The results of the physicochemical characterization of the samples during Al and Fe-EC and EAF are presented in Table 2.

Table 2. Monitoring of Al and Fe electrochemical coagulation for UF-treated concentrate (conductivity = 17 − 22 mS cm^{-1}, true color = 7825 − 8100 Pt-Co L^{-1}, and Abs254 = 20.20 − 28.10 cm^{-1}) at pH = 9.0 – 9.5 (Al) and pH ≈ 3 (Fe), 6.0 V, and 500 − 550 mA.

Time (min)	Aluminum (Al) electrodes				Iron (Fe) electrodes			
	pH	Conductivity (mS cm^{-1})	True color (mg L^{-1})	Abs254 (cm^{-1})	pH	Conductivity (mS cm^{-1})	True color (mg L^{-1})	Abs254 (cm^{-1})
10	9.2	21.9	7750	23.85	4.9	18.5	7825	28.10
20	9.3	21.6	7800	24.25	5.9	21.7	8375	28.70
30	9.4	21.3	6050	19.85	7.2	20.7	4675	15.65
40	9.4	20.9	6250	20.9	7.5	20.8	3175	12.30
50	9.5	20.6	10,450	20.1	7.4	19.2	31200	10.25

It was observed that the pH of the UF-treated concentrate at both the iron and aluminum electrodes increased over time, as expected due to the hydroxyl ions (^-OH) produced at the cathode and by the liberation of ^-OH due to the exchange of some anions such as, Cl^- and SO_4^{-2}, with $Al(OH)_3$ or $Fe(OH)_3$ (Chen *et al.*, 2000; Top *et al.*, 2011).

In EC, effluent conductivity is a crucial parameter because it affects current density, coagulant generation, energy consumption, and treatment efficiency (Bassa *et al.*, 2026; Yusmaini *et al.*, 2026). In this study, the conductivity varied differently between the Al and Fe

electrodes. At the Al-EC, effluent conductivity decreased from 0 to 50 minutes. In contrast, behavior at the Fe-EC was variable over the 50-minute treatment period. A previous study has demonstrated that conductivity behavior depends strongly on electrode material, with Al electrodes generally showing a progressive decrease in conductivity due to hydroxide precipitation, whereas iron electrodes may exhibit more variable behavior because of Fe^{2+}/Fe^{3+} release from the anode into the solution before complete precipitation of iron hydroxides and floc formation (Rezaei *et al.*, 2026).

Regarding true color and Abs254 parameters, they decrease in Al-EC over the first 30 minutes. Then, after 40 minutes, the Abs254 values increased sharply. On the other hand, when iron electrodes were used, true color and Abs254 decreased during the 50-minute experiment.

Rezaei *et al.* (2026) have shown that extended treatment times may result in the formation of a passive layer on aluminum electrodes, thereby limiting electrocoagulant generation and, consequently, reducing contaminant removal efficiency, whereas iron electrodes may sustain pollutant removal over longer operational periods.

Thus, in this study, the operational conditions for Al and Fe experiments of 30 minutes (Al) and 50 minutes (Fe), an initial pH of ≈ 9 (Al) and ≈ 3 (Fe), 6.0 volts, and 500–550 mA showed the highest removal efficiencies of color and absorbance at 254 nm.

Mass losses due to electrode consumption in Al and Fe-EC were determined to estimate operating costs and to calculate H_2O_2 dosage for the EAF process. Additionally, for the EAF operating expenses, electrode consumption was measured at 30 and 50 minutes of electrolysis.

For Al-EC and Fe-EC, the mass loss due to electrode consumption was 0.395 kg m^{-3} and 1.725 kg m^{-3}, respectively. In EAF, there were registered mass losses of 1.763 and 2.325 kg m^{-3} in 30 and 50 minutes.

From the iron electrode consumption in Fe-EC (50 min), an H_2O_2/Fe(II) ratio of 4, with 50 mmol L^{-1} H_2O_2, was applied in electro-assisted Fenton. A treatability test with H_2O_2 was also performed to assess the direct oxidation of the UF-treated concentrate samples.

Table 3 shows the results of physicochemical parameters for H_2O_2 oxidation, and EAF monitored for 50 minutes.

Table 3. Monitoring of H_2O_2 oxidation (50 mmol L^{-1}) and electro-assisted Fenton treatment for UF-treated concentrate (conductivity = 19 – 20 mS cm^{-1}, true color = 5688 – 6300 Pt-Co L^{-1}, and Abs254 = 20.30 – 21.60 cm^{-1}) treatment at pH ≈ 3, 50 mmol L^{-1} H_2O_2, 3.6 V, and 500 – 550 mA.

