JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(6), 95–109
https://doi.org/10.12911/22998993/202092
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.02.05
Accepted: 2025.04.07
Published: 2025.04.15

Optimizing chemical oxygen demand and total nitrogen removal from tofu wastewater using a multi-rod helical electrocoagulation system in a tubular reactor

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ABSTRACT

Tofu production generates significant volumes of wastewater, which are primarily managed by micro, small, and medium-sized enterprises (MSMEs) that lack adequate treatment infrastructure. As characterised by high chemical oxygen demand **(**COD) (3,175 mg/L) and nitrogen levels (13.56 mg/L), tofu wastewater poses severe environmental risks to aquatic ecosystems. Traditional and advanced treatment methods are often ineffective or financially unfeasible for MSMEs. This study investigates a novel MRHS EC reactor for the continuous-flow treatment of tofu wastewater with a focus on COD and TN removal. The MRHS reactor uses a helical electrode configuration to enhance mixing, coagulant dispersion, and pollutant removal efficiency. Under optimal conditions, the MRHS reactor achieved an average of COD removal of 50–76.9% and TN removal of 58–72%, with energy consumption 2.69–10.6 kWh/m³ for TN removal, 1.96–8.35 kWh/m³ COD Removal using aluminium and iron anodes. The system demonstrated superior performance compared to conventional batch EC setups, particularly in terms of scalability and operational efficiency. Key parameters such as current density, electrode material, and pH were systematically optimised to maximise pollutant removal while minimising energy use. The findings highlight the potential of MRHS EC systems as scalable, energy-efficient, and cost-effective solutions for MSMEs. Beyond its academic contribution, this research offers practical implications for sustainable wastewater management in tofu production and other industries producing high organic content effluents. By addressing the pressing need for regulatory compliance and reducing environmental impact, the MRHS EC reactor represents a transformative approach to wastewater treatment for small-scale enterprises.

Keywords: electrocoagulation, tofu wastewater treatment, cod removal, nitrogen removal, helical electrocoagulation reactor.

INTRODUCTION

The global demand for tofu, a nutritionally valuable and versatile plant-based protein, continues to grow. However, tofu production generates significant volumes of wastewater, primarily managed by micro, small, and medium-sized enterprises (MSMEs). These enterprises often operate without adequate wastewater treatment infrastructure, leading to the discharge of untreated effluents into the environment. Tofu wastewater is characterized by elevated levels of COD and nitrogen compounds, with concentrations reaching as high as 2912 mg/L for COD and 282.3 mg/L for nitrogen (Widyaningrum, 2020; Aristiana and Purnomo, 2020; Zahrina et al., 2022). The discharge of such pollutants poses severe environmental threats, particularly to aquatic ecosystems. Traditional wastewater treatment methods, including biological processes such as aerobic and anaerobic systems, have shown limited efficacy for high organic loads typical of tofu wastewater. These methods often require extensive pretreatment to reduce COD and nitrogen levels to manageable concentrations (Yan et al., 2024). Advanced systems such as membrane bioreactors and ultrafiltration have been explored but are hindered by high operational costs and fouling issues, rendering them impractical for widespread use by MSMEs (Osman and Hodaifa, 2023;

Kammakakam and Lai, 2023). Therefore, there is an urgent need for scalable, energy-efficient, and cost-effective solutions tailored to the challenges of tofu wastewater treatment.

Electrocoagulation has emerged as a promising alternative to traditional treatment methods. Unlike chemical coagulation, electrocoagulation offers the advantages of reduced chemical usage, minimal sludge generation, and high removal efficiencies for organic and nutrient pollutants (Boinpally et al., 2023; Ardhianto et al., 2024). Studies employing iron (Fe) and aluminum (Al) electrodes have demonstrated COD removal efficiencies of up to 90%TSS and COD removal of 76% in batch configurations (Pangestu et al., 2021; Ardhianto and Bagastyo, 2019). However, most EC studies are limited to batch setups (Girón-Navarro et al., 2024), which lack scalability and fail to simulate real-world continuous-flow conditions. Additionally, research addressing EC's effectiveness for nitrogen-rich wastewater, such as tofu effluents, remains limited. This study introduces a novel Multi-Rod Helical System (MRHS) EC reactor designed for continuous-flow operation. The MRHS configuration enhances mixing, maximizes electrode-wastewater contact, and improves coagulant dispersion, resulting in superior pollutant removal efficiencies. Recent advancements in MRHS technology have demonstrated its effectiveness in treating textile wastewater effluents, achieving pollutant removal efficiencies for COD while maintaining low energy consumption of 0.65–0.71 kWh/m³ (Maharani et al., 2024). Despite these successes, the application of MRHS for tofu wastewater treatment remains unexplored, particularly in the context of MSMEs.

This research aims to address these gaps by optimizing the removal of COD and total nitrogen (TN) from tofu wastewater using an MRHS system in a continuous-flow reactor. The study stands out in several critical aspects: (1) Innovative reactor design: the MRHS reactor introduces a helical electrode configuration that creates enhanced turbulence and increases the effective surface area for the EC. This design has not been previously applied to tofu wastewater treatment, representing a significant advancement in EC technology for handling high-organic-content effluents. (2) Pilot-Scale Implementation: unlike previous studies confined to laboratory-scale setups, this research employs a pilot-scale continuous-flow system. This approach ensures the practical applicability of the findings and addresses the scalability challenges faced by MSMEs. (3) Integrated parameter optimization: the study systematically optimises key operational parameters, including current density, pH, and electrode material, to achieve maximum pollutant removal with minimal energy consumption. This comprehensive approach contrasts with prior studies that often consider these parameters in isolation (Mousazadeh et al., 2023). By integrating these innovative aspects, the study provides a robust framework for advancing Electrocoagulation technology, specifically tailored for tofu wastewater treatment. The MRHS reactor's unique design and operational efficiency offer a practical, energy-efficient, and cost-effective solution for MSMEs, addressing the pressing need for sustainable wastewater management in the tofu production industry. The implications of this research extend beyond academia to practical industrial applications. Academically, it contributes to the expanding body of knowledge on advanced Electrocoagulation systems, particularly for nitrogen-rich effluents. Industrially, it offers a scalable and adaptable solution that aligns with the needs of wastewater treatment, enabling them to achieve regulatory compliance and reduce environmental impacts. Furthermore, the adaptability of the MRHS EC system holds promise for broader applications in other high-organic-content industrial effluents.

MATERIAL AND METHODS

Materials and equipment

The materials and equipment used in this study were selected to ensure precision in analyzing the parameters associated with the performance of the electrocoagulation process. Chemical reagents included potassium dichromate ($K_2Cr_2O_7$, ≥ 99.9%), sulfuric acid (H_2SO_4, 98%), mercuric sulfate ($HgSO_4$, ≥ 99%), and silver sulfate (Ag_2SO_4, ≥ 99.99%) for COD analysis, all procured from Chemind Chemicals Co., Ltd, India. For pH measurement, a Metrohm 780 pH Master from Switzerland was utilized. $PO4^{3-}$ analysis employed UV-visible spectrophotometry using an HACH DR6000 spectrophotometer (USA), which was also applied for TN determination. TDS measurements were conducted using a conductivity meter (Hanna Instruments HI5522, USA). Hydrochloric acid (HCl, ≥ 37%) and sodium hydroxide (NaOH, ≥ 98%) were purchased

from Merck KGaA, Germany. All solutions were prepared using DI water to avoid contamination. Reagents were stored and prepared as per APHA standards to maintain analytical integrity. The equipment for electrocoagulation experiments included a set reactor electrocoagulation unit with multirods helical system as cathode (SS 304) and with Fe and Al electrodes as anode sourced locally in Jakarta, Indonesia. The detail of equipment of electrocoagulation experiments provides in Figure 1.

