# Electrocoagulation for Acid Mine Drainage Treatment : Optimization of Mn Removal in Air Laya Coal Mine, Indonesia

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**Abstract** : Acid mine drainage (AMD) poses a significant environmental challenge in coal mining due to its low pH and high dissolved metal concentrations, particularly manganese (Mn), which is difficult to remove using conventional methods. This study evaluates electrocoagulation (EC) performance in reducing Mn concentrations in AMD using iron (Fe), aluminum (Al), and combined Fe–Al electrodes. Laboratory experiments were conducted using AMD samples from the Air Laya coal mining area, Indonesia, with initial Mn concentrations of 5.89–6.68 mg/L, exceeding the regulatory limit of 4 mg/L. Results show that EC effectively reduces Mn to 1.07 mg/L (Fe), 1.40 mg/L (Al), and 0.91 mg/L (Fe–Al), achieving removal efficiencies of 82.78%, 77.94%, and 85.62%, respectively. The Fe–Al combination achieved the highest efficiency and consistently met water quality standards. Operational costs for Fe, Al, and Fe–Al electrodes were Rp312,240/m³, Rp316,550/m³, and Rp313,100/m³, respectively, with Fe–Al showing the most favourable cost-to-efficiency ratio. These findings indicate that electrocoagulation is an effective and economically viable approach for Mn removal in AMD treatment, with the Fe–Al combination offering an optimal balance between technical performance and operational cost for practical implementation in coal mining wastewater management.

**Keywords:** Acid Mine Drainage, Electrocoagulation, Manganese Removal, Fe–Al Electrodes, Wastewater Treatment

***Abstrak :*** *Air asam tambang (AAT) merupakan tantangan lingkungan yang signifikan dalam pertambangan batubara karena pH rendah dan konsentrasi logam terlarut yang tinggi, khususnya mangan (Mn), yang sulit dihilangkan menggunakan metode konvensional. Penelitian ini mengevaluasi kinerja elektrokoagulasi (EK) dalam menurunkan konsentrasi Mn pada AAT menggunakan elektroda besi (Fe), aluminium (Al), dan kombinasi Fe–Al. Eksperimen skala laboratorium dilakukan menggunakan sampel AAT dari wilayah tambang batubara Air Laya, Indonesia, dengan konsentrasi Mn awal 5,89–6,68 mg/L, melebihi baku mutu 4 mg/L. Hasil penelitian menunjukkan bahwa EK efektif menurunkan Mn menjadi 1,07 mg/L (Fe), 1,40 mg/L (Al), dan 0,91 mg/L (Fe–Al), dengan efisiensi penyisihan masing-masing sebesar 82,78%, 77,94%, dan*

*85,62%. Kombinasi Fe–Al mencapai efisiensi tertinggi dan secara konsisten memenuhi baku mutu air. Biaya operasional untuk elektroda Fe, Al, dan Fe–Al masing-masing sebesar Rp312.240/m³, Rp316.550/m³, dan Rp313.100/m³, dengan kombinasi Fe–Al menunjukkan rasio biaya-terhadap-efisiensi yang paling menguntungkan. Temuan ini menunjukkan bahwa elektrokoagulasi merupakan pendekatan yang efektif dan layak secara ekonomi untuk penghilangan Mn dalam pengolahan AAT, dengan kombinasi elektroda Fe–Al menawarkan keseimbangan optimal antara kinerja teknis dan biaya operasional untuk implementasi praktis dalam pengelolaan air limbah pertambangan batubara.*

***Kata kunci:*** *Air Asam Tambang, Elektrokoagulasi, Penghilangan Mangan, Elektroda Fe–Al, Pengolahan Air Limbah*

## INTRODUCTION

This study was conducted in a coal mining area located in the Air Laya region, South Sumatra, Indonesia. The area is part of a Tertiary sedimentary basin that has developed into a major center of large-scale open-pit coal mining. Intensive mining activities in this region have contributed to the formation of acid mine drainage (AMD), primarily due to the exposure of sulfide-bearing materials to oxygen and water. Field observations indicate that the resulting AMD is characterized by low pH and elevated concentrations of dissolved metals, particularly manganese (Mn), which is considered a key parameter in mine water quality management (Akcil & Koldas, 2006; Kefeni et al., 2017). From a geological perspective, the Air Laya area is dominated by coal-bearing formations consisting of clastic sedimentary rocks such as sandstone, claystone, and interbedded coal layers containing sulfide minerals, especially pyrite ($FeS_2$). The oxidation of pyrite plays a central role in AMD formation, generating sulfuric acid and mobilizing various dissolved metals, including manganese ($Mn^{2+}$), into the water system (Nordstrom et al., 2015). Under acidic conditions ($pH < 4$), manganese tends to remain in a stable dissolved form, which limits its natural precipitation. As a result, Mn concentrations in AMD remain relatively high and persistent, even after conventional treatment processes such as sedimentation (McBeath et al., 2020).

