

Article

Resource Recycling and Wastewater Remediation: Application of Turning Metal Scrap as Anode in Electrochemical Treatment of Soluble Cutting Fluids

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Highlights

What are the main findings?

- Aluminum turning scrap demonstrated the most favorable balance between COD_{Cr}/TOC removal efficiency and specific energy consumption among the tested scrap-based anodes.
- Electrolyte addition (particularly NaNO₃) improved energy efficiency under constant-current operation, although pollutant removal slightly decreased.

What are the implications of the main findings?

- Metal working turning scrap can be reutilized as a sustainable and cost-effective alternative anode material in electrochemical wastewater treatment.
- Process optimization through electrolyte selection and pH control can enhance the trade-off between removal efficiency and energy consumption in scrap-based electrochemical systems.

Abstract

Soluble cutting fluids (SCFs) from metalworking processes pose significant treatment challenges. Here, SCFs were treated using a monopolar electrochemical (EC) system, using turning scrap generated from metalworking operations as the anode. The system was operated for 60 min under various conditions, including different anode materials, electrolyte addition, aeration, and initial pH. Treatment performance was evaluated in terms of chemical oxygen demand (COD_{Cr}) and total organic carbon (TOC) removal efficiencies and specific energy consumption (SEC) for COD_{Cr} removal. The Al scrap (20 g/L) showed the optimal overall performance, achieving COD_{Cr} and TOC removal efficiencies of 29.28% and 25.62%, respectively, with an SEC comparable to that of the Al electrode. Electrolyte addition improved the energy efficiency under all conditions, with NaNO₃ 10 mM yielding the lowest SEC (0.57 kWh/kg-COD_{Cr}), and aeration negatively affected both removal efficiency and energy consumption. Although acidic conditions (pH 2) resulted in high apparent removal, most of the reduction occurred during pre-treatment pH adjustment, and the highest energy efficiency was achieved at pH 7 (0.47 kWh/kg-COD_{Cr}). These



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results demonstrate that Al turning scrap is a promising alternative anode material for electrochemical treatment of SCFs with optimized electrolyte addition and operating pH enabling improved energy efficiency.

Keywords: COD_{Cr}; TOC; SEC; SCFs turning scrap; electrolyte; pH; aeration; electrolysis system

1. Introduction

Metalworking processes are widely employed to manufacture components in various industries such as machinery, electronics, and shipbuilding [1]. In these processes, cutting fluids play a critical role in providing cooling, lubrication, and cleaning functions, thereby significantly contributing to productivity improvements [2,3]. Cutting fluids are generally classified into oil- and water-based types, among which water-based cutting fluids are the most widely used because of their cost-effectiveness, low fire risk, and superior cooling performance [4]. However, wastewater generated from conventional SCFs typically exhibits high concentrations of chemical oxygen demand (COD) and total organic carbon (TOC) owing to the presence of surfactants, lubricants, and various additives, which are often refractory in nature [5]. Furthermore, SCF wastewater may contain toxic chemical constituents, such as biocides and corrosion inhibitors, raising concerns regarding the potential adverse effects on human health, including respiratory and skin disorders, particularly under occupational exposure conditions [6,7]. Moreover, the low biological oxygen demand (BOD)/COD ratio of SCF wastewater reflects its poor biodegradability [5,8], and the presence of oily pollutants further impairs the biological treatment performance by forming an oil layer on microbial surfaces, which hinders oxygen and nutrient transfer to the biomass [9,10]. In addition, SCF wastewater typically exists as a highly stable oil-in-water emulsion stabilized by surfactants, which hinders phase separation and significantly reduces the effectiveness of conventional physicochemical treatment processes such as gravity separation, coagulation–flocculation, and filtration [11,12].

To address this issue, electrochemical treatment methods have been investigated, in which electric energy is applied between electrodes to degrade pollutants in wastewater. Electrochemical treatment refers to a process in which an electrical current is applied between electrodes to induce a variety of physicochemical reactions such as coagulation, flotation, adsorption onto electrode surfaces, and electrochemical oxidation, thereby removing pollutants from wastewater [13,14]. Electrochemical treatment is an effective approach for removing refractory organic pollutants. In addition, this process requires a relatively small installation area and enables rapid pollutant removal within a short reaction time, making it an attractive alternative to conventional treatment technologies [15]. In contrast, electrochemical treatment processes commonly rely on sacrificial metal electrodes, particularly aluminum and iron, which are continuously consumed during operation as metal ions are released into the solution. Electrode consumption has been recognized as a major limitation because it increases the operational costs and generates secondary sludge [15,16]. Accordingly, the need to mitigate electrode consumption through the development of alternative electrode materials or configurations has been emphasized in previous studies [17]. Additionally, metalworking processes generate large quantities of metallic scrap, which is often oxidized and contaminated with cutting fluids during machining operations, diminishing its recycling value and consequently resulting in additional treatment and disposal burdens [18]. Under these circumstances, the reuse of waste metallic scrap as a functional material, rather than as a recyclable resource, has attracted increasing inter-

est. However, its direct application as an electrode material in electrochemical treatment systems, particularly for SCF wastewater, has rarely been explored.

In this study, metallic scrap generated from metalworking processes was used as the anode in an electrochemical treatment system to treat SCFs originating from the same industrial sector. From a circular economy perspective, this approach represents a promising strategy for simultaneously addressing the electrode consumption issue inherent in conventional electrochemical processes while valorizing waste metallic scrap, thereby reducing both resource consumption and waste generation. Accordingly, this study aimed to evaluate the feasibility and performance of metallic scrap as an anode for the electrochemical treatment of SCFs. The treatment performance was assessed in terms of the COD_{Cr} and TOC removal efficiencies, as well as the SEC for COD_{Cr} removal.

2. Materials and Methods

2.1. Experimental Components

2.1.1. Test Sample

The experimental wastewater was prepared by diluting the W-1 type water-soluble cutting fluid obtained from Company U (Gimhae, Republic of Korea) to a concentration of 5% (v/v). According to previous studies [19], significant variations in electrical conductivity have been reported, particularly within the temperature range of 5–30 °C, which can substantially influence the electrochemical treatment performance. Therefore, prior to each experiment, the wastewater temperature was adjusted to 20 °C using a water bath to minimize temperature-induced variation. The characteristics of the 5% diluted wastewater samples are summarized in Table 1.

Table 1. Characteristics of SFCs (diluted to 5% [v/v], at 20 °C).

Material	Specific Gravity
Al	2.6 g/cm ³
SUS	7.2 g/cm ³
Fe	7.9 g/cm ³

2.1.2. Turning Scraps

Turning scrap (i.e., the metal scrap generated during the turning process) was obtained from a domestic supplier, Company D (Suwon city, Republic of Korea). The scraps consisted of aluminum (Al), cast iron (Fe), and stainless steel (SUS); their average specific gravities are summarized in Table 2.

Table 2. Specific gravity of scrap materials.

Parameter	Value
pH	10.00
EC	1.00 mS/cm
COD_{Cr}	109,200 mg/L
TOC	26,300 mg/L

2.1.3. Electrode and Turning Scrap Case

The electrodes used in this study were fabricated from Al, SUS, and Fe, with dimensions of 105 mm (W) $\times$ 110 mm (L) $\times$ 5 mm (H), similar to those of the turning scraps generated during metalworking processes. To eliminate regions with limited solution exchange and promote smooth circulation of the solution, the electrodes were perforated at regular intervals, as shown in Figure 1 [20].