Source of tofu wastewater and initial characterization

The tofu wastewater used in this study was sourced from a home industry (UMKM) in Purwantoro District, Wonogiri, Central Java Province, Indonesia (located at coordinates 7°51'00.0"S, 111°10'00.0"E). The effluent primarily originated from the washing and soaking processes in tofu production, with additional contributions from grinding, boiling, and pressing stages. Samples were collected directly from the final washing tank, stored in plastic containers, and transported under controlled conditions at approximately 4 °C to the Environmental Engineering Laboratory of Institut Teknologi PLN (ITPLN), Jakarta, following the wastewater sampling guidelines outlined in SNI 6989.59:2008. Initial characterization of the effluent revealed a high concentration of organic and inorganic compounds. The COD was 3.175 mg/L, significantly exceeding the Indonesian Government Effluent Standard of 300 mg/L. The wastewater was also highly acidic, with a pH of 3.67, falling below the permissible range of 6–9. Furthermore, the effluent contained PO_4^{3-}, TDS, and TN, which require treatment to mitigate their environmental impact. The initial wastewater characteristics produced by the tofu industry in Wonogiri's UMKM sector are detailed in Table 1.

Experimental set up

The EC reactor used in this study was a tubular system designed for batch recirculation flow operation. The reactor uses 50 mm diameter pipes (PVC) with a length of 50 cm. There are two pieces in total. The system was operated at a flow rate of 1 L/min in batch recirculation methods. Each helical electrode had a wire diameter of 5 mm, a coil diameter of 48 mm, a height of 50 cm, with two electrodes in total as cathode. The anode consisted of solid Fe and Al rods, measuring 25 mm in diameter and 50 cm in length, while Fe electrode, also 50 cm in length and 25 mm in diameter, were utilized in the setup. A direct current (DC) power supply was used, capable of delivering a current of 0–20 A and a voltage range of 0–60 V. The EC process was conducted under a constant voltage mode, allowing the current strength to vary based on the operational conditions. The reactor was operated at a water temperature of 28 °C, To adjust the pH of the wastewater to the desired level, 0.1 M HCl and 0.1 M NaOH solutions were used. This pH adjustment was critical to optimize the removal efficiency of COD and TN. The reactor's performance was supported a pump with a maximum capacity of 19.6 L/min, ensuring precise and consistent flow at the required rate of 1 L/min. The EC system was configured and optimized following established guidelines to ensure efficient removal of pollutants. A schematic representation of the experimental setup is provided on Figure 1.

Analytical methods and data analysis

This study analyzed several key parameters, including COD, TN, and pH, to evaluate the effectiveness of the EC process in treating tofu wastewater. The methodologies adhered strictly to standardized protocols for water and wastewater analysis as outlined by the Indonesian National Standards (SNI). For COD analysis, the closed

Table 1. Initial characteristics of tofu waswater as raw water

Parameter	Unit	Method	Concentration	*Effluent Standard
COD	mg/L	SNI 6989.2:2019	3.175	300
pH	-	SNI 06-6989.11-2004	3.67	6–9
PO_3^{-4}	mg/L	SNI 06-6989.31-2005	2.36	-
TDS	mg/L	SNI 06-6989.27-2005	1.047	-
TN	mg/L	SNI 06-6989.49-2005	13.56	-

Note: *Regulation of the Minister of Environment of the Republic of Indonesia No. 5 of 2014 on Wastewater Quality Standards.

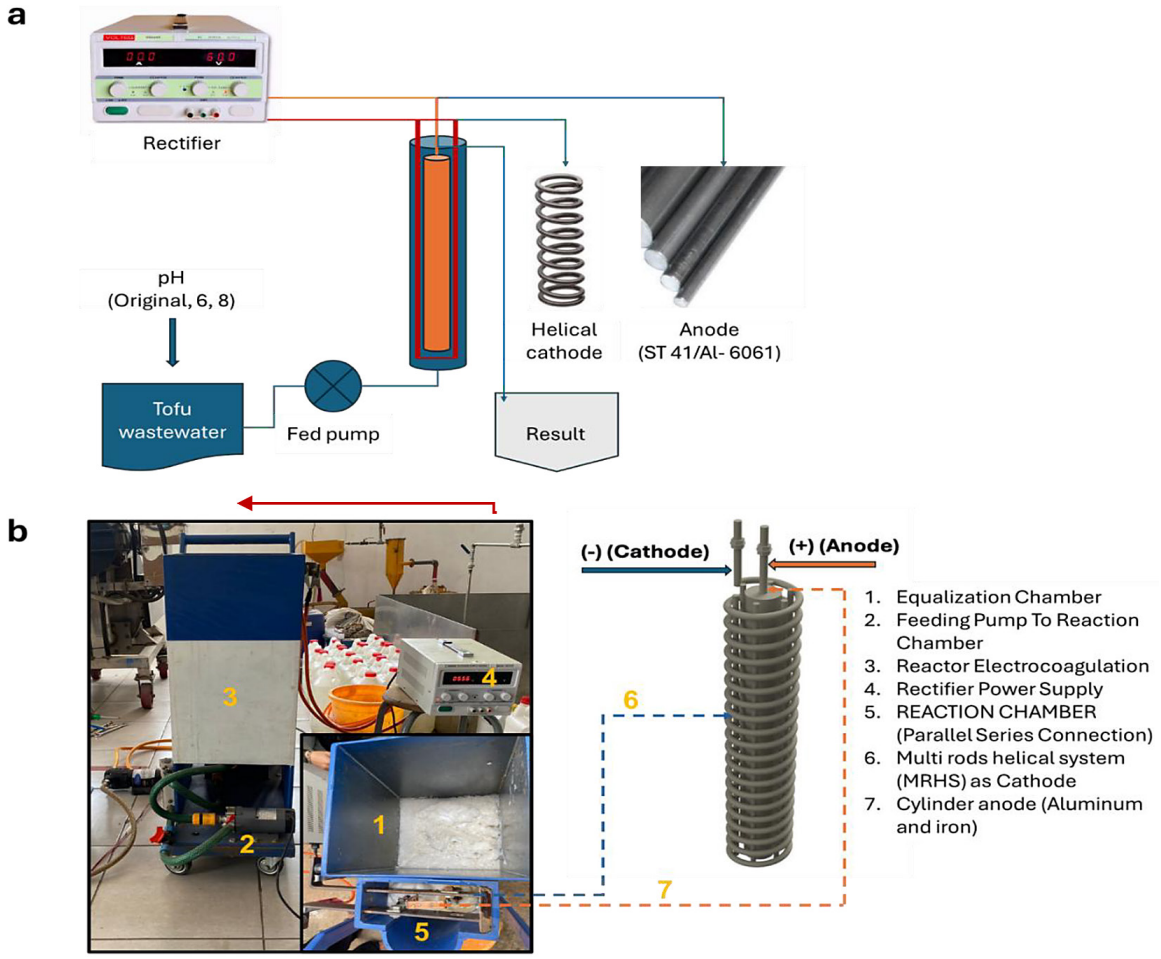

Figure 1. (a) Configuration of the electrocoagulation-based tubular system; and (b) a pilot scale visualization of the electrocoagulation reactor in this study using an MRHS in continuous flow