In Indonesia, mine water quality management is regulated through environmental policies that define permissible limits for various contaminants, including manganese. According to the Regulation of the Minister of Environment and Forestry No. 5 of 2022 concerning wastewater quality standards, the maximum allowable Mn concentration for coal mining activities is 4 mg/L (Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia, 2022). This standard serves as the primary benchmark for assessing the performance of AMD treatment systems. However, previous studies have shown that Mn levels in AMD frequently exceed this limit and are difficult to reduce effectively using conventional treatment methods (Skousen et al., 2017). Various treatment approaches have been applied to address AMD, including chemical neutralization, precipitation, adsorption, and electrocoagulation. Conventional methods such as lime addition are generally effective in increasing pH and removing certain metals, but they are often less efficient for Mn removal due to the slow oxidation kinetics of manganese under typical treatment conditions (Sajjad et al., 2024). In this context, electrocoagulation (EC) has gained increasing attention as an alternative treatment technology, as it can generate coagulants in situ through electrochemical reactions. The use of metal electrodes, such as iron (Fe) and aluminum (Al), leads to the formation of metal hydroxides that function as coagulants, facilitating the removal of dissolved metals through adsorption and precipitation mechanisms (Al-Qodah et al., 2025).

Moreover, the combination of Fe and Al electrodes has been reported to enhance treatment performance through synergistic effects involving oxidation, coagulation, and adsorption processes (Mollah et al., 2004; Razzak et al., 2022). This combined mechanism is particularly relevant for Mn removal in AMD, where both oxidative conditions and effective floc formation are required.

Therefore, the selection of electrode materials and the optimization of operational parameters are critical factors in improving the efficiency of the electrocoagulation process (Chen, 2004; Alkhadra et al., 2022). The motivation for this study arises from the need to develop more effective and efficient AMD treatment technologies capable of reducing manganese concentrations to meet environmental standards. The persistence of high Mn levels, coupled with the limitations of conventional treatment methods, highlights the importance of exploring alternative approaches that are better suited to field conditions (Wu et al., 2022). In addition, increasing emphasis on environmental sustainability and regulatory compliance in the mining sector necessitates the adoption of treatment technologies that are not only technically effective but also economically viable (Matebese et al., 2024).

This study aims to evaluate the performance of the electrocoagulation method in reducing manganese concentrations in acid mine drainage and to determine the most effective electrode configuration. Specifically, the study compares the performance of Fe, Al, and combined Fe–Al electrodes in the treatment process. The findings are expected to contribute to the advancement of AMD treatment technologies and provide practical insights for their application in the field. This study is limited to laboratory-scale experiments with controlled operating conditions, including reaction time and sample volume. The analysis focuses primarily on manganese (Mn) as the main parameter, without detailed evaluation of other contaminants or microbiological aspects. The expected outcome is the identification of an optimal electrode configuration and corresponding Mn removal efficiency, which may serve as a reference for further development and scale-up of AMD treatment systems.

## METHODS

This study employed a laboratory-scale experimental approach to evaluate the effectiveness of the electrocoagulation method in reducing manganese (Mn) concentrations in acid mine drainage. The research was conducted from January to March 2026 at the Environmental Laboratory, Department of Mining Engineering, Sriwijaya University. Acid mine drainage samples were collected from a settling pond in the Air Laya mining area, South Sumatra, and stored under sealed conditions to maintain chemical stability prior to testing. The subject of the study was acid mine drainage samples with initial Mn concentrations of 5.89–6.68 mg/L, while the objects of the study included Mn removal efficiency, energy consumption, electrode consumption, and operational costs across three electrode variations: iron (Fe), aluminium (Al), and a combination of Fe–Al. The experimental procedure was carried out through several stages, including sample and electrode preparation, electrocoagulation treatment in a batch reactor with equal sample volume for each treatment, post-treatment water sampling, and laboratory analysis using Atomic Absorption Spectroscopy (AAS) to measure Mn concentrations before and after treatment (Skoog et al., 2018). The electrocoagulation process operates through anodic oxidation producing metal ions ($Fe^{2+}$ or $Al^{3+}$) which react with hydroxide ions to form hydroxide flocs ($Fe(OH)_3$ or $Al(OH)_3$), while water reduction at the cathode generates hydrogen gas which aids the flotation process (Mao et al., 2023; Jaafar et al., 2025; Sahu et al., 2014; Brillas & Martínez-Huitle, 2015).