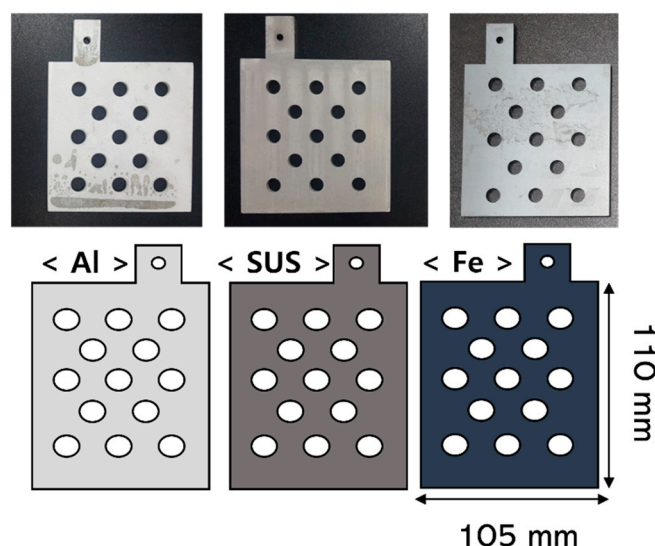


Figure 1. Schematic diagram of the electrode.

To employ turning scrap as the anode, a cage made of 1T-thick stainless steel with dimensions of 105 mm (W) $\times$ 20 mm (L) $\times$ 110 mm (H) was fabricated to contain the scrap (Figure 2). Considering the differences in material density and scrap morphology, the amount of each metal scrap was determined by filling the cage with an equivalent volumetric capacity rather than on a fixed mass basis. Consequently, Al, SUS, and Fe scraps were loaded at 20, 30, and 40 g, respectively, corresponding to fully packed conditions within the cage. This approach was adopted to ensure a comparable effective electrode volume and contact area during the electrochemical operation.

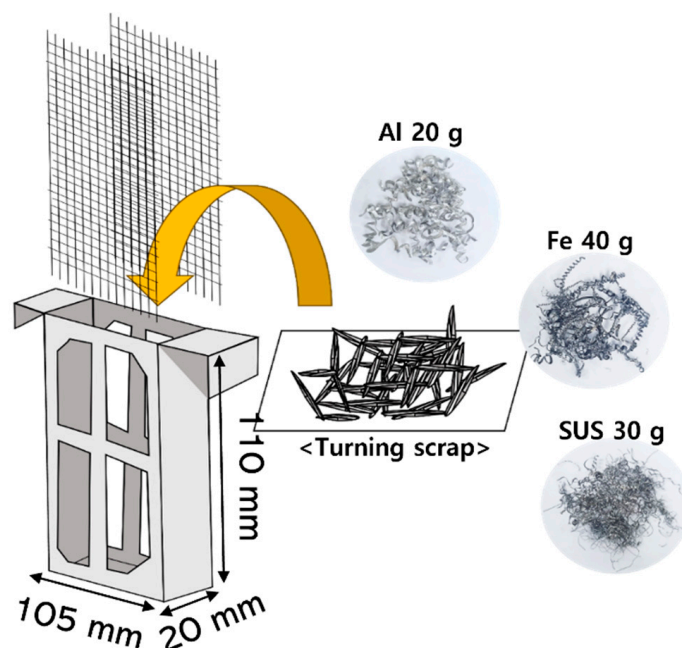


Figure 2. Schematic diagram of the turning scrap with case.

2.1.4. Electrolysis Apparatus

A schematic of the experimental setup used in this study is shown in Figure 3. The reactor containing the sample was constructed of 10 mm-thick acrylic with internal dimensions of 113 mm (W) $\times$ 117 mm (L) $\times$ 150 mm (H), and a valve was installed at the bottom of the reactor to facilitate periodic sampling. A Direct Current (DC) power supply was

used to apply a constant current to the system, and an automatic voltage regulator was installed to prevent voltage fluctuations from the Alternating Current (AC) power source.

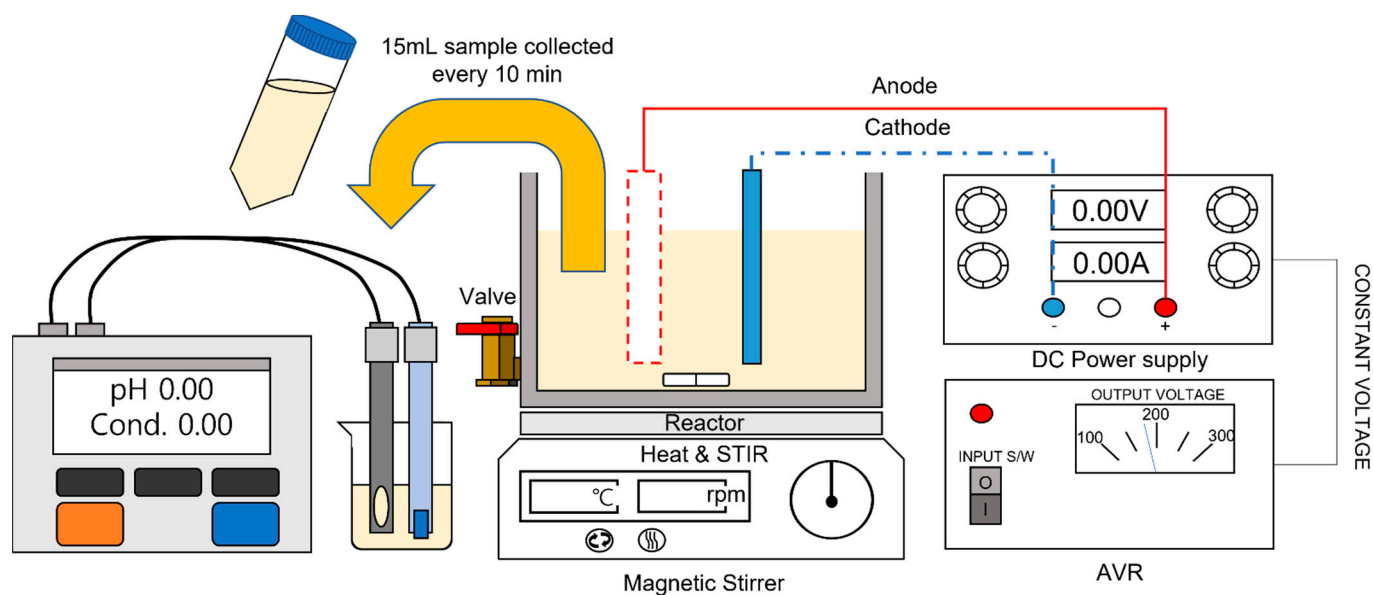


Figure 3. Schematic diagram of the electrolysis apparatus (Adapted from ref. [13]).

A magnetic stirrer equipped with a magnetic bar was used to maintain a homogeneous concentration of the solution throughout the experiment.