reflux method outlined in SNI 6989.2:2019 was employed, while TN was quantified using the Kjeldahl method in accordance with SNI 6989.49:2005. The pH measurements were conducted using a calibrated digital pH meter (SNI 06-6989.11-2004) to ensure high accuracy and reproducibility. Wastewater samples were collected at intervals ranging from 0 to 20 min during the EC process, and measured every 5 minutes during the 20-minute EC process. The collected data were statistically analyzed using appropriate models to identify significant trends and relationships, utilizing minitab statistical software 22.1.0.0. The process efficiency was assessed by analyzing COD and TN removal rates was computed using Equation 1, while energy consumption and electrode dissolution were also monitored to evaluate system sustainability. Performance of COD and TN reductions in EC processes were investigated. The removal efficiency of COD, and TN reductions in these processes was calculated as shown in Equation 1.

$$R\ (\%) = \frac{C_t - C_0}{Co} \cdot 100\% \quad (1)$$

where: R denotes the removal efficiency, C_0 is the initial concentration in the feed solution (mg/L), and C_t represents the concentration of COD and TSS, with Pt-Co indicating color concentration in the EC, MBBR and adsorption processes (mg/L).

The current density during continuous EC varies based on the applied current and the electrode surface area. The current density formula is enumerated using Equation 2.

$$j = \frac{I}{A} \quad (2)$$

where: j represents the current density (A/m^2), I is the applied current (A), and A is the electrode surface area (m^2).

The energy consumption is the major cost component in EC (Guvenc et al., 2019) and can be calculated using Equation 3.

$$C_{energy} = \frac{IU \cdot i \cdot t}{V} \quad (3)$$

where: C_{energy} is the energy consumption (kWh/m^3), U is the applied voltage (V), i is the applied current (A), t is the EC time (h), and V is the volume of the wastewater (m^3). Faraday's law (Equation 4) is applied to determine the quantity of metal ions dissolved during the EC process (Cherifi et al., 2016). Equation 4 provides the actual anode dissolution per unit volume of treated wastewater.

$$m_{theoritical} = \frac{I\,t\,M}{z\,F\,V} \quad (4)$$

The theoretical anode dissolution (g/L) is represented by $m_{theoretical}$ equations, where I is the applied current (A), t is the EC time (s), M is the anode's molar mass (g/mol), z is the number of consumed electrons, Fis Faraday's constant (96.485 C/mol), and V is the volume of treated wastewater (L).

RESULT AND DISSCUSION

Effect of current density

The effectiveness of the EC process is primarily influenced by three critical parameters: (1) current density (Chow and Pham, 2021). (2) electrode type (Svilović et al., 2022), and (3) initial pH of the wastewater (Bae et al., 2022). Applied current density plays a pivotal role as it governs the rate of coagulant generation and bubble formation, which in turn affect the destabilization and aggregation of colloidal particles (Liu et al., 2021). Efficiency performance of COD and TN based on Equation 1, The results, as shown in Figure. 2, indicate that with an applied current of 5.0 A, the removal efficiency of total nitrogen (TN) was 24.5%, which increased to 70% over a 5–20 minute contact time when using both aluminum and iron anodes. In contrast, when using a current of 10 A and 15 A over the same period, the TN removal efficiency was 80–92% when using an aluminum anode, whereas an iron anode produced a lower TN removal efficiency compared to the aluminum one. A current range of 5–20 amperes was used to achieve COD reduction. The results show that for a 20-min process, aluminum anodes achieved COD efficiency rates between 50 and 56.9%. In contrast, iron anodes yielded efficiency levels of 60–75%. The average TN and COD efficiencies for the aluminum electrode were 65.2% and 35.2%, respectively, with the initial pH as the reference point. In contrast, the iron electrode achieved an average TN and COD removal of 70.1% and 65.2%, respectively, over a 20-min period.

The impact of current on wastewater was also examined, considering the pH level. When the wastewater was subjected to pH values of 6 and 8, the TN efficiency of both electrodes decreased. The iron electrode achieved a high level of efficiency in terms of COD reduction, with efficiency improvements seen from 60% to 76.9% in both pH 6 and pH 8. In comparison, the COD efficiency of the aluminum anode decreased from 60.6% to 24% as the pH increased from 6 to 8. In studies using aluminium and iron anodes, it has been observed that higher current densities result in improved COD and nitrogen removal efficiencies (Figure. 2) COD removal efficiency using Al electrodes rose from approximately 65% to over 90% at an initial pH of originial, as depicted in Figure. 2b. This improvement is attributed to the higher availability of Al ions (Al^{3+}) and OH^- radicals that form flocs, enhancing pollutant removal through adsorption on each electrode and precipitation processes. However, excessively high current densities can lead to increased energy consumption and electrode passivation (Lu et al., 2021), highlighting the need for optimization.

For optimal TN and COD efficiency, the electrolysis duration of the electrocoagulation process should be optimized. Decreasing process time has implications for energy consumption; however, it is crucial to elevate the current density, as illustrated in Figure 2. High current density affects the production of aluminum and iron ions, as per Faraday's law. The generated Fe and Al ions often react with OH ions in water to form aluminum–iron hydroxide, which serves as an oxidative adsorbent that adsorbs TN and COD over a substantial surface area. The application of the multy rods helical system resulted in the production of more hydrogen bubbles on the cathode surface compared to the plate-based electrocoagulation concept. The results show that using iron as the anode yields superior efficiency compared with an aluminum electrode. In this electrode type, it is predicted that during the increase in current density, ionic monomers and polymeric species such as $FeOH^+$, $FeOH^{2+,}$ $Fe(OH)_2^+$, $Fe(H2O)_5OH^{2+}$, $Fe(H_2O)_4\,(OH)^{2+}$, $Fe(H_2O)_8\,(OH)_2^{4+}$ (Mohammadi

