Electrocoagulation as Alternative Active Treatment for Hexavalent Chromium Removal from Nickel Mine Water in Indonesia

Umar Kasmon[1], Muhammad Sonny Abfertiawan[2], Faiz Hasan[2],
Nur Latifa Ristiaramdani[3*], Lionie Butar Butar[1], Irfa Darojat[1]

[1]Environmental Strategic Department, PT Vale Indonesia Tbk., Indonesia

[2]Water and Wastewater Engineering Research Group, Faculty of Civil and Environmental Engineering, Bandung Institute of Technology, Bandung, Indonesia

[3]Research and Consulting Division, PT Ganeca Environmental Services, Bandung, Indonesia

**corresponding author: latifa@ganeca.co.id*

Abstract

Indonesia, the world's largest nickel producer, faces challenges in managing mine water due to high rainfall and hexavalent chromium (Cr^{6+}) contamination. This study evaluates electrocoagulation as an alternative treatment method. A 100 L continuous reactor with iron electrodes operated for 72 hours at 5 A and 7 L/min. Results showed stable pH (6.8–7.1), with Cr^{6+} removal reaching 97% after one HRT and 99% after 72 h, reducing concentrations from 0.89 mg/L to below 0.001 mg/L. Findings suggest electrocoagulation is a promising and efficient approach for treating nickel mine water and supports further scale-up development.

Keywords: Electrocoagulation, chromium hexavalent, mine water, nickel mine

Introduction

Approximately 40% of global nickel production currently originates from laterite ores, and Indonesia is recognized as one of the countries with the largest nickel laterite resources in the world. At present, Indonesian nickel laterite ore is processed industrially using both pyrometallurgical and hydrometallurgical approaches, with a national development target of achieving 2.9 million tons of annual production by 2030 (ChuanYu *et al.* 2025). Nickel exploration in Indonesia began during the period of 1967–1976 (van Leeuwen 1994), leading to the discovery of extensive laterite nickel reserves in the eastern regions of the country, particularly in Maluku and Sulawesi

Indonesia's nickel resources are derived exclusively from surficial laterite-type ore deposits. These deposits are formed through intense chemical weathering of ultramafic massifs under tropical climatic conditions. Laterite-type deposits typically occur as tabular ore bodies characterized by extensive lateral distribution but relatively limited vertical thickness, generally less than approximately 30–40 m (Choi *et al.* 2021). Owing to their near-surface occurrence, laterite deposits in Indonesia are mined exclusively using open-pit methods (Heijlen and Duhayon 2024). Open-pit mining operations are widely acknowledged to pose potential environmental impacts on surrounding ecosystems (Abfertiawan *et al.* 2020). One of the most critical environmental concerns associated with nickel mining is mine runoff water.

Ultramafic rocks represent one of the most important geogenic sources of chromium (Cr), particularly its hexavalent form (Cr(VI)), which is a major environmental concern. Intensive weathering of ultramafic rocks in tropical regions generates substantial reservoirs of Cr(VI) (Delina *et al.* 2020). If mine water is not properly managed, dissolved metals may adversely affect biotic systems due to their non-biodegradable nature, making effective metal removal essential to prevent environmental contamination.

This issue is further exacerbated by Indonesia's high rainfall intensity. As a tropical country located between the Pacific and Indian Oceans and between the Asian and Australian continents, Indonesia experiences substantial precipitation. Extreme rainfall events in Indonesia are strongly influenced by global climate variability phenomena such as the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Madden–Julian Oscillation (MJO) (Bakri *et al.* 2021; Doyle *et al.* 2023). These climatic phenomena considerably increase the volume of mine runoff water that must be effectively managed.

The conventional treatment for Cr(VI) in mine water involves chemical reduction followed by precipitation as $Cr(OH)_3$, commonly using ferrous sulfate ($FeSO_4$) as the reducing agent (Xu *et al.* 2024). However, the use of chemical reagents presents several limitations, including inefficiency at low contaminant concentrations, generation of toxic sludge, and the requirement for pH adjustment (Itankar and Patil 2022). Alternatively, electrocoagulation offers a rapid and efficient active treatment technology capable of removing a wide range of pollutants. Despite this, electrocoagulation is frequently associated with high capital costs and energy-intensive operation (Phu *et al.* 2025; Genawi *et al.* 2025). Nevertheless, energy consumption can potentially be mitigated through integration with renewable energy systems, such as solar panels, which are particularly suitable for remote mining locations. Several studies have demonstrated that electrocoagulation can achieve high hexavalent chromium removal efficiencies, reaching up to 99% (Rusman 2024; Harahap *et al.* 2024). However, field-scale applications of electrocoagulation for Cr(VI) removal in mine water remain limited. Therefore, this study focuses on evaluating the durability and stability of Cr(VI) removal efficiency during short-term continuous operation as a step toward practical field-scale implementation of the technology.