Data collection techniques involved direct measurement of key parameters, including initial and final Mn concentrations using AAS, initial pH values, electrical energy consumption ($V \times I \times t$), and dissolved electrode mass. The instruments used included an atomic absorption spectrophotometer (AAS), DC power supply, voltmeter, ammeter, and analytical balance. Secondary data, including electricity tariffs and electrode material prices, were collected for economic analysis. Data analysis employed a quantitative descriptive approach by comparing final Mn concentrations, removal efficiency ($\eta = (C_0 - C_t)/C_0 \times 100\%$), energy consumption ($kWh/m^3$), electrode consumption based on Faraday's law ($m = (I \times t \times M)/(z \times F)$), and operational costs among electrode variations (Niza et al., 2025; Vepsäläinen & Sillanpää, 2020). A cost-to-removal-efficiency ratio analysis (Cost-effectiveness = Operating Cost / $\eta$) was used to determine the most technically and economically optimal electrode configuration (Thakur & Mondal, 2017). All data were analysed comparatively to determine the most effective and efficient acid mine drainage treatment method recommendation.

## RESULTS AND DISCUSSION

The results of this study indicate that the electrocoagulation method has significant capability in reducing manganese (Mn) concentrations in acid mine drainage (AMD) compared to the control treatment. In general, the initial Mn concentration was in the range of approximately ±6 mg/L and decreased to varying degrees depending on the type of electrode used. In the control treatment, the reduction of Mn was very limited and did not show a significant change, indicating that natural processes such as sedimentation are not effective in removing dissolved Mn. This condition is related to the nature of Mn, which predominantly exists in the form of $Mn^{2+}$ in acidic environments, characterized by high solubility and resistance to precipitation without oxidation processes or pH increase (Wu et al., 2022). In addition, the stability of $Mn^{2+}$ is influenced by the low redox potential in AMD systems, making passive removal processes highly limited (Zhang et al., 2023). The visualization of the research results is presented in Table 1, which shows a comparison of initial Mn concentration, final Mn concentration, and removal efficiency for each electrode treatment.

The data in Table 1 show a consistent pattern, where all electrocoagulation treatments significantly reduced Mn concentrations compared to the control. The Fe electrode reduced Mn to nearly 1 mg/L with an efficiency of more than 82%, while the Al electrode reduced Mn to around 1.3–1.5 mg/L with an efficiency of approximately 78%. The Fe–Al electrode combination demonstrated the best performance, achieving a final concentration below 1 mg/L and the highest efficiency of up to 85.78%. These differences indicate that electrode type directly affects the formation of active coagulant species in the system. Fe tends to produce $Fe(OH)_3$ with an amorphous structure and high surface area, while Al produces $Al(OH)_3$, which is more stable in forming fine flocs (Mollah et al., 2004; Boinpally et al., 2023).

**Table 1.** Average Efficiency of Three Electrode Types in Reducing Mn Concentration in Acid Mine Drainage

| Treatment | n | Initial Mn (mg/L) | Final Mn (mg/L) | Efficiency (%) | Baku Mutu (mg/L) | Standard |
|---|---|---|---|---|---|---|
| Control (Sedimentation) | 5 | 6,23 | 5,84 | 6,21 | ≤ 4 | Not Compliant |
| Fe | 5 | 6,19 | 1,07 | 82,78 | ≤ 4 | Compliant |
| Al | 5 | 6,34 | 1,40 | 77,94 | ≤ 4 | Compliant |
| Fe–Al | 5 | 6,32 | 0,91 | 85,62 | ≤ 4 | Compliant |

The data trend shows a systematic increase in efficiency from control → Al → Fe → Fe–Al. This pattern indicates that the complexity of the electrocoagulation mechanism is directly proportional to the system's ability to remove Mn. For the Fe electrode, Mn reduction is indicated by a large difference between initial and final values, with relatively stable results across samples, reflecting process consistency. Meanwhile, the Al electrode shows a more moderate reduction pattern with very small variation between replicates, indicating system stability in producing uniform water quality. The Fe–Al combination exhibits the most optimal pattern, with the largest gap between initial and final values and a very narrow distribution of final values, reflecting the highest level of consistency and efficiency. This pattern suggests that the interaction between electrodes enhances the formation of more effective complex flocs in binding Mn ions (Mollah et al., 2004; Al-Shannag et al., 2015).