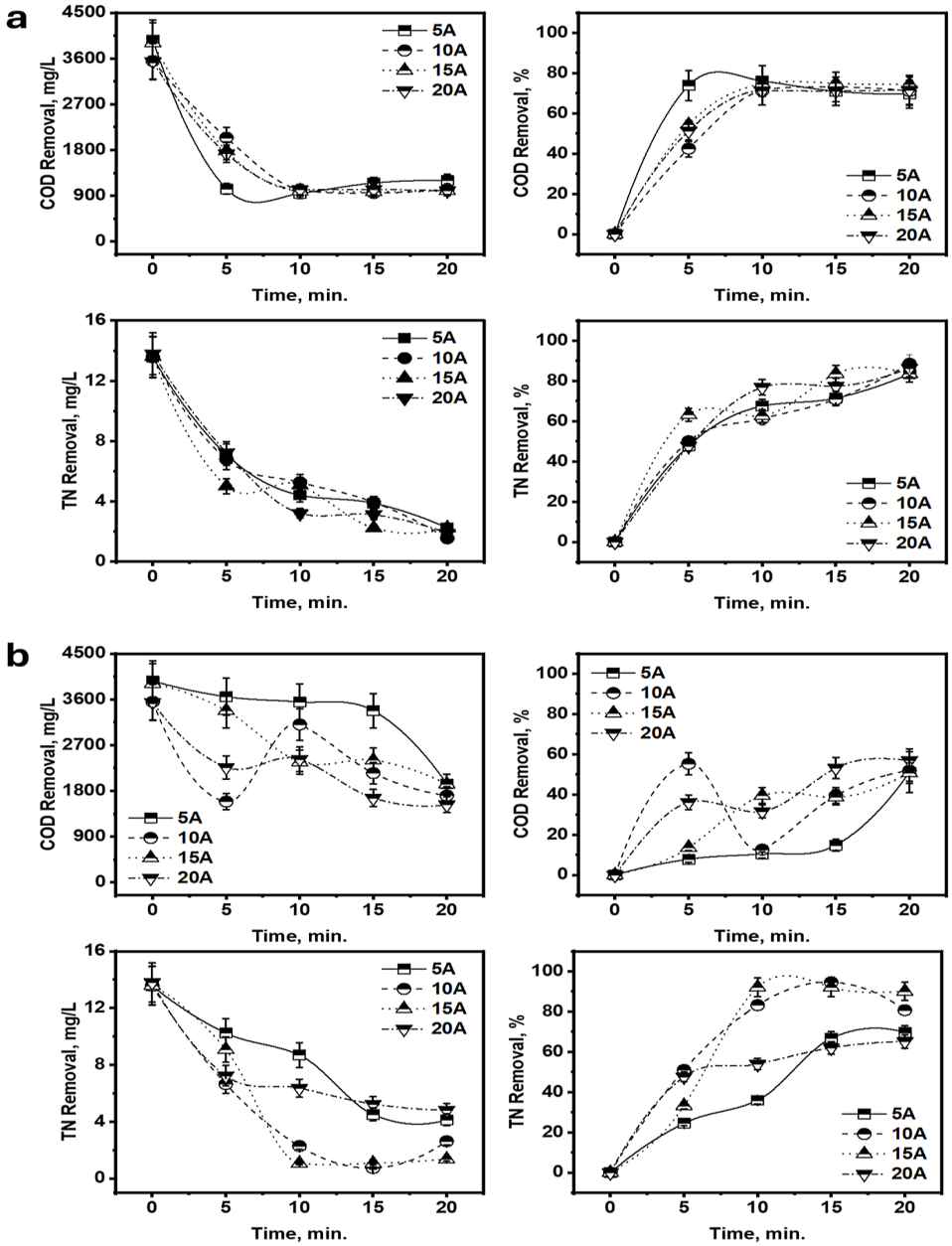

Figure 2. COD and TN removal using (a) Fe and (b) Al electrode with the current application strategy and pH differential

et al., 2019), these monomers are capable of adsorbing TN and COD. Adjusting the pH level will affect the total dissolved solids (TDS) content of wastewater, with sodium ions from sodium hydroxide (NaOH) contributing to increased alkalinity, thereby causing the TDS value to rise.

The condition will influence the application of power to a degree that is lower than the power applied at the original pH level. The initial TDS in the pH original process was 1047 mg/L; TDS increased by 2150 mg/L after adding a pH value of 6, and TDS was 2930 mg/L at pH value 8. The reduction in internal resistance generated during the electrolysis process is impacted by this circumstance. The application aluminium electrodes to the wastewater's initial pH level led to power consumption of 0.77, 2.69, 6.34, and 10.6 kWh/m^3 (Figure. 3a). At pH 6, power generation was 0.56, 1.83, 4.69, and 9.27 kWh/m^3. During electrolysis at pH 8, energy consumption was recorded as 0.51, 1.62, 3.26, and 7.92 kWh/m^3, with respective working currents of 5, 10, 15, and 20 A, over a 20-minute period. However, in terms of power consumption, Fe electrodes provide smaller energy requirements compared to aluminium electrodes when increasing pH values (Figure 3b).

Furthermore, the reduction in power consumption observed in the aluminium and Fe electrode applications is consistent with the increase in current, pH, and conductivity values from the original as shown in Figure 2 and 5.

Effect of pH

The pH of tofu wastewater increases during electrocoagulation, as illustrated in Figure 4. During 20-minute contact time, electrocoagulation

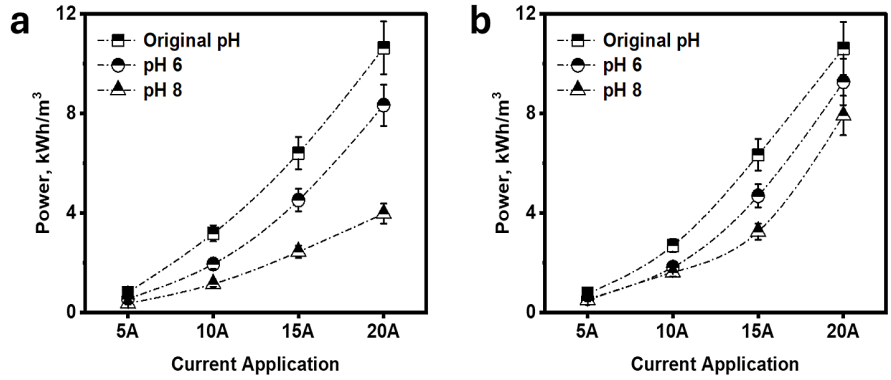

Figure 3. Power consumption during electrocoagulation (a) Al and (b) Fe electrode