Time (min)	H_2O_2 oxidation				Electro-assisted Fenton			
	pH	Conductivity (mS cm^{-1})	True color (mg L^{-1})	Abs254 (cm^{-1})	pH	Conductivity (mS cm^{-1})	True color (mg L^{-1})	Abs254 (cm^{-1})
10	3.8	22.5	7275	19.9	2.61	19.40	525	7.41
20	4.0	21.7	8150	20.3	2.87	20.25	150	4.88
30	4.4	19.9	9650	20.2	4.41	20.50	88	4.30
40	4.9	19.2	7700	18.5	5.60	22.78	2163	10.23
50	5.2	20.0	5525	20.6	5.9	21.90	2170	12.30

Regarding the EAF process, the treatability results were superior to those obtained in the EC experiments. Reductions in color and Abs254 were observed between 10 and 30 minutes of monitoring. Both pH and conductivity increased throughout the treatment, reaching final values of 5.6 and 22.78 mS cm^{-1}, respectively. The best EAF performance was observed at 30 minutes of electro-oxidation, pH ≈ 3, 3.6 V, and 500–550 mA.

Figure 2 shows the results for color, Abs254, and DOC removal under the ideal conditions for the Al and Fe-EC tests and the EAF experiment.

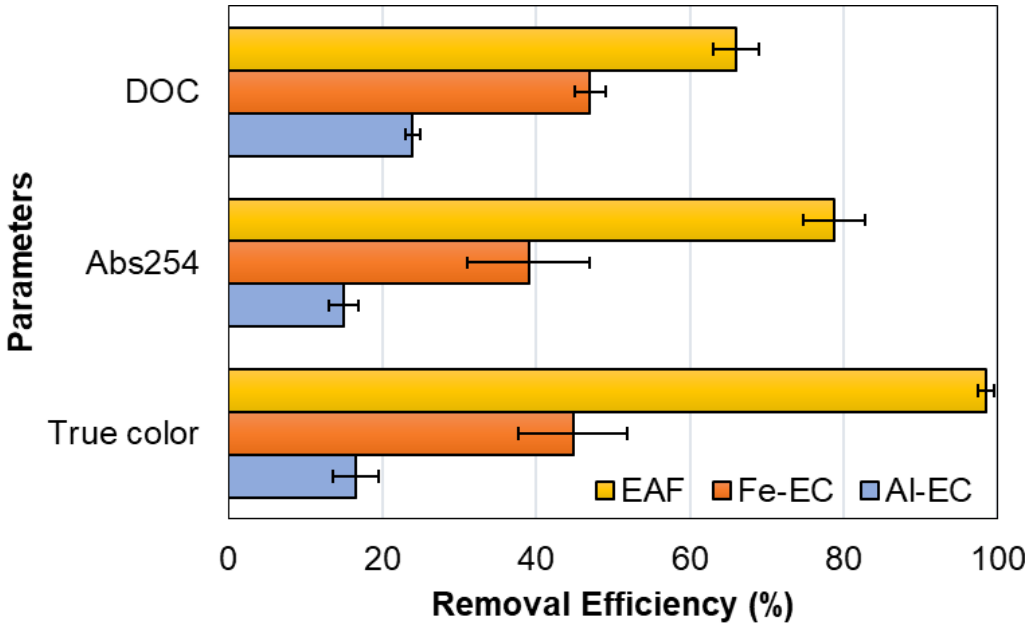

Figure 2. Results of true color, Abs254, and DOC removal of Al and Fe EC and electro-assisted Fenton for UF-treated samples. Al (pH ≈ 9, 30 minutes, 6.0 volts, and 500 – 550 mA), Fe (pH ≈ 3, 40 minutes, 6.0 volts, and 500 – 550 mA). Electro-assisted Fenton (pH ≈ 3, 30 minutes, 3.6 volts, and 500 – 550 mA). EC = electrocoagulation. DOC = dissolved organic carbon.

Under the ideal operational conditions evaluated in this study, the following treatability results were obtained: 17±3% true color removal, 15±2% Abs254 reduction, and 24±1% DOC removal for Al-EC; 45±7% true color removal, 39±8% Abs254 reduction, and 47±2% DOC removal for Fe-EC; and 99±1% true color removal, 79±4% Abs254 reduction, and 66±3% DOC removal for EAF.