2.2. Experimental Conditions and Methods

2.2.1. Experimental Conditions

The fixed and variable parameters used in this study are listed in Table 3. In each experiment, 1000 mL of synthetic wastewater was introduced into the batch-type reactor, and six 15 mL samples were collected at 10 min intervals during 60 min of operation. All experiments were conducted in triplicate, and the reported values represent the median of the experimental results. Error bars shown in the figures indicate the corresponding variability. A single SUS electrode was installed as the cathode in the electrochemical treatment system; whereas, Al, SUS, and Fe electrodes, or their corresponding turns, were employed as the anode, depending on the experimental conditions. The distance between the electrodes was fixed at 40 mm. The system was operated under constant-current (galvanostatic) conditions, with a fixed current of 0.8 A applied throughout the experiments. The applied current of 0.8 A was selected based on preliminary tests performed under monopolar operating conditions, taking into account the voltage limitation of the DC power supply (0–60 V). Several current levels were evaluated in advance to ensure stable galvanostatic operation without exceeding the allowable voltage range across different electrode materials and experimental conditions. Based on these preliminary evaluations, a current of 0.8 A was determined to be suitable and was therefore adopted as the fixed operating condition throughout this study. To minimize experimental error resulting from electrode contamination after each run, the electrodes were immersed in a mixed acid solution (containing > 10% sulfuric acid and nitric acid) for ≥ 12 h. The electrodes were then thoroughly rinsed with distilled water and dried prior to reuse.

Table 3. Constant and variable conditions.

Constant & Variable	Items	Conditions
Constant conditions	Flow control	Batch type
	Process time/Sampling time	60 min/10 min
	Quantity of SCFs	1000 mL
	Cathodic electrode material	SUS
	Applied current	0.8 A
	Distance between electrode	40 mm
Variable conditions	Anodic electrode material	Al, SUS, Fe
	Anodic turning scrap materials	Al 20 g/L, SUS 30 g/L, Fe 40 g/L
	Concentration of electrolyte	Non-addition. NaCl 10 mM, Na ₂ SO ₄ 10 mM, NaNO ₃ 10 mM, KCl 10 mM
	Aeration line	Non-aeration, 2 aeration line
	Initial pH	10 (Non-change), 2, 4, 7

2.2.2. Measurement Instruments and Methods

The COD_{Cr} and TOC removal efficiencies and the SEC for COD_{Cr} removal were evaluated under various operating conditions, including different electrode materials, applied current, electrolyte addition, aeration, and initial pH. Detailed models and manufacturers of the equipment used are summarized in Table 4.

Table 4. Apparatus and equipment used in the experiments (Adapted from ref. [13]).

Machine Name	Model	Manufacturer
Water analyzer	HS-3300	HUMAS Co., (Daejeon, Republic of Korea)
Total Organic Carbon Analyzer	Multi N/C 3100	Analytik Jena., (Jena, Germany)
pH Meter	pH 330i	WTW GmbH., (Weilheim, Germany)
Electrical conductivity meter	Cond 7110	WTW inoLab., (Weilheim, Germany)
Hotplate & Magnetic Stirrer	MS-300	MTOPS (Shen-zhen, China)
Regulated DC power supply	TDP-6020B	TOYOTECH Co., (Dongguan, China)
Automatic Voltage Regulator	SYAVR-2KVASPST	Samyang AVR (Bucheon-si, Republic of Korea)

COD_{Cr} was analyzed using a water analyzer based on the spectrophotometric method [21], and TOC was analyzed using the non-purgeable organic carbon method [22].

The SEC for COD_{Cr} removal was calculated using Equation (1) [23,24]:

$$SEC = \frac{VIt}{\Delta COD} \text{ (kWh/kg-COD}_{Cr}\text{)}, \quad (1)$$

where V is the voltage across the electrodes (V); I is the current (A); t is time; and ΔCOD is the amount of COD removed.

3. Results and Discussion

3.1. Effect of Anode Materials

This section examines how anodic material influences pollutant removal and energy consumption under monopolar conditions (0.8 A, no supporting electrolyte), using a SUS electrode as the cathode. Both electrodes (Al, Fe, SUS) and their corresponding turning scraps were evaluated to identify material-dependent trends and performance gaps.

3.1.1. Effect of Anode Material on COD_{Cr} Removal

As shown in Figure 4a, the Fe electrode exhibited the highest removal efficiency (43.18%), followed by the Al electrode (35.87%), whereas the SUS electrode exhibited the lowest value (33.89%) after 60 min.

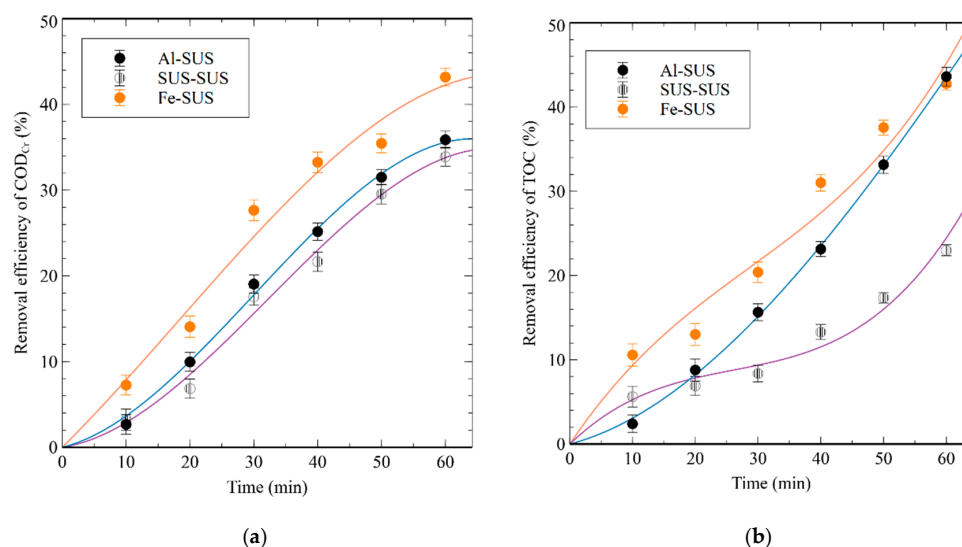


Figure 4. Effect of anode materials (electrode) on removal efficiency of: (a) COD_{Cr}, and (b) TOC (non-electrolyte addition).

As shown in Figure 5a The use of turning scraps as anodes led to lower removal efficiencies than those achieved with conventional electrodes. Among the scrap materials, Al scrap (20 g/L) showed the highest COD_{Cr} removal efficiency (29.28%), while Fe scrap (40 g/L) and SUS scrap (30 g/L) reached 17.93% and 13.81%, respectively.