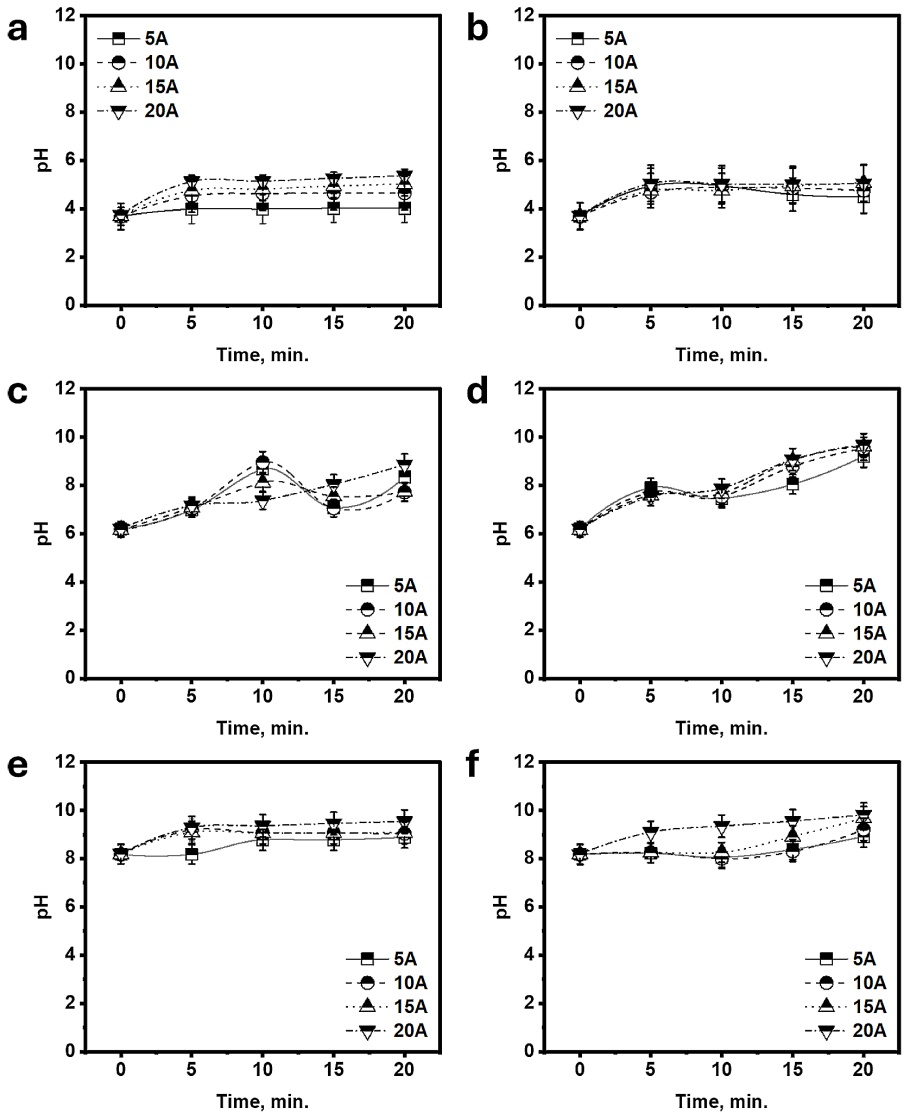

Figure 4. pH during electrocoagulation processes; (a, b, c) Al electrodes; (d, e, f) Fe electrodes

with an aluminium anode results in an increase in pH, rising from the original pH of 3.6 to 5.0. When used with a current of 20 A, an Iron anode generates a rising pH, ultimately reaching a value of 5.36, compared to its original pH. Compared to using an iron anode, the pH aluminium anode during electrocoagulation removes 10.45 mg/L of total nitrogen, whereas with an iron anode, 5.68 mg/L of total nitrogen is removed. Applying the current in a pH 6.0 environment of tofu wastewater resulted in pH increases to 7.53, 7.87, 9.07, and 9.67 when using applied currents of 5A, 10A, 15A, and 20A, respectively. Iron anodes also produce an increase in pH from 6.0 to 8.6, just like aluminum anodes do. In this initial pH environment, both iron and aluminum anodes remove 9.42 mg/L and 7.26 mg/L of total nitrogen, respectively, when 15A of current is applied. In this study, a pH of 8 produced a significant effect in increasing pH levels. The highest pH increase was observed at pH values of 9.82 and 9.54 after 20 minutes of contact time at an applied current of 20 A. The pH simultaneously produces 8.12 and 7.38 mg/L of total nitrogen. The pH during the electrolysis process is comparable to that observed in previous research (Syaichurrozi et al., 2021).

Based on (Figure 5), adjusting the pH level during electrolysis also affects COD reduction. COD removal can be increased by average 60–70% when conducted at a pH of 6, whereas under acidic conditions, efficiency typically reaches only 50%. Reducing efficiency can alternatively

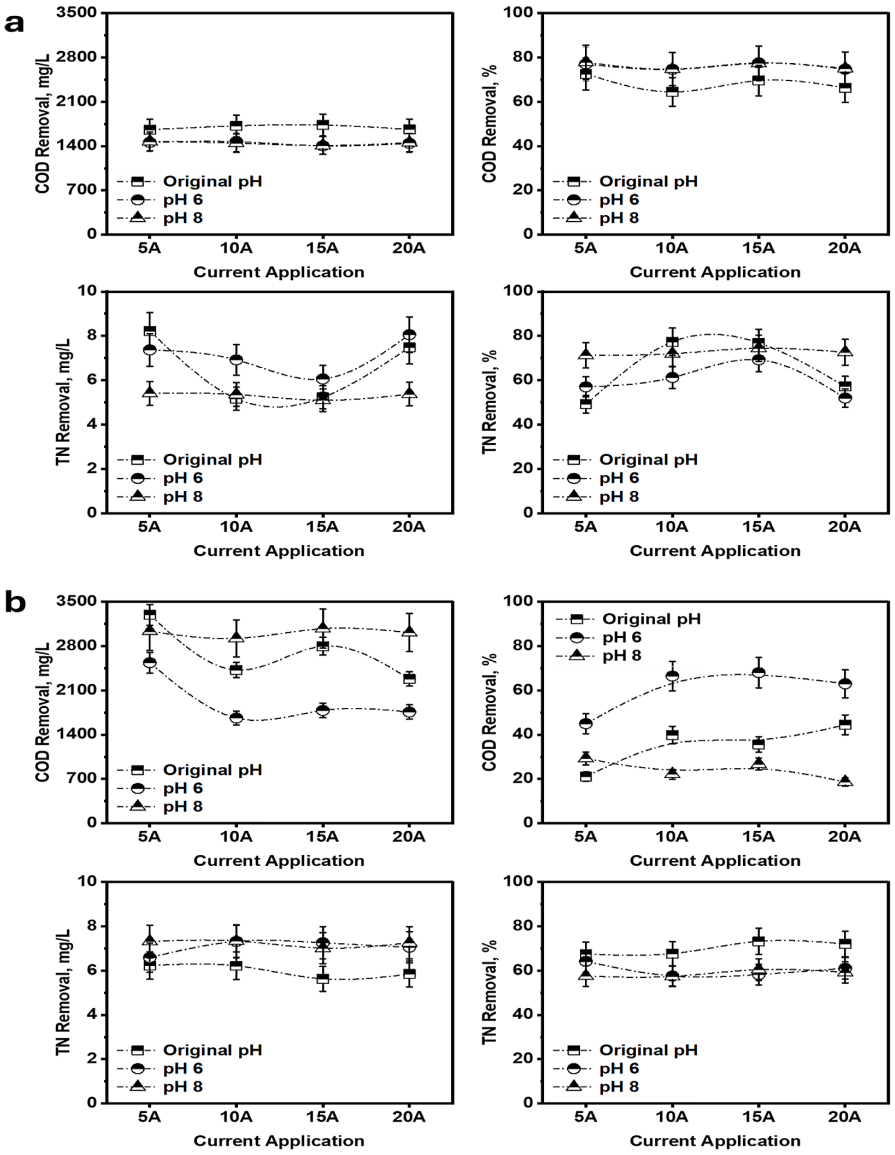

Figure 5. TN and COD removal during electrocoagulation processes; (a) Fe electrodes and (b) Al electrodes with the pH differential

be lowered by a strong electrical current of 10 A to 20 A for a duration of 20 minutes. The efficiency of pH 8 is lower than the original pH 6 when aluminium is used as the anode. Employing iron as the anode resulted in varying efficiencies, with the process yielding 50–70% efficiency at the original pH, 75–76.9% at a pH of 6, and 70–76.5% at pH 8. The findings of this study indicate that iron anodes offer benefits for COD efficiency across a range of pH and current applications. This study is consistent with the research conducted by (Phalakornkule et al., 2010), Who found in their study on electrocoagulation for textile and organic wastewater treatment that iron outperformed aluminium. Linares-Hernandez et al. discovered that iron was more successful in decreasing COD, whereas aluminum proved more effective in eliminating colour, as noted by (Phalakornkule et al., 2010); (Ilhan et al., 2008); (Linares-Hernández et al., 2010).