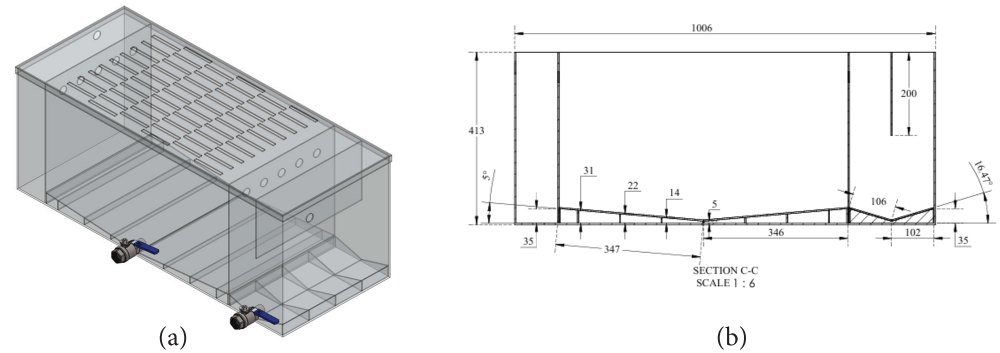
Methods

The experiment was conducted using raw nickel mine water collected from an operating nickel mining site in South Sulawesi, Indonesia. Mine water was taken from the inlet of the sedimentation pond using a pump and stored in an Intermediate Bulk Container (IBC). From the IBC, a submersible pump was used to continuously feed the water into the electrocoagulation (EC) reactor. The electrocoagulation experiment scheme and water intake conditions for the experiment can be seen in Figure 1.

The experiment was carried out for 72 hours under continuous operation. Effluent samples were collected from the reactor outlet at nine different time points to analyze pH, total suspended solids (TSS), and hexavalent chromium (Cr^{6+}) concentrations. Sampling

(a) (b) (c)

Figure 1 (a) Electrocoagulation scheme, (b) sediment pond as experimental intake, and (c) visual appearance of mine water samples for experiment.



(a) (b)

Figure 2 (a) 3D reactor design and (b) reactor dimensions (in mm scale).

was performed at 15 and 25 minutes, followed by 5, 24, 29, 48, 53, and 72 hours of operation, hereafter referred to as t0, t1, t2, t3, t4, t5, t6, t7, and t8, respectively. The reactor configuration, hydraulic retention time (HRT), and applied current were adopted and scaled up from previously reported optimum conditions (Rusman *et al.* 2025). The electrocoagulation zone of the reactor had dimensions of 100 × 41.3 × 40.6 cm. The reactor was designed to ensure uniform flow distribution and high electrocoagulation efficiency. A total of 30 iron electrodes (40 cm × 10 cm × 0.2 cm) were installed with an inter-electrode spacing of 3 cm. The electrode arrangement consisted of 15 anodes and 15 cathodes configured in a monopolar connection. The electrodes were installed in a baffle configuration and connected to a DC power supply (MDB 0–60 V, 0–20 A). The reactor had a working volume of 100 L and was operated at a constant current of 5 A with an HRT of 15 minutes. The design of the electrocoagulation reactor used in this experiment can be seen in Figure 2.

No operational variations were applied, as the primary objective of this study was to evaluate the durability and consistency of electrocoagulation performance, particularly in achieving stable and sustained Cr^{6+} removal efficiency over extended operation.

Results and Discussion

Electrocoagulation operates through oxidation–reduction reactions, where oxidation occurs at the anode. At the iron anode, solid iron $Fe_{(s)}$ is oxidized to Fe^{2+} or Fe^{3+}, leading to the formation of iron hydroxides such as $Fe(OH)_2$ and $Fe(OH)_3$. The principal electrode reactions can be expressed as follows (Tabash *et al.* 2024).