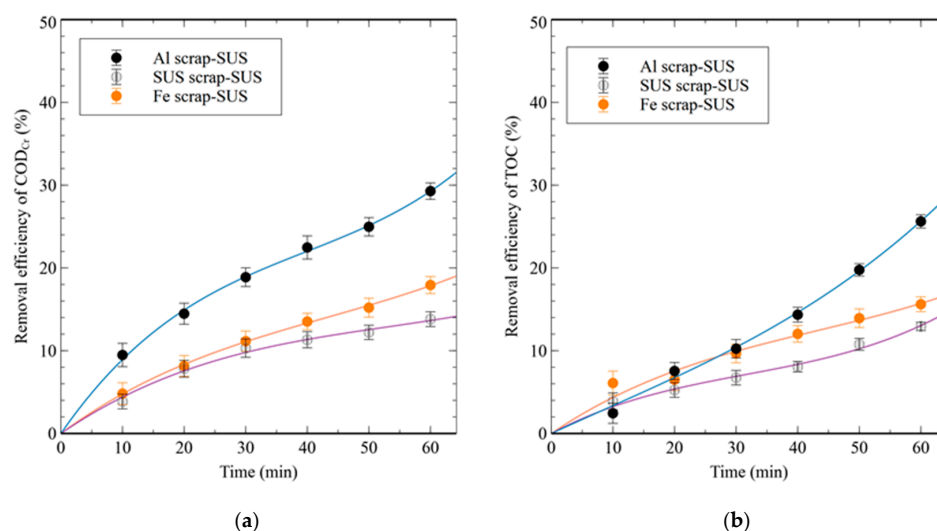


Figure 5. Effect of anode materials (turning scraps) on removal efficiency of: (a) COD_{Cr}, and (b) TOC (non-electrolyte addition).

The consistent underperformance of SUS in both configurations suggests that its limited anodic dissolution reduced the electrocoagulation contribution to pollutant removal. These findings align with previous reports indicating superior removal performance of soluble Al-based anodes compared to stainless-steel systems under similar conditions [25].

3.1.2. Effect of Anode Material on TOC Removal

As shown in Figure 4b, A comparable material-dependent trend was observed for TOC removal. Under conventional electrode conditions, Fe and Al electrodes exhibited similar and relatively high efficiencies (43.78% and 43.62%, respectively), whereas SUS exhibited the lowest value (22.99%) after 60 min.

As shown in Figure 5b, Among the scrap materials, Al scrap (20 g/L) showed the highest TOC removal efficiency (25.62%), while Fe scrap (40 g/L) and SUS scrap (30 g/L) reached 15.61% and 12.94%, respectively.

The close correspondence between COD_{Cr} and TOC trends indicates that the influence of anodic material is not pollutant-specific but is instead governed by fundamental electrochemical dissolution behavior and coagulant generation capacity.

3.1.3. Effect of Anode Material on SEC

As shown in Figure 6, material-dependent differences were also evident in terms of SEC. The Fe electrode exhibited the highest energy efficiency (0.66 kWh/kg- COD_{Cr}) at the final reaction time of 60 min. In contrast, the Al electrode showed 0.72 kWh/kg- COD_{Cr} efficiency, and the SUS electrode showed the lowest efficiency (0.73 kWh/kg- COD_{Cr}).

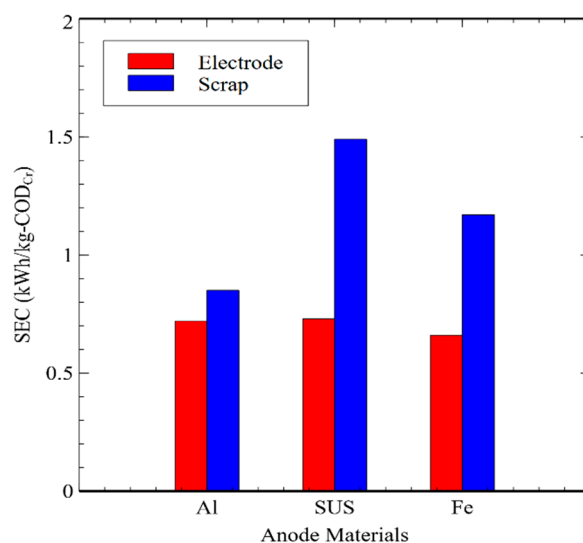


Figure 6. Effect of metal material on specific energy consumption (SEC) (non-electrolyte addition).

For scrap-based anodes, SEC values increased for all materials, reflecting the reduced electrochemical efficiency associated with the packed scrap configuration. Nevertheless, Al scrap (20 g/L) demonstrated the most favorable SEC among the scrap materials (0.85 kWh/kg- COD_{Cr}) compared to 1.19 and 1.49 kWh/kg- COD_{Cr} for Fe scrap (40 g/L) and SUS scrap (30 g/L), respectively.

Under both electrode and scrap conditions, soluble materials such as Al and Fe exhibited higher removal efficiencies than the insoluble SUS. A similar trend was reported in a previous study [26,27], which also found that under conditions with an insoluble titanium (Ti) electrode as the cathode, the use of an Al anode resulted in higher energy efficiency compared to that using an SUS anode.

From an energy-efficiency perspective, it should be noted that SEC is inherently linked to COD_{Cr} removal, as defined in Equation (1) presented in Section 2.2.2. Accordingly, although the absolute SEC value obtained for Al scrap may appear relatively high, its lower SEC compared to other scrap materials reflects a more favorable trade-off between pollutant removal efficiency and energy consumption under identical operating conditions.

To place these findings in context, the comparison between conventional electrodes and scrap-based anodes under monopolar operating conditions consistently demonstrated that scrap anodes exhibited lower baseline performance than their conventional electrode counterparts under identical operating conditions, not only in terms of COD_{Cr} removal but also with respect to TOC removal and SEC. Accordingly, subsequent experiments such as electrolyte addition, were intentionally designed to enhance the treatment efficiency of scrap-based anodes rather than to repeat direct performance comparisons with conventional electrodes.

3.2. Effect of Electrolyte Addition

This section investigates the effects of supporting electrolyte addition under constant-current conditions (0.8 A) on COD_{Cr} and TOC removal, operating voltage, and SEC in scrap-based electrochemical systems. Particular emphasis is placed on elucidating how changes in solution conductivity influence both treatment efficiency and energy performance.

3.2.1. Effect of Electrolyte Addition on COD_{Cr} Removal

As shown in Figure 7a, when comparing the COD_{Cr} removal efficiency using Al scrap (20 g/L) as the anode, the non-addition exhibited the highest removal efficiency (29.28%) after 60 min. The addition of 10 mM NaNO_3 , NaCl , KCl and Na_2SO_4 reduced efficiencies of 23.80%, 20.00%, 18.93%, and 18.11%, respectively.

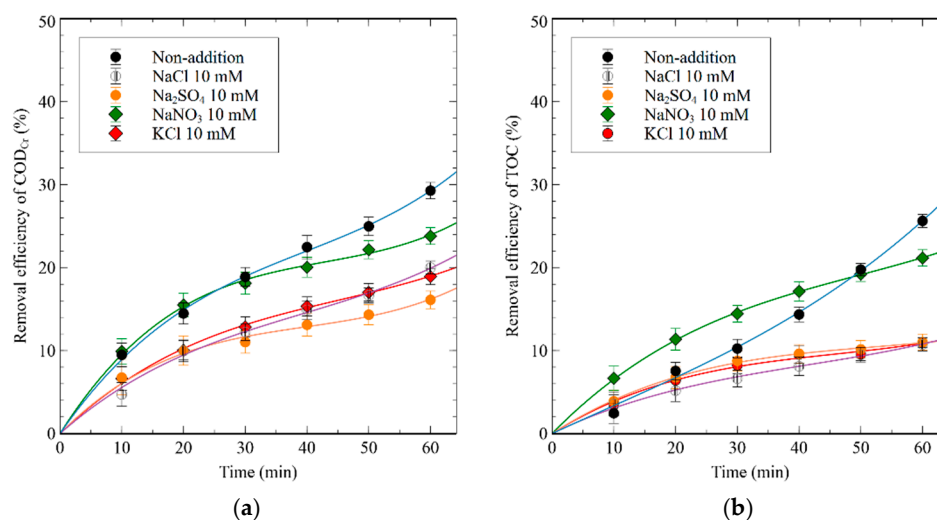


Figure 7. Effect of electrolyte addition on the removal efficiency of: (a) COD_{Cr} ; and (b) TOC using Al scrap (20 g/L) as the anode.