Effect of electrode

The choice of electrode material significantly influences the electrochemical reactions occurring during EC. Fe/Al electrodes are commonly used due to their cost-effectiveness and high efficiency in pollutant removal. The use of Al electrodes generally results in the formation of $Al(OH)_3$ precipitates, which have strong adsorption properties, thereby enhancing COD removal. On the other hand, Fe electrodes produce $Fe(OH)_2$ and $Fe(OH)_3$ flocs, which also exhibit high coagulative capacity. Figure. 5a shows that the removal efficiency of COD using Fe electrode reached up to 80% at a applied current of 15A and pH 6. The higher efficiency of Fe electrode at lower pH values can be attributed to the increased solubility of $Fe(OH)_3$, leading to more effective floc formation and pollutant adsorption. Moreover, Fe electrode is advantageous in scenarios where the treated water requires a lower residual metal concentration, as the solubility of Fe electrode decreases significantly at near-neutral pH values.

According to the study's findings (Ano et al., 2020) the process is greatly impacted by acidic pH values. (Aguilar-Ascon, 2020) results, however, show that pH has no effect on nitrogen reduction. The performance of the resulting process is illustrated by these results: for aluminium electrodes, the optimal process value is produced by the current application value of 10–15 A in original pH, and for Fe electrodes, it is produced by 5–20 A in 20 minutes (Figure. 5). However, the overall results for pH values of 5, 6 and 8 show identical outcomes in the decrease for TN of both aluminium and Fe electrodes with current applications of 5A, 10A, 15A and 20A.

Effect of electrolysis time

The application of the cathode model in the multirod helical system enables a high current density, thereby reducing the electrolysis time. The electrolysis process using either aluminum or iron electrodes achieved a substantial removal efficiency over a period of 20 minutes, as illustrated in Figure 2. The efficiency of the electrolysis process, lasting 5–20 minutes, improved significantly, particularly for TN reduction at the initial pH, where both the aluminium and iron electrodes were used. COD demonstrated an improvement in efficiency during the electrolysis process, notably at iron electrodes, where elevated pH levels and prolonged contact time resulted in significant efficiency gains, specifically reaching 76.9% COD at a pH range of 6–8. The aluminium electrodes process with a 20-minute contact time exhibited a decrease, as depicted in Figure. 2.

The feasible mechanism for COD and TN removal by electrocoagulation

In this study utilized a continuous-flow multirod helical electrocoagulation system with Fe/Al electrodes, offering several advantages compared to batch systems and other configurations. The mechanism for the removal of COD and TN in the electrocoagulation system revolves around the anodic dissolution of Fe and Al, the generation of hydroxyl ions at the cathode, and the subsequent precipitation and adsorption processes. At the anodes, the dissolution of Fe and Al generates metal ions as shown in Figure 6, which form coagulants through hydrolysis as shown in Equation 5 and 6. These ions react with hydroxyl ions (OH^-) in the solution to form insoluble hydroxides, which are effective coagulants (Equation 7 and 8). The hydroxides serve as coagulants, aggregating organic pollutants and nitrogenous compounds into flocs. At the cathode, hydrogen gas is produced through water reduction, and hydroxyl ions are generated (see in Equation 9). The hydrogen gas facilitates flotation by carrying lightweight flocs to the surface, while the hydroxyl ions contribute to maintaining optimal pH for the coagulation process.

$$Fe \rightarrow Fe^{3+} + 3e^{-} \quad (5)$$

$$Al \rightarrow Al^{3+} + 3e^{-} \quad (6)$$

$$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_3 \quad (7)$$

$$Al^{2+} + 2OH^{-} \rightarrow Al(OH)_3 \quad (8)$$

$$2H_2O + 3e^{-} \rightarrow H_{2(g)} + 2OH^{-} \quad (9)$$

The removal of COD involves the adsorption of organic pollutants onto flocs formed by metal hydroxides, as well as direct oxidation at the anode. Hydroxyl radicals (·OH) generated at the anode further oxidize organic compounds, as represented in Equation 10, where R denotes organic pollutants. Additionally, the flotation of lighter pollutants via hydrogen gas bubbles enhances the removal process. The removal of TN occurs through multiple mechanisms. First, NH_3 is removed by adsorption onto hydroxide flocs or converted into N_2 through cathodic reduction, as described in Equations 11 and 12. Organic and inorganic nitrogen species are also adsorbed onto the hydroxides formed during the process, effectively removing them from the wastewater. The combination of gas bubbles and flocculation plays a critical role in pollutant separation. Hydrogen gas aids in flotation, bringing lighter pollutants to the surface, while heavier particles settle as sludge. This dual mechanism significantly enhances the efficiency of both COD and TN removal. The integration of these reactions leads to substantial reductions in COD and TN levels, as evidenced in the experimental setup, which achieved average 72% and maximum in 76.9% COD removal (~2.960 mg/L) and 70% TN removal (~7.0 mg/L) under optimal conditions.

$$M(\cdot OH) + R \rightarrow M + CO_2 + H_2 \quad (10)$$

$$NH_4^{+} + 2OH^{-} \rightarrow NH_3 + H_2O \quad (11)$$

$$2NH_4^{+} + 6e^{-} \rightarrow N_2 + {}_6H_2O \quad (12)$$

Several studies highlight high COD removal efficiencies exceeding 80% under optimum experimental configurations. For instance, Shah et al. (2024) reported a 98.72% COD removal from vegetable oil refinery wastewater using Al-Fe electrodes under neutral pH conditions and a current density of 20 mA/cm², with an energy consumption of 6.97 kWh/m³. Similarly, Ogedey and Oguz (2024) achieved 87% COD removal from sanitary landfill leachate with Al electrodes at pH 5 and a current density of 25 mA/cm², albeit with a significantly higher energy consumption of 218.56 kWh/m³. These results demonstrate the crucial role of current density and pH in optimizing both removal efficiency and energy consumption. This discrepancy underscores the sensitivity of EC performance to wastewater composition and operational parameters, suggesting that different wastewater characteristics may require tailored electrode configurations and operating conditions for optimal results. Nitrogen removal efficiency also varied widely across different studies, with Mohammadi et al. (2019) reporting up to 81.59% nitrogen removal from anaerobic digester effluent at pH 10.1 using Fe-Al electrodes, while Bagastyo et al. (2021) observed only 29.8% total nitrogen removal from stabilized landfill leachate under acidic pH and 29.17 mA/cm² current density. The differences in nitrogen removal outcomes reflect the critical influence of pH on the formation of flocs and the effectiveness of electrochemical oxidation processes in nitrogen removal. This finding highlights the potential for significant energy savings when operating under optimized conditions. At higher current densities, such as those applied in studies by Choudhury et al. (2022), energy consumption rose sharply to 570 kWh/m³ for 99% COD removal from anaerobically digested leachate, underscoring the trade-off between removal efficiency and operational cost. Based explanation above, this study provide optimum removal for removing TN and COD of tofu wastewater.