Anode: $Fe \rightarrow Fe^{(2+)} + 2e^-$ (1)

Cathode: $2H_2O + 2e^- \rightarrow H_{2(g)} + 2OH^-$ (2)

The Fe^{2+} ions produced subsequently react with water to form ferrous hydroxide, $Fe(OH)_2$, which acts as a flocculant that promotes the aggregation.

$$Fe^{2+} + 2H_2O \rightarrow Fe(OH)_2 + 2H^+ \quad (3)$$

Continuous generation of Fe^{2+} enhances floc formation, as Fe^{2+} is gradually oxidized to Fe^{3+}, forming ferric hydroxide, $Fe(OH)_3$, which is recognized as a more effective coagulant.

$$4[Fe^{2+} + 2OH^-] + O_2 + 2H_2O \rightarrow Fe(OH)_3 \quad (4)$$

In addition to forming $Fe(OH)_2$ and $Fe(OH)_3$ precipitates, hexavalent chromium (Cr(VI)) removal using iron electrodes primarily occurs through chemical reduction by anodically generated Fe^{2+}. The Fe^{2+} species react with Cr(VI), reducing it to trivalent chromium (Cr(III)), which subsequently precipitates as $Cr(OH)_3$. The overall Cr(VI) removal reactions can be represented as follows (Heidmann and Calmano 2008; El-Taweel *et al.* 2015).

For 6,5 < pH < 7,5: $CrO_4^{2-} + 3Fe^{2+} + 4H_2O \rightarrow Cr^{3+} + 3Fe^{3+} + 8OH^-$ (5)

For pH > 7: $CrO_4^{2-} + 3Fe(OH)_2 + 4H_2O \rightarrow Cr(OH)_{3(s)} + 3Fe(OH)_{3(s)} + 2OH^-$ (6)

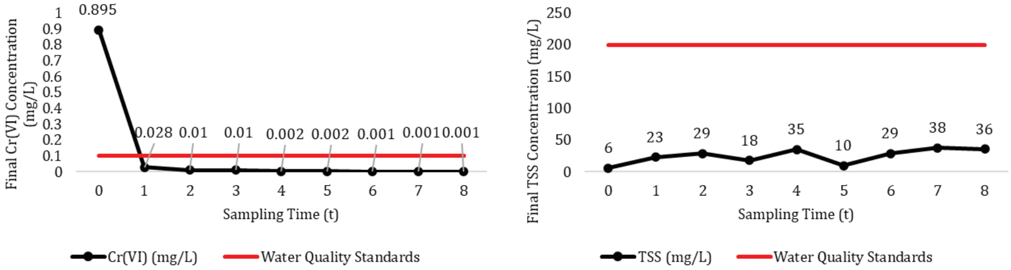
The reduction of hexavalent chromium is therefore considered the primary mechanism responsible for Cr(VI) removal in nickel mine water. Experimental results indicated that substantial Cr(VI) reduction occurred within the first 15 minutes of operation, corresponding to hydraulic retention time (HRT). At this point, the Cr(VI) concentration decreased by approximately 97%, reaching 0.028 mg/L.

This removal performance remained stable throughout the 72-hour continuous operation, with Cr(VI) concentrations consistently maintained at low levels. The sustained efficiency demonstrates that the electrocoagulation system operated reliably without performance deterioration over time. These findings indicate that the process not only achieves rapid initial reduction but also provides stable and consistent treatment performance, highlighting its potential applicability for continuous nickel mine water treatment. This rapid decline and subsequent stabilization of Cr(VI) concentration are illustrated in Figure 3a.

The formation of $Cr(OH)_3$ precipitates as a result of Cr(VI) reduction, together with $Fe(OH)_2$ and $Fe(OH)_3$ generated from the iron-based electrocoagulation process, was confirmed by the observed increase in total suspended solids (TSS) over time. The development of these flocs led to a rise and fluctuation in TSS concentrations at the reactor outlet, increasing from an initial value of 6 mg/L to a maximum of 38 mg/L.