A similar tendency was observed (Figure 8a). Using SUS scrap (30 g/L) as the anode, non-addition and 10 mM NaNO_3 exhibited the highest removal efficiency (13.81%). The addition of 10 mM NaCl , Na_2SO_4 , KCl resulted in lower values of 12.40%, 11.08%, and 9.44%, respectively.

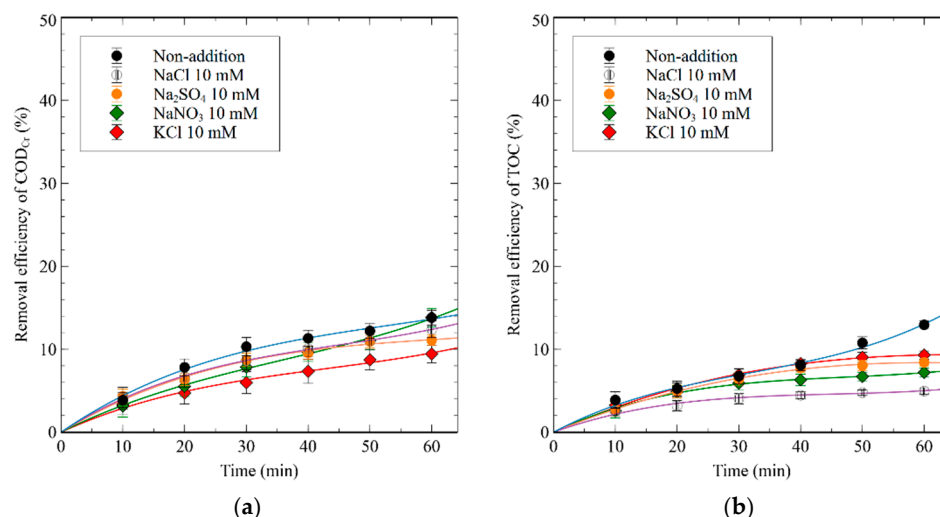


Figure 8. Effect of electrolyte addition on the removal efficiency of: (a) COD_{Cr} ; and (b) TOC using SUS scrap (30 g/L) as the anode.

Figure 9a shows that using Fe scrap (40 g/L) as the anode, no addition exhibited the highest removal efficiency (17.93%). The addition of 10 mM NaCl, NaNO_3 , Na_2SO_4 , KCl resulted in lower values of 16.14%, 14.20%, 12.20%, and 9.12%, respectively.

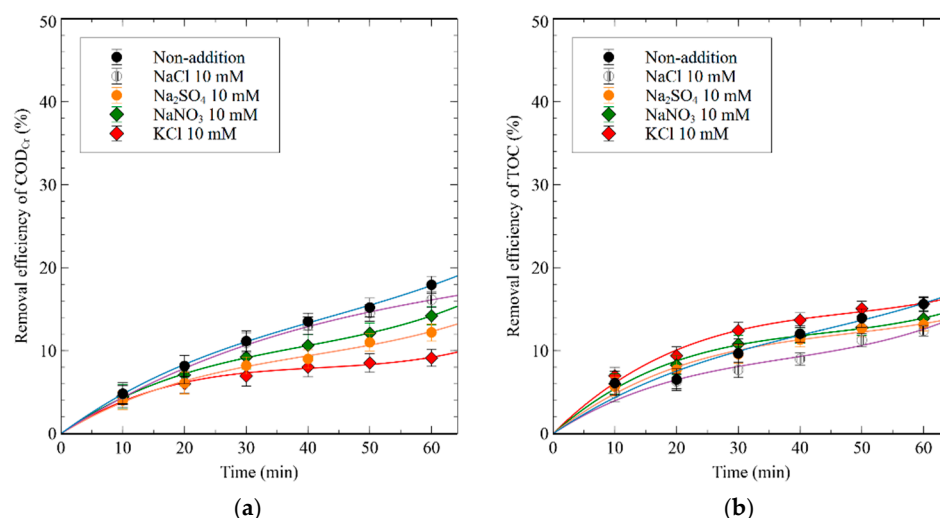


Figure 9. Effect of electrolyte addition on the removal efficiency of: (a) COD_{Cr} ; and (b) TOC using Fe scrap (40 g/L) as the anode.

3.2.2. Effect of Electrolyte Addition on TOC Removal

A comparable trend was observed for TOC removal. As shown in Figure 7b, when comparing the TOC removal efficiency using Al scrap (20 g/L) as the anode, non-addition exhibited the highest efficiency (25.62%) at a final reaction time. The addition of 10 mM NaNO_3 , Na_2SO_4 , KCl, NaCl resulted in lower values of 21.16%, 11.00%, 10.96%, and 10.73%, respectively.

A similar tendency was observed (Figure 8b), using SUS scrap (30 g/L) as the anode, non-addition exhibited the highest efficiency (12.94%). The addition of 10 mM KCl, Na_2SO_4 , NaNO_3 , NaCl resulted in lower values of 9.29%, 8.41%, 7.19%, and 4.95%, respectively.

Figure 9b shows that using Fe scrap (40 g/L) as the anode, non-addition and 10 mM KCl exhibited the highest efficiency (15.61%). The addition of 10 mM NaNO_3 , Na_2SO_4 , NaCl resulted in lower values of 13.86%, 13.13%, and 12.41%, respectively.

The decrease in COD_{Cr} and TOC removal efficiencies observed upon electrolyte addition can be explained by changes in electrochemical operating conditions. As electrolyte concentration increased, solution electrical conductivity (EC) also increased (Figure 10), leading to a reduction in the operating voltage required to maintain the imposed constant current.