Descriptive statistical analysis shows that the average Mn removal efficiencies for each treatment are 6.32% (control), 77.90% (Al), 82.74% (Fe), and 85.64% (Fe–Al) (Table 2). The relatively small standard deviation values across all electrocoagulation treatments indicate low data dispersion and homogeneous results among replicates. This condition reflects the stability of the electrocoagulation system in producing consistent outcomes. Additionally, the low standard error values indicate that the estimated means are close to the true population values. This is consistent with experimental design principles stating that low variability is an indicator of good data quality (Kotronoulas et al., 2023).

**Table 2.** Descriptive Statistical Analysis of Mn Removal Efficiency

| Electrode | Mean (%) | Standard Deviation | Variance | Coefficient of Variation (%) |
|---|---|---|---|---|
| Al | 77.94 | 0,12 | 0,001 | 0,15 |
| Fe | 82.78 | 0,08 | 0,006 | 0,10 |
| Fe–Al | 85.62 | 0,06 | 0,004 | 0,07 |

Normality testing using the Shapiro–Wilk method shows that most data are normally distributed, while homogeneity testing indicates that variances between groups are homogeneous. With these assumptions satisfied, ANOVA analysis can be validly applied. The ANOVA results indicate that the differences in efficiency between treatments are statistically significant with $p < 0.05$ (Table 3). This demonstrates that variations in electrode type have a significant effect on electrocoagulation performance. This statistical significance reinforces that performance differences are not due to chance but result from differences in electrochemical mechanisms within the system (Song, 2022).

**Table 3.** One-Way ANOVA Results

| Source of Variation | SS | df | MS | Fcalculated | Ftable (0.05) |
|---|---|---|---|---|---|
| Between Groups | 156,32 | 2 | 78,16 | 842,50 | 3,89 |
| Within Groups | 1,11 | 12 | 0,09 | | |
| Total | 157,43 | 14 | | | |

From a mechanistic perspective, these results can be explained by the role of electrodes in generating active coagulants. Fe electrodes produce $Fe^{2+}$ and $Fe^{3+}$ ions that form $Fe(OH)_3$ and contribute to the oxidation of $Mn^{2+}$ into insoluble $MnO_2$. Meanwhile, Al electrodes produce $Al(OH)_3$, which acts as a high-capacity adsorbent for metal ions. The combination of both electrodes results in dual mechanisms oxidation and adsorption occurring simultaneously, thereby enhancing Mn removal efficiency. This mechanism has been widely reported as a key factor in improving electrocoagulation performance (Mollah et al., 2004; Al-Shannag et al., 2015). From an operational cost perspective, the results show that Fe electrodes have the lowest cost, followed by Fe–Al combinations, while Al electrodes have the highest cost. These differences are mainly influenced by electrode material prices and electrical energy consumption. However, the cost-to-efficiency ratio analysis indicates that the Fe–Al combination has the most optimal value. This suggests that increased efficiency is not accompanied by a significant increase in cost, resulting in a more economical system. These findings align with studies stating that energy efficiency and electrode consumption are key factors in determining the economic feasibility of electrocoagulation (Thakur & Mondal, 2017; Vepsäläinen & Sillanpää, 2020).

Compared to the literature, these findings are consistent with previous studies reporting that electrode combinations enhance efficiency through synergistic effects. Electrode combinations improve floc formation and heavy metal removal efficiency (Mahmood et al., 2025; Al-Shannag et al., 2015). Mixed electrodes increase floc stability and active surface area (Mollah et al., 2004; Boinpally et al., 2023). Thus, this study not only supports existing theory but also strengthens empirical evidence in the context of AMD treatment. Furthermore, these results expand the understanding that electrocoagulation can overcome the limitations of conventional methods in removing Mn under acidic conditions. Mn, which is stable in the $Mn^{2+}$ form, can be oxidized through electrochemical processes that increase the system's redox potential. This demonstrates that electrocoagulation provides reaction conditions that cannot be achieved through passive methods (McBeath et al., 2020; Skousen et al., 2017).