The MRHS-based cathode function significantly influences the electrocoagulation process, as previously explained. The use of Equation 2 yields a higher current density compared to a conventional electrocoagulation process, as described by Plate, with current density values of 63.69 A/m², 127.39 A/m², 191.08 A/m², and 254.78 A/m² achieved when applied currents of 5 A, 10 A, 15 A, and 20 A are used, respectively. The application of a current density of 127.39 A/m² at 10 A and 191.08 A/m² at 15 A, as evident from Figures 2 and 5, respectively, affects the optimal COD and TN reduction. Comparing the effectiveness of eliminating the COD parameter with that of the MRHS approach yields benefits over the electrocoagulation method employing a standard plate electrode. Previous research has documented the effectiveness of an electrocoagulation plate reactor for treating tofu wastewater, yielding a 51.9% removal rate after a 60-min contact time when combined with an additional

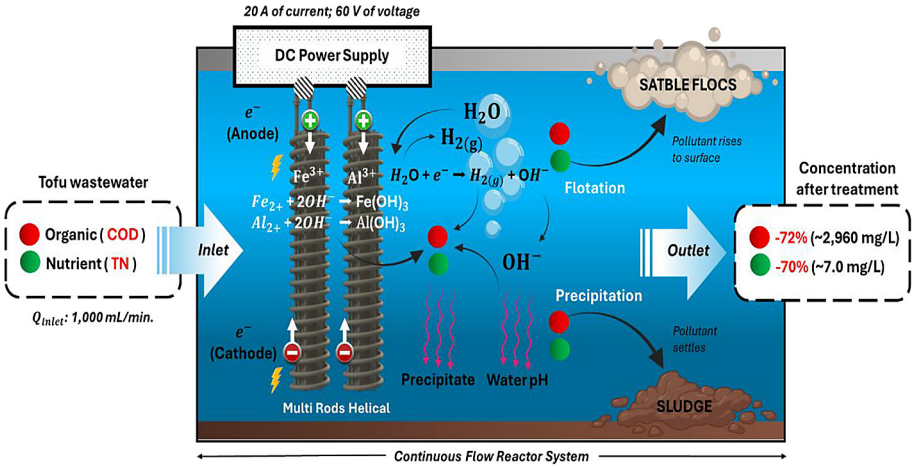

Figure 6. COD and TN removal in EC based continuous flow reactor system using a MRHS cathode and Fe/Al anode

ozone treatment process (Oktiawan et al., 2022). The MRHS system yields improved ion removal efficiency for in situ coagulation, as per Equation 4, compared to conventional electrocoagulation and conventional coagulation processes. According to Figure 7, the MRHS system provides an optimal aluminum-ion decay range of 55.96–83.94–83.94 to 83.94 mg/L, which effectively minimizes TN levels. Conversely, iron yields a decay range of 174.09–261.14 mg/L, resulting in the optimum COD and TN removal rates, as shown in Figures 2 and 5.

According to Figure 7, the MRHS system offers a more optimal outcome in terms of coagulant ion usage during electrolysis than the conventional process, as documented by Oktariany and Kartohardjono (2018), The coagulation method implemented in tofu wastewater treatment was found to be effective in reducing COD content by 28% at a dosage of 400 mg/L poly aluminum chloride (PAC). Compared to traditional electrocoagulation and conventional coagulation processes, the MRHS system has advantages in terms of reduced process time, higher current density, and requirement for a smaller reactor scale. As shown in Table 2, These findings suggest that EC with MRHS provide efficient of power consumption, faster removal of COD and TN, while Fe electrodes are highly effective for TN and COD removal, the integration of Fe electrodes can enhance nitrogen removal efficiency and improve floc stability, especially in wastewater containing high concentrations of

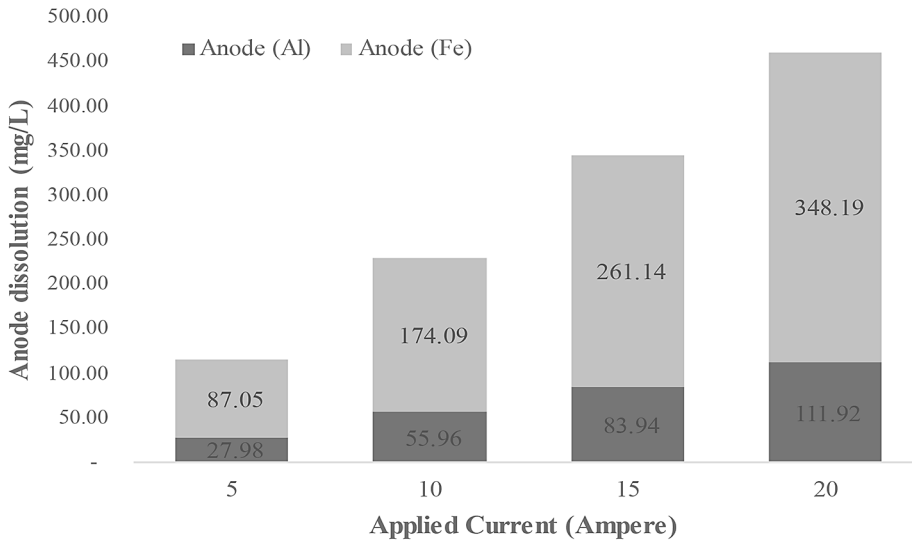

Figure 7. COD and TN removal in EC based continuous flow reactor system using a MRHS cathode and Fe/Al anode

Table 2. Available studies on application of the EC process for COD and TN removal from wastewater