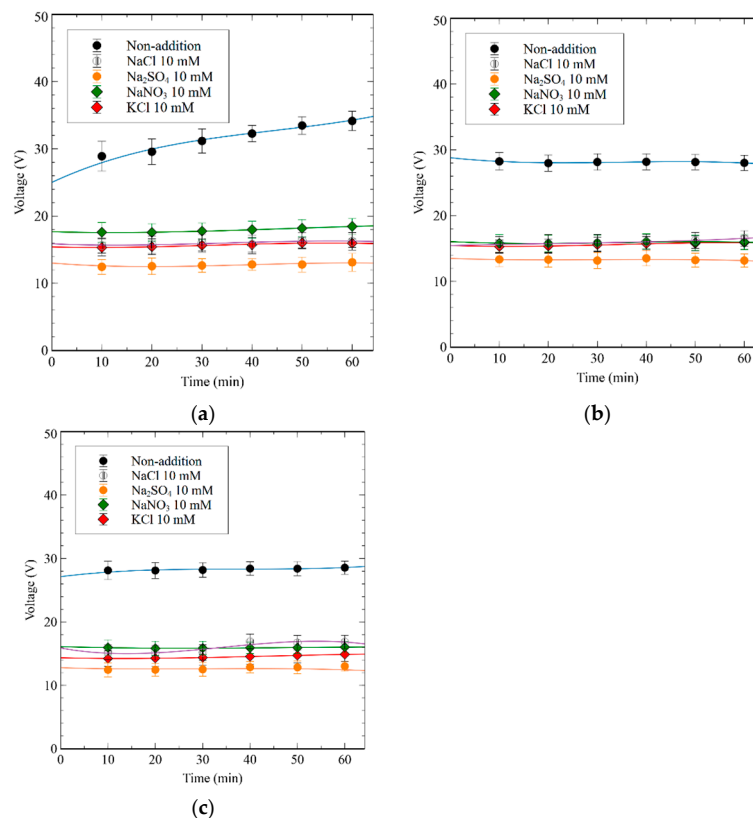


Figure 10. Effect of electrolyte addition on cell voltage under constant-current conditions (0.8 A) using: (a) Al scrap (20 g/L), (b) SUS scrap (30 g/L), and (c) Fe scrap (40 g/L) as the anode.

The lower operating voltage may have been insufficient to provide the activation overpotential necessary to disrupt the passivation layer on the scrap anode [28]. Consequently, anodic dissolution and coagulant generation were limited, resulting in reduced pollutant removal efficiency. Similar voltage-dependent limitations have been reported previously for Al and Fe anodes, where insufficient voltage suppressed anodic dissolution and treatment performance [29,30].

Moreover, previous studies have demonstrated that voltage decreases with increasing wastewater conductivity under constant-current conditions [23], and have suggested that electrocoagulation systems may operate more efficiently under constant-voltage control rather than constant-current operation.

3.2.3. Effect of Electrolyte Addition on SEC

In contrast to removal efficiency, electrolyte addition significantly improved energy efficiency under constant-current operation. As shown in Figure 11, the SEC for COD_{Cr} removal was compared under the condition using Al scrap (20 g/L) as the anode, 10 mM NaNO_3 exhibited the highest energy efficiency (0.57 kWh/kg- COD_{Cr}) at the final reaction time. In contrast, 10 mM NaCl and 10 mM Na_2SO_4 showed efficiency of 0.60 kWh/kg- COD_{Cr} , 10 mM KCl showed efficiency of 0.62 kWh/kg- COD_{Cr} , and non-addition showed the lowest efficiency (0.85 kWh/kg- COD_{Cr}).

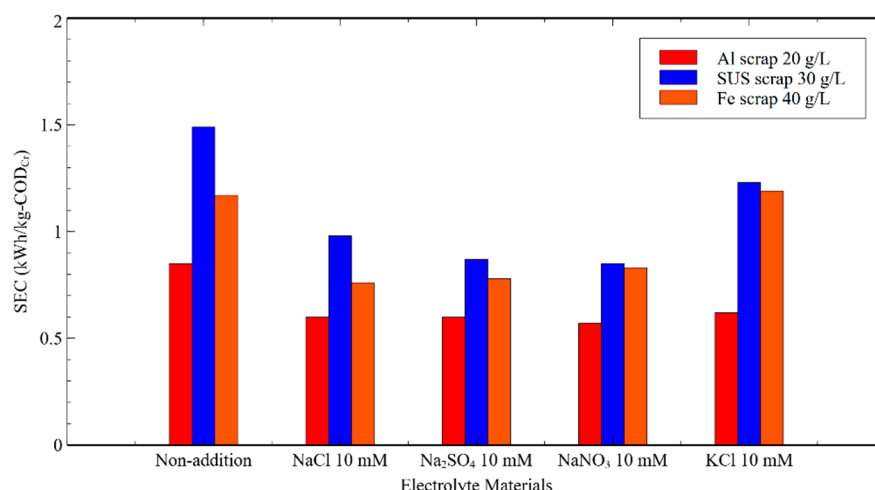


Figure 11. Effect of electrolyte addition on SEC using: Al scrap (20 g/L), SUS scrap (30 g/L), and Fe scrap (40 g/L) as the anode.

A similar tendency was observed (Figure 11), using SUS scrap (30 g/L) as the anode, and 10 mM NaNO₃ exhibited the highest energy efficiency (0.85 kWh/kg-COD_{Cr}) at the final reaction time of 60 min. In contrast, 10 mM Na₂SO₄ showed efficiency of 0.87 kWh/kg-COD_{Cr}, 10 mM NaCl showed efficiency of 0.98 kWh/kg-COD_{Cr}, 10 mM KCl showed efficiency of 1.23 kWh/kg-COD_{Cr}, and non-addition showed the lowest efficiency (1.49 kWh/kg-COD_{Cr}).

Figure 11 shows that, using Fe scrap (40 g/L) as the anode, and 10 mM NaCl exhibited the highest energy efficiency (0.76 kWh/kg-COD_{Cr}) at the final reaction time of 60 min. In contrast, 10 mM Na₂SO₄ showed efficiency of 0.78 kWh/kg-COD_{Cr}, 10 mM NaNO₃ showed efficiency of 0.83 kWh/kg-COD_{Cr}, 10 mM KCl showed efficiency of 1.17 kWh/kg-COD_{Cr}, and non-addition showed the lowest efficiency (1.19 kWh/kg-COD_{Cr}).

Although the COD_{Cr} and TOC removal efficiencies were the highest under non-addition conditions across all anode types, the SEC exhibited an opposite trend, with electrolyte-added conditions showing improved energy efficiency. Notably, under Al and SUS scrap conditions, NaNO₃ addition resulted in the lowest SEC among the electrolytes tested, indicating more efficient energy utilization under these specific conditions. This behavior can be attributed to the increased ionic conductivity provided by electrolyte addition, which reduces ohmic resistance between the electrodes and improves energy efficiency [31]. However, it should be noted that the favorable SEC observed with NaNO₃ was evaluated in a comparative context, and the potential environmental implications of nitrate-based electrolytes must be carefully considered for practical applications.

3.3. Effect of Aeration

Based on the results presented in Sections 3.1 and 3.2, Al scrap (20 g/L) was selected as the anode for the aeration experiments. In this section, the effect of aeration on the removal efficiency performance was evaluated under constant-current conditions (0.8 A) using a SUS cathode and the selected Al scrap anode without supporting electrolytes.

3.3.1. Effect of Aeration Addition on COD_{Cr} Removal

As shown in Figure 12a, when comparing the COD_{Cr} removal efficiencies using Al scrap (20 g/L) as the anode, non-aeration exhibited the highest efficiency (29.28%) at a final reaction time. In contrast, the 2 aeration line showed the lowest efficiency (13.40%).