Previous studies have investigated electro-treatment for managing concentrated leachate. Top *et al.* (2011) treated nanofiltration (NF) leachate concentrate (pH 6.8 – 7.0; 18.98 – 28.80 mS cm^{-1}; and 8200 – 12,800 color (Hazen)) using four plates of Al-electrodes. Removal efficiencies were 45% for organic matter (reported as chemical oxygen demand, COD) and 60% for color at 15.9 mA cm^{-2} and a reaction time of 30 min. In another study, NF leachate concentrate (pH 7.74±0.07; 18.72±0.65 mS cm^{-1}; and 14,800±155 mg Pt-Co L^{-1}) was Fe-electrocoagulated, and 57.4% COD and 77.1% color removals at pH 7, 3500 mA, and 20 min were recorded (Yazici Guvenc *et al.*, 2019).

In both previous EC studies on concentrate treatment, color reductions were greater than in the present study. Different operating conditions and the composition of the liquid matrix subjected to electrocoagulation could explain the treatability results for each assessment.

On the other hand, as in previous evaluations (Yazici Guvenc *et al.*, 2019), iron electrodes had better outcomes than Al electrodes in the present research. This result can be attributed to the formation of distinct hydrolyzed iron species with greater affinity for recalcitrant organics, such as humic substances – a heterogeneous mixture of organic compounds like humic acid and fulvic acid, than the aluminum-hydrolyzed species generated during the Al-EC process (Mollah *et al.*, 2001). In addition, acidic conditions of Fe-EC (pH≈3 vs. 9.0 Al-EC) can also improve pollutant removal as they enhance electrode dissolution and the production of hydrolyzed iron species, contributing to flocculation and precipitation of contaminants. Besides, humic acids, a major component of humic substances and an important pollutant in concentrated leachate, become insoluble at low pH due to protonation of their phenolic and carboxylic groups. Protonated humic acids can interact with other leachate compounds by hydrogen bonds, leading to aggregation and precipitation (Costa *et al.*, 2025; Yusmaini *et al.*, 2026).

Electro-assisted Fenton treatment was evaluated by Yazici Guvenc *et al.* (2019) for treating concentrated landfill leachate. Under optimal conditions (pH 3.5, current intensity of 2750 mA, H_2O_2/COD ratio of 1.25, and reaction time of 30 min), COD and color removals of 69.4% and 87.6%, respectively, were achieved. In the present study, superior treatment performance was achieved under comparable pH and reaction-time conditions, but at a lower current intensity.

In another study, electro-assisted Fenton-like (EAF-like) treatment was applied to dye wastewater. Under optimal operating conditions (4.7 g L^{-1} H_2O_2 and 9.2 V), the process achieved 32% total organic carbon removal and 90% color removal (Ateş *et al.*, 2025).

The SUVA varied depending on the electro-method used. In Al-EC, the ratio increased to 9.9 ± 0.2 L mg^{-1} m^{-1}, whereas no significant change was observed for Fe-EC, with values of 6.3 ± 0.4 and 6.5 ± 0.3 L mg^{-1} m^{-1} for Fe-EC- and UF-treated samples, respectively.

In contrast, EAF treatment reduced the SUVA to 3.4 ± 0.2 L mg^{-1} m^{-1}. This shows that, among the electro-techniques assessed, only the EAF reduced recalcitrant dissolved organic matter. In contrast, the increase of SUVA in the Al-EC may indicate an enrichment of aromatic organic structures in the residual dissolved organic matter. It is supposed that the condensation of simpler compounds into polycondensed aromatic structures with high molecular weights occurs. Although this mechanism could contribute to this behavior, this hypothesis cannot be confirmed with the available data and would require complementary molecular-level analyses. Future investigations may include the characterization of functional groups in dissolved organic matter using FTIR or NMR spectroscopy, the assessment of molecular-level aromaticity using high-resolution mass spectrometry (e.g., FT-ICR-MS or Orbitrap-MS), and the evaluation of molecular weight distribution using size-exclusion chromatography (SEC/GPC).

The reduction in SUVA/aromaticity is particularly important for concentrate stream management, as the presence of recalcitrant organic compounds has been associated with inhibited microbial activity in landfill cells and reduced treatment performance in reverse osmosis systems (Calabrò *et al.*, 2010; de Almeida *et al.*, 2022b). Given that recirculation into the landfill body is the most common disposal strategy for RO concentrates, integrating UF and EAF processes to reduce concentrate volume and recalcitrance appears to be a promising alternative. This approach may help mitigate the operational challenges associated with concentrate infiltration.