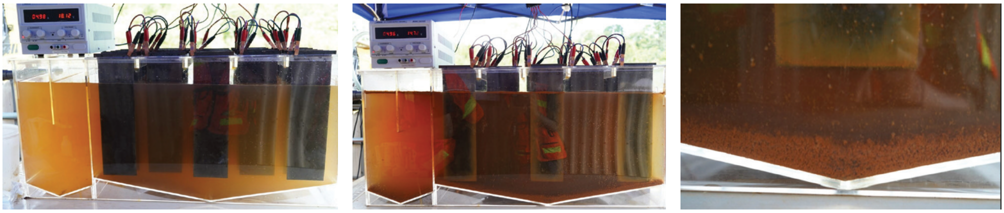
Despite this increase, the TSS concentration remained well below the regulatory limit of 200 mg/L established by the Indonesian environmental regulation (Minister of Environment Regulation No. 09 of 2006 concerning wastewater quality standards for nickel ore mining activities). The fluctuation in TSS during the experiment is presented in Figure 3b.

The presence of visible precipitates further indicates that chromium removal was occurring. As illustrated in Figure 4, turbidity within the electrocoagulation reactor increased progressively over time, visually confirming the formation of hydroxide flocs and precipitation processes.



(a) (b)

Figure 3 *(a) Final chromium hexavalent concentration (mg/L) and (b) Final Total Suspended Solid (TSS) concentration (mg/L).*



(a) (b) (c)

Figure 4 *Visual documentation of the electrocoagulation reactor: (a) initial condition at T0 (0 h), (b) reactor condition at T3 (24 h), and (c) precipitate accumulated at the reactor bottom at T3 (24 h).*

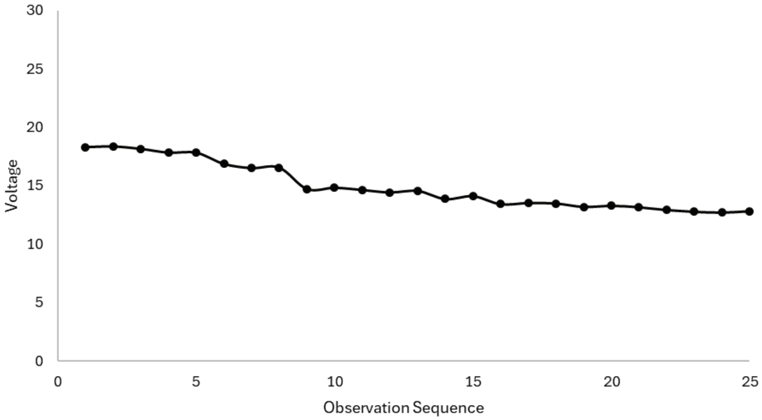


Figure 5 *Voltage profile during 72-h continuous electrocoagulation operation.*

During the 72 h electrocoagulation operation, the electrical voltage remained relatively stable, as shown in Figure 5, and did not show an increasing trend that would indicate scaling or electrode passivation. The average voltage was 14.91 V, with an average fluctuation between observation points of 7.61%. This relatively stable voltage profile suggests that the overall system resistance, including the solution, electrode, and electrode–electrolyte interface resistances, remained relatively constant throughout the operation. Therefore, the electrocoagulation process was maintained under steady operating conditions, supporting consistent energy demand.

Conclusions

This study demonstrates that electrocoagulation using iron electrodes is an effective method for treating nickel mine water containing hexavalent chromium. The process achieved rapid Cr(VI) reduction within one hydraulic retention time (15 minutes), with removal efficiency reaching approximately 97% and reducing concentrations to 0.028 mg/L. Further operation up to 72 hours increased the Cr^{6+} removal efficiency to 99%, lowering the concentration to 0.001 mg/L. Importantly, the treatment performance remained stable throughout 72 hours of continuous operation, indicating reliable and consistent system behavior.

The formation of $Fe(OH)_2$ and $Fe(OH)_3$ flocs played a dual role as coagulants and reducing agents, facilitating both chromium reduction and solid-phase precipitation. Although TSS increased due to hydroxide formation, concentrations remained well below the Indonesian regulatory limit (200 mg/L), confirming compliance with environmental standards.

Overall, the findings highlight electrocoagulation as a robust, fast, and dependable active treatment alternative for managing chromium-contaminated nickel mine water. The stable short-term continuous operation performance observed in this study supports its potential for scale-up and practical field implementation in Indonesia's nickel mining industry

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