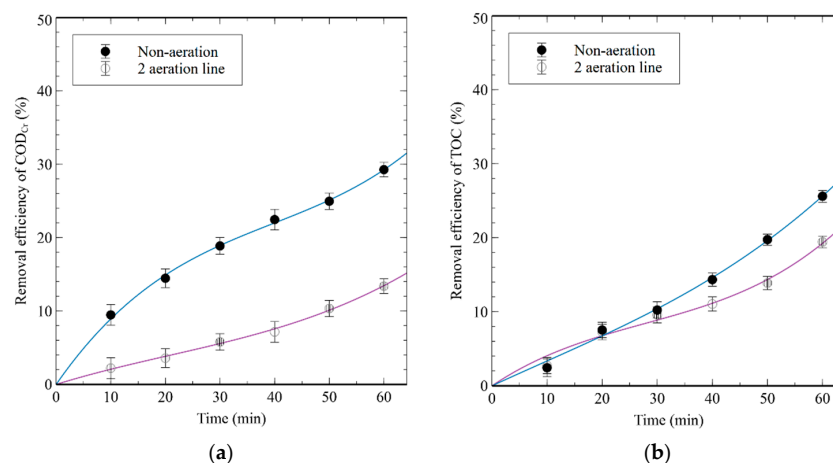


Figure 12. Effect of aeration on the removal efficiency of: (a) COD_{Cr}, and (b) TOC using Al scrap (20 g/L) as the anode.

3.3.2. Effect of Aeration on TOC Removal

As shown in Figure 12b, when comparing the TOC removal efficiencies using Al scrap (20 g/L) as the anode, non-aeration exhibited the highest efficiency (25.62%). In contrast, the two aeration lines exhibited the lowest efficiency (19.45%). Consequently, it was confirmed that the removal efficiencies of both COD_{Cr} and TOC decreased under aerated conditions. This phenomenon may have been attributed to additional hydrodynamic disturbances introduced during aeration, which could have destabilized the coagulated flocs [32]. A similar trend was reported in a previous study [33], in which a decrease in COD removal efficiency was observed when agitation and aeration were simultaneously applied. In addition, it was previously reported that COD concentrations, which initially decreased, subsequently increased under aerated conditions [34]. This behavior is attributed to the destabilization and breakup of the coagulated flocs induced by the air bubbles generated during the aeration process.

3.3.3. Effect of Aeration on SEC

As shown in Figure 13, the SEC for COD_{Cr} removal was compared under the condition using Al scrap (20 g/L) as the anode, and non-aeration exhibited the highest energy efficiency (0.85 kWh/kg-COD_{Cr}) at the final reaction time. In contrast, the two aeration lines showed the lowest efficiency (1.87 kWh/kg-COD_{Cr}). However, the voltage profiles over time were nearly identical under the same applied current (Figure 14). This suggested that the increased specific energy consumption was not due to an increase in the overpotential or ohmic resistance caused by air bubbles, as reported previously [35]. Consistent with the explanation provided in Section 3.3.2, this was attributed to the destruction of the coagulated flocs by air bubbles.

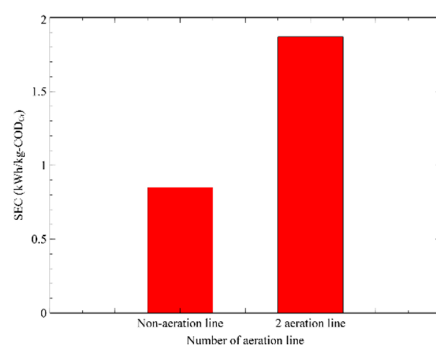


Figure 13. Effect of aeration on SEC using Al scrap (20 g/L) as the anode.

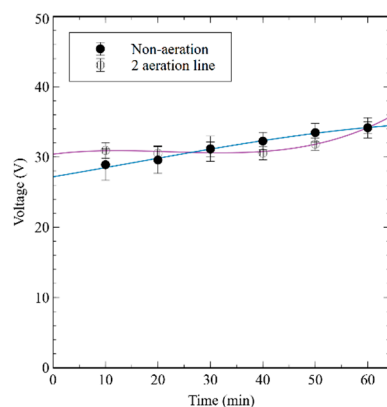


Figure 14. Effect of aeration on cell voltage under constant-current conditions (0.8 A) using Al scrap (20 g/L) as the anode.

3.4. Effect of Initial pH

Based on the results presented in Sections 3.1 and 3.2, Al scrap (20 g/L) was selected as the anode for the aeration experiments. In this section, the effect of the initial pH adjustment on the removal efficiency was evaluated under constant-current conditions (0.8 A) using an SUS cathode and the selected Al scrap anode, without supporting electrolytes. The initial pH was adjusted using NaOH and H₂SO₄. The temporal variations in solution pH under different initial pH conditions are shown in Figure 15.

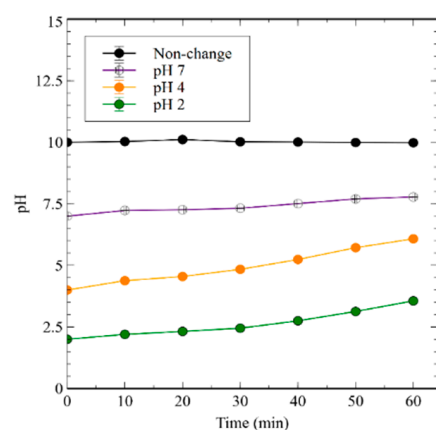


Figure 15. Temporal variation in solution pH under different initial pH conditions using Al scrap (20 g/L) as the anode.

3.4.1. Effect of Initial pH on COD_{Cr} Removal

As shown in Figure 16a, when comparing the COD_{Cr} removal efficiencies using Al scrap (20 g/L) as the anode, pH 2 exhibited the highest efficiency (60.01%) at a final reaction time. In contrast, the efficiency at pH 10 (no change) was 29.28%, that at pH 7 was 23.15%, and that at pH 4 showed the lowest efficiency (12.19%). However, during the pH adjustment process, COD_{Cr} removal efficiencies of 0.15, 10.31, and 47.99% were observed under the pH 7, 4, and 2 conditions, respectively. These results indicated that a substantial portion of COD_{Cr} was already removed during the initial pH adjustment process, making it difficult to attribute the subsequent COD_{Cr} removal efficiency to the electrochemical treatment.

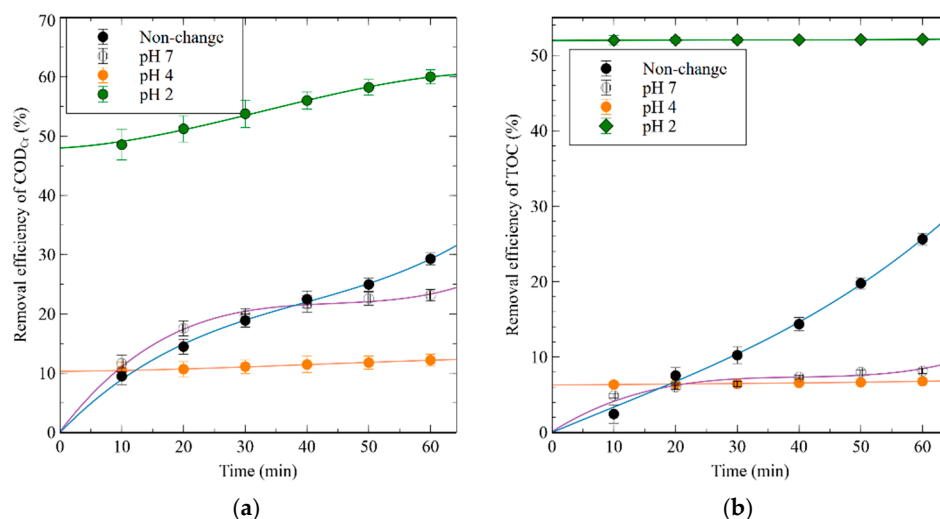


Figure 16. Effect of initial pH on removal efficiency of: (a) COD_{Cr}; and (b) TOC using Al scrap (20 g/L) as the anode.