3.3. Operating costs

A preliminary cost assessment was performed to compare the operating costs of Al/Fe-EC and EAF processes. The following reference prices were adopted for industrial-grade reagents: H_2O_2 at 0.48 USD kg^{-1} and concentrated sulfuric acid (95–98% purity) at 0.25 USD kg^{-1} (Torres *et al.*, 2025). The average electricity price in Brazil was estimated at 0.11 USD kWh^{-1} (de Almeida *et al.*, 2022a). Reference prices for aluminum and iron electrode sheets were 1.78 USD kg^{-1} and 0.24 USD kg^{-1}, respectively (Hashim *et al.*, 2017; Zevallos *et al.*, 2025).

The operating costs were estimated at 1.16 USD m^{-3} for Al-EC, 1.03 USD m^{-3} for Fe-EC, and 2.84 USD m^{-3} for EAF. The contribution of each cost component varied considerably among the electrochemical processes (Figure 3).

In Al-EC, operating costs were strongly influenced by the high price of aluminum electrodes, which accounted for 0.70 USD m^{-3} of treated effluent. In contrast, Fe-EC benefited from the lower cost of iron electrodes, with energy consumption representing the major cost component (0.61 USD m^{-3}).

For EAF, the addition of H_2O_2 increased treatment costs, contributing 2.01 USD m^{-3} to the total operating expenses. This finding is consistent with the results reported by Ateş *et al.* (2025), who identified H_2O_2 concentration as one of the main parameters affecting the operating costs of EAF-like processes for dye wastewater treatment. A similar H_2O_2 dosage was employed in both studies (4.2 kg m^{-3} in the present work versus 4.7 kg m^{-3} reported by the authors).

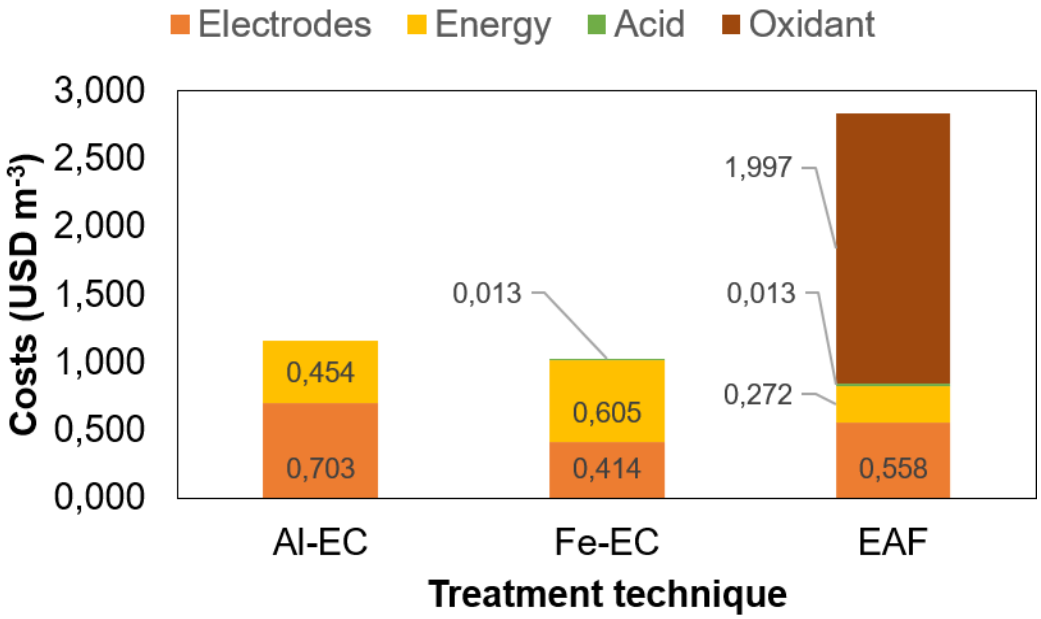

Figure 3. Contribution of cost components to total treatment costs (USD m^{-3}) for each treatment technique. EC = electrocoagulation. EAF = electro-assisted Fenton.

Among the electrochemical methods evaluated, EAF presented the highest operating costs. However, it is important to note that the cost estimate assumed an iron electrode mass loss of 2.325 kg Fe m-3 over 50 min of treatment, whereas the optimal operating time was determined to be 30 min. Consequently, H_2O_2 was added in excess, increasing the overall operating expenses. Therefore, further optimization of the EAF process may reduce treatment expenses. Still, the EAF treatment cost obtained in the current study was comparable to that reported by Yazici Guvenc *et al.* (2019), who estimated a cost of 1.86 € m^{-3} (≈2.20 USD m^{-3}).