Wastewater	Initial concentration	Removal efficiency	Optimum experimental configuration						Ref.
			Electrodes	Current density	pH	T	Optimum time	Energy consumption	
Vegetable oil refinery wastewater	600 mg/L COD	98.72% COD	Al (anode) Fe (cathode)	20 mA/cm²	7	25 ºC	120 min	6.97 kWh/m³	(Shah et al., 2024)
Sanitary landfill leachate	4.175 mg/L COD 2.438 mg/L NH_3-N	87% COD 33% NH_3-N	Al (anode) SS (cathode)	25 mA/cm²	5	20 °C	40 min	218.56 kWh/m³	(Ogedey & Oguz, 2024)
Anaerobic digester effluent	900 mg/L TN	81.59% TN	Fe (anode) Al (cathode)	9 mA/cm²	10.1	20 °C	100 min	19.01 kWh/m³	(Mohammadi et al., 2019)
Domestic wastewater	300 mg/L COD 40 mg/L TN	68% COD 10% TN	Al (anode) Al (cathode)	3 mA/cm²	7.5	20 °C	30 min	-	(Devlin et al., 2018)
Domestic wastewater	-	90% COD	Fe (anode) Fe (cathode)	4.5 mA/cm²	9	25 °C	60 min	-	(Bote, 2021)
Anaerobically digested leachate	10.000 mg/L COD 1.000 mg/L TN	98% COD 100% TN	BDD (anode) SS (cathode)	3.2 mA/cm²	4	22 °C	360 min	570 kWh/m³	(Choudhury et al.. 2022)
Stabilized landfill leachate	1.552 mg/L COD 1.280 mg/L TN	81% COD 59% TN	Al (anode) SS (cathode)	29 mA/cm²	4	22 °C	360 min	17.31 kWh/m³	(Bagastyo et al.. 2021)
Egg-wash wastewater	11.000 mg/L COD 133 mg/L TN	97.46% COD 97% TN	Al (anode) SS (cathode)	25 mA/cm²	7	22 °C	60 min	90 kWh/m³	(Bhatt et al.. 2024)
Tofu wastewater	3.175 mg/L COD 13.56 mg/L TN	62.5% COD 76.4% TN	Al Anode MRHS Cathode	5A-20A (63.69 A/m²-254.7 A/m²	3.6.8	28 °C	20 min	7.92–10.6 kWh/m³	This Study
Tofu wastewater	3.175 mg/L COD 13.56 mg/L TN	76.9% COD 85.5% TN	Fe Anode MRHS Cathode	5A-20A (63.69 A/m²-254.7 A/m²	3.6.8	28 °C	20 min	7.92–10.6 kWh/m³	This Study

Note: MRHS – multi rods helical system – cathode, SS – stainless steel, Al – aluminium, Fe – iron.

Table 3. Result of statistical test

Parameter	N removal			%N removal			COD removal			%COD removal		
	Mean	SD	Kruskal Wallis Test*	Mean	SD	Kruskal Wallis Test*	Mean	SD	Kruskal Wallis Test	Mean	SD	Kruskal Wallis Test*
Current density	6.536	3.791	0.523	51.56	28.59	0.557	2039	1142	0.786	45.41	30.46	0.853
pH			0.179			0.182			0.060			0.076
Electrode			0.208			0.263			0.000			0.000
Time			0.000			0.000			0.000			0.000

Note: * There was a significant differences in median value if p-value < 0.05.

organic matter and nitrogenous compounds. Future investigations could explore advanced electrode designs, such as tubular or helical systems, and alternative electrode materials that offer better conductivity and longevity, with the goal of further reducing energy requirements while maintaining high removal performance.

Statistics analysis

The data from running process were analyzed using hypothesis statistical test with minitab statistical software 22.1.0.0 to determine whether there was a significant difference in each parameter variations. The parameters analyzed were current density, pH, electrode, and time as shown in Table 3. Before conducting the hypothesis test, a residual normality test (Kolmogorov-Smirnov) was perfomed first to know whether the data followed a normal distribution or not (De-Los-Ríos-Mérida et al., 2021). Residual normality test results showen the TN removal (mg/L), TN removal efficiency (%), COD removal (mg/L), and COD removal efficiency (%) data did not meet normality distribution (Kolmogorov-Smirnov, p-value < 0.05). Since all data did not satisfy a normality distribution, the hypothesis test used was nonparametric test, specifically the Kruskal-Wallis test, followed by a post hoc test, namely the Mann-Whitney test (Salcedo et al., 2024). The results of the Kruskal-Wallis hypothesis test showed that there were significant differences (p-value < 0.05) in the median values of TN removal (mg/L) and TN removal efficiency (%) for

the parameter time (groups 0, 5, 10, 15, and 20 minutes), as well as the average values of COD removal (mg/L) and COD removal efficiency (%) for the parameters electrode (Al and Fe) and time. However, for other parameters, there were no significant differences (p-value > 0.05) in the median values of TN removal, TN removal efficiency, COD removal, and COD removal efficiency. A post hoc Mann-Whitney test was subsequently performed to determine which time group showed significant differences in the median values. The post hoc test results indicated that significant differences (p-value < 0.05) were found in the median values of TN removal and TN removal efficiency between the 0-minute and 5-minute time groups. Meanwhile, for COD removal and COD removal efficiency, significant differences (p-value < 0.05) were found only for the 0-minute time group. Based on the statistical test results, it could be concluded that in this study, COD removal in tofu wastewater using the MRHS EC reactor was influenced by the type of electrode used, while TN removal was influenced by the time parameter at the 0-minute and 5-minute marks.

Economic analysis

The cost of applying the treatment resulted in a cost of 18,177.30 Rp/m^3 or \$1.1 Rp/m^3, yielding reductions of 49.2–76.9% in COD and 52.1–85.5% in TN content. The operational economics can be observed by considering an initial dosage of 261.4 mg/L iron ions used as an in situ coagulant, along with an application energy input of 10.6 kWh/m^3. The cost incurred from the application is 18.177,30 Rp/m^3 or \$/1.1 per m^3 of wastewater to reduce COD and TN content by 49.2–76.9% COD 52.1–85.5% TN. A comparison with the results from a previous study that used 400 mg/L of PAC in the same volume showed a reduction in COD of 28%, resulting in operational costs of 9.000 Rp/m^3 or \$ 0.55 per m^3 of wastewater. The MRHS system's electrocoagulation process is considered the most cost-effective option compared with the costs associated with PAC consumption, but it yields low efficiency despite this. The expenses are separate from the cost of pH adjustment and sludge consumption. Comparing the process to non-MRHS-based electrocoagulation methods is not feasible due to the lack of a comprehensive study on the application of non-MRHS-based electrocoagulation in treating tofu wastewater. Large-scale applications of MRHS systems for tofu wastewater treatment can be achieved by taking into account the fundamental operational parameters of the electrocoagulation process, specifically the passivation factor at the electrode and current density which is a key weakness of this process.

CONCLUSIONS

It was discovered that the electrocoagulation process, with changes in pH, electrode, and working current, had an average removal efficiency of 39.1–78.9% for TN, 11.7–76.9% of COD parameters in wastewater from the tofu industry. The original pH value produced the best results compared to pH 6 and pH 8 for TN. Moreover, the aluminium electrodes produced the best results for nitrogen removal under acidic conditions (original pH), with a removal efficiency of 80–94.6% or an average of 78.9% at a current application of 10–15 A. In contrast, when a current of 10–15 A was applied, the efficiency of the Fe electrodes dropped to 80–88.6% of TN removal. Meanwhile COD removal achieve 49.2–76.9% using Fe electrode than aluminium. However, as the pH level increased, both electrodes showed a decrease in the efficiency of removing nitrogen. Nevertheless, as the pH level increased, the nitrogen removal efficiency of both electrodes decreased. The reduced internal resistance and increased water conductivity decreased the available working energy, which in turn affected this phenomenon. When the pH value of the wastewater input was set, the pH value rose noticeably. UMKM-based tofu industry wastewater can generally be treated with a multi-rods helical cathode-based electrocoagulation process, which allows for advanced processing in terms of limited area load and processing load value.

Acknowledgments

The authors are grateful to LPPM Institut Teknologi PLN for the financial support granted to cover the publication fees of this research article.

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