3.4.2. Effect of Initial pH on TOC Removal

As shown in Figure 16b, when comparing the TOC removal efficiency using Al scrap (20 g/L) as the anode, pH 2 exhibited the highest efficiency (52.11%) at a final reaction time. In contrast, pH 10 showed 25.62% efficiency, pH 7 showed 8.13% efficiency, and pH 4 had the lowest efficiency (12.19%). However, during the pH adjustment process, COD_{Cr} removal efficiencies of 0.10, 6.28, and 51.96% were observed for the pH 7, 4, and 2 conditions, respectively. These results indicated that a substantial portion of the TOC had already been removed during the initial pH adjustment process, making it difficult to clearly attribute the subsequent TOC removal efficiency to the electrochemical treatment.

In this regard, both COD_{Cr} and TOC were substantially removed under the initial pH 2 adjustment conditions. This behavior is consistent with previously reported emulsion destabilization phenomena during acidification of oil-in-water systems [36,37]. Under strongly acidic conditions, the surface charge of surfactant molecules can be neutralized, leading to a loss of emulsion stability, as visually observed in Figure 17. Consequently, dispersed oil droplets may coalesce and separate from the aqueous phase, contributing to reductions in COD_{Cr} and TOC prior to electrochemical treatment. Therefore, the overall removal efficiencies observed after pH adjustment, particularly at pH 2, should be interpreted with caution, as they likely reflect the combined contribution of pH-induced physicochemical destabilization and subsequent electrochemical treatment rather than the effect of electrochemical processes alone.



Figure 17. Visual appearance of SCFs under different initial pH conditions: pH 7 (left), pH 4 (middle), and pH 2 (right).

3.4.3. Effect of Initial pH on SEC

Based on the net COD_{Cr} removal achieved during the electrochemical treatment stage, excluding the COD_{Cr} removal occurring during the pH adjustment process, the SEC for COD_{Cr} removal was evaluated under the condition using Al scrap (20 g/L) as the anode. As shown in Figure 18, pH 7 exhibited the highest energy efficiency (0.47 kWh/kg- COD_{Cr}) at the final reaction time. In contrast, pH 2 showed efficiency of 0.69 kWh/kg- COD_{Cr} , pH 10 showed efficiency of 0.85 kWh/kg- COD_{Cr} , and pH 4 showed the lowest efficiency (5.58 kWh/kg- COD_{Cr}).

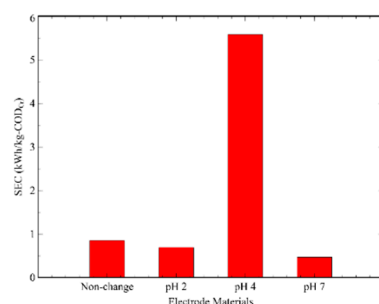


Figure 18. Effect of initial pH on SEC using Al scrap (20 g/L) as the anode.

As shown in Figure 19, pH adjustment led to an increase in EC, which reduced the cell voltage required to maintain a constant current, thereby improving energy efficiency [38,39]. However, despite the enhanced EC, a significant deterioration in the energy efficiency was observed at pH 4. This behavior may have been attributed to the transitional nature of the electrochemical reaction pathways at this pH [40–42], where oxidative reactions dominate under strongly acidic conditions, and coagulation reactions, prevalent under near-neutral conditions, are both insufficiently developed [43,44].

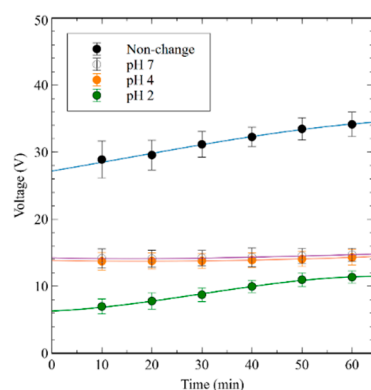


Figure 19. Effect of initial pH on cell voltage under constant-current conditions (0.8 A) using Al scrap (20 g/L) as the anode.

Under varying initial pH conditions, the electrochemical treatment results indicated that energy consumption efficiency was maximized at pH 7. A similar trend was reported in a previous study [8,45], in which the highest removal efficiency was observed under neutral pH conditions. However, in the present study, the removal efficiency at pH 7 was lower than that under non-adjusted pH conditions. As discussed in Section 3.2, this can be attributed to the relatively low operating voltage at pH 7, which was insufficient to provide the activation energy required to disrupt the passivation layer formed on the scrap anode surface [28].

4. Conclusions

This study demonstrated the feasibility of using turning scrap as a sacrificial anode in a monopolar electrochemical system for the treatment of SCFs. The performance of scrap-based anodes was systematically evaluated in comparison with conventional electrodes under various operating conditions, including anode material, electrolyte addition, aeration, and initial pH.

Among the investigated materials, Al scrap exhibited the most balanced overall performance, achieving comparatively high COD_{Cr} and TOC removal efficiencies while maintaining favorable energy efficiency. Notably, Al scrap showed the smallest performance discrepancy relative to its conventional electrode counterpart, indicating its strong potential as a viable alternative anode material. These results suggest that metal scrap can be effectively reutilized in electrochemical wastewater treatment without a substantial loss in treatment performance.

The results further revealed that operational parameters exerted a strong influence on the trade-off between pollutant removal efficiency and energy consumption. While non-addition conditions generally resulted in higher COD_{Cr} and TOC removal, electrolyte addition significantly improved energy efficiency by enhancing solution conductivity and reducing ohmic resistance. In particular, NaNO₃ addition led to lower specific energy consumption under certain conditions; however, its practical application should be carefully evaluated in light of potential environmental implications. Similarly, although acidic conditions (pH 2) enhanced apparent removal efficiencies, a substantial portion of this removal occurred during the pH adjustment step, highlighting the need for cautious interpretation of electrochemical treatment performance.

Overall, the findings emphasize that process optimization should focus on balancing removal efficiency and energy consumption rather than maximizing a single performance metric. Future studies should investigate system-scale optimization strategies, such as bipolar electrode configurations, electrode number, and applied current density, as well as conduct comprehensive economic and life-cycle assessments to further evaluate the long-term sustainability and practical applicability of scrap-based electrochemical treatment systems.

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Abbreviations

The following abbreviations are used in this manuscript:

Al Aluminum
BOD Biochemical oxygen demand

COD	Chemical oxygen demand
EC	Electrical conductivity
Fe	Iron
SCFs	Soluble cutting fluids
SEC	Specific energy consumption
SUS	Stainless steel
TOC	Total organic carbon

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