In addition, it is noted that for all treatment techniques, costs, particularly energy expenses, could be reduced by implementing solar-powered electro-treatment or, where landfill gas recovery is available, using it as an energy source to treat concentrated leachate (Karmankar *et al.*, 2023; Messineo *et al.*, 2012). As an example, Karmankar *et al.* (2023) demonstrated that solar photovoltaic-based EC achieved 50−52% lower energy consumption than conventional power-based Al-EC and Fe-EC for treating rice grain-based distillery biodigester effluents while maintaining similar treatment effectiveness.

Recent investigations have also proposed combining chemical coagulation and electrocoagulation to treat industrial wastewater (Abudaia *et al.*, 2026; Pacheco *et al.*, 2023; Weber *et al.*, 2026). Chemical coagulation reduces the current density requirements of electrotreatments, lowering the energy demand to operate the electro-process (Weber *et al.*, 2026). In particular, biocoagulants have gained attention for their eco-friendly approach, as they promote synergistic pollutant removal, reduce toxicity, and generate less sludge (Abudaia *et al.*, 2026; Pacheco *et al.*, 2023). When coagulation and electrocoagulation are integrated, these benefits may maximise contaminant removal in electrotreatments while minimising energy consumption. This could make electrotechniques more attractive.

Overall, our results indicate that the electrochemical process using iron electrodes is more cost-effective for concentrate samples. Despite For benchmarking of performance indicators for treatment costs (i.e., USD g-1 DOC removed), the results are as follows: 32.28 USD g^{-1} DOC (Al-EC), 14.74 USD g^{-1} DOC (Fe-EC), and 29.27 USD g^{-1} DOC (EAF). These results indicate that Fe-EC was the most cost-effective method. However, despite the higher cost-effectiveness of Fe-EC compared to EAF, the removal efficiencies of electro-assisted Fenton were higher across all parameters assessed: 99±1% for true color, 79±4% for Abs254, and 66±3% for DOC. In addition, EAF was the only process capable of reducing SUVA, indicating

lower recalcitrance of organic matter in the treated effluent.

This assessment did not consider sludge management costs. Although the sludge volume generated during the Al/Fe-EC and EAF treatments represented less than 2% of the treated effluent volume, sludge generation data were not systematically collected and, therefore, were not included in the cost estimation. Consequently, the estimated operating costs may be underestimated and should be interpreted with caution. Nevertheless, the analysis fulfills its intended purpose by providing a preliminary estimate of treatment costs and indicating the relative order of operating costs among the assessed methods. Based on our findings, we suggest that electrochemical processes involving the *in situ* electrogeneration of H_2O_2 may represent a promising strategy to reduce the operational costs of EAF while maintaining high treatment efficiency and are thus recommended for future investigations.

4. CONCLUSIONS

Based on the findings of this research, the following conclusions are formulated:

- The treatability performance of electrochemical methods, based on color, Abs254, and DOC removal, was determined as follows: EAF > Fe-EC > Al-EC;
- Operating costs, in USD g^{-1} COD removed, are reported as follows: 32.28 USD g^{-1} DOC (Al-EC), 14.74 USD g^{-1} DOC (Fe-EC), and 29.27 USD g^{-1} DOC (EAF), indicating that the electrochemical process using iron electrodes is more cost-effective for concentrate samples;
- The electro-assisted Fenton was the only process capable of reducing SUVA, indicating a decrease in the recalcitrance/ aromaticity of the treated effluent (from 6.5±0.3 to 3.4±0.2 L mg^{-1} m^{-1});
- The integration of EAF following a concentrate volume reduction step, such as UF, may therefore represent a viable pre-treatment strategy to mitigate concentrate recalcitrance prior to RO concentrate recirculation in landfills when this management approach is adopted;
- The optimization of iron-based electrochemical methods for concentrate pre-treatment, as well as *in situ* electrogeneration of H_2O_2 in advanced electrochemical systems, is recommended for future studies. In addition, further experiments combining electro-oxidation with other treatment processes under continuous operation are needed to advance the scale-up of concentrate management technologies. Ecotoxicity evaluation of electro-treated samples and life cycle analysis are recommended to assess the environmental performance of the treatment process.

5. DATA AVAILABILITY STATEMENT

The survey data is only available upon request.

6. ACKNOWLEDGEMENTS

Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ), grant number E-26/204.425/2024.

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