However, the results also show that the difference in efficiency between Fe and Al electrodes is not very large. This may be due to suboptimal operating conditions, such as insufficient electric current or reaction time to maximize Mn oxidation. Additionally, the slow kinetics of Mn oxidation may limit the effectiveness of Fe electrodes within limited reaction times (McBeath et al., 2020; Mao et al., 2023). This kinetic factor indicates that although Fe has higher oxidation potential, the process requires sufficient time and appropriate conditions to achieve maximum efficiency (McBeath et al., 2020; Mao et al., 2023). In contrast, Al, which relies on adsorption mechanisms, can act more quickly under initial conditions, resulting in efficiency relatively close to that of Fe. This demonstrates that differences in reaction mechanisms influence the final system performance (Mollah et al., 2004; Boinpally et al., 2023). Operational cost analysis shows that although there are differences between electrode types, the cost structure in the electrocoagulation system is dominated by electrical energy consumption rather than electrode material consumption (Table 4). This is evident from electricity costs contributing more than 90% of total operational costs, while electrode costs contribute only a minor portion. This phenomenon is common in electrocoagulation systems, where energy requirements to maintain electric current are the primary determinant of total process cost (Thakur & Mondal, 2017; Vepsäläinen & Sillanpää, 2020). Therefore, energy efficiency becomes a key parameter in system optimization, not only contaminant removal efficiency.

**Table 4.** Operational Cost Analysis

| Electrode | Efficiency (%) | Cost (Rp/m$^3$) | Cost/Efficiency Ratio |
|---|---|---|---|
| Al | 77.94 | 330,000 | 4,234 |
| Fe | 82.78 | 312,240 | 3,772 |
| Fe–Al | 85.62 | 313,100 | 3,657 |

Further analysis shows that Fe electrodes have the lowest operational cost compared to others. This is due to two main factors: the relatively lower price of Fe material and the lower electrode consumption rate due to its smaller electrochemical equivalent value. In addition, Fe has better current conversion efficiency in generating active coagulants, making energy requirements for achieving Mn reduction targets more efficient. This finding is consistent with studies indicating that Fe electrodes tend to be more economical than Al in wastewater treatment applications due to a balance between technical performance and operational cost (Kobya et al., 2016). In contrast, Al electrodes show the highest operational cost despite having efficiency not far from Fe. This is mainly due to the higher price of aluminum and the relatively larger electrode mass required to produce equivalent coagulant amounts. Additionally, Al tends to form a passivation layer on the electrode surface, which increases electrical resistance and leads to higher energy consumption during the process (Kobya et al., 2016; Yasri et al., 2022). This condition makes the system less economically efficient, even though it remains technically effective in reducing Mn.

Interestingly, the Fe–Al electrode combination shows a unique position in cost analysis. Although its total cost is slightly higher than Fe alone, it produces the highest Mn removal efficiency. This results in the most optimal cost-effectiveness ratio. Conceptually, this indicates that improved technical performance can offset additional operational costs, resulting in a more efficient overall system. In process engineering, this approach is more relevant than simply choosing the lowest-cost option, as it considers the benefits gained per unit cost (Thakur & Mondal, 2017; Kobya et al., 2016). From a process mechanism perspective, the cost efficiency of the Fe–Al combination can be explained by synergistic effects that simultaneously reduce energy and material requirements. This combination enables faster and more stable floc formation, shortening effective reaction time and reducing energy consumption. In addition, the presence of two types of active coagulants increases the probability of interaction with Mn ions, thereby improving removal efficiency without significant increases in electric current (Mahmood et al., 2025). Optimizing electrode types can reduce energy consumption by up to 20–30% in electrocoagulation systems (Jafari et al., 2023).

From a field implementation perspective, these results indicate that electrode selection cannot be based solely on material cost or technical efficiency separately but must consider both simultaneously. In this case, although Fe has the lowest cost, the Fe–Al combination provides better long-term economic value by producing higher water quality with minimal additional cost. This is particularly important in AMD management, where regulatory standards must be consistently met, making high-efficiency systems more desirable. However, it should be noted that the cost analysis in this study is still limited to laboratory scale and does not fully represent field operational conditions. At the industrial scale, other factors such as electrode maintenance costs, material replacement, electrical distribution system efficiency, and energy price fluctuations may have a greater impact on total operational cost (Mao et al., 2023; Al-Qodah et al., 2025). Therefore, these results need to be further evaluated at the pilot scale to obtain more realistic cost estimates.

The implications of this study indicate that electrode selection is a key factor in optimizing electrocoagulation. The Fe–Al combination provides a balance between technical efficiency and operational cost, making it more feasible for industrial-scale application. This finding contributes significantly to the development of more efficient and economical AMD treatment technologies. From a scientific perspective, this study provides a deeper understanding of Mn removal mechanisms through electrocoagulation, particularly in combined electrode systems. This opens opportunities for developing more innovative and adaptive electrocoagulation-based technologies for various wastewater conditions. The limitations of this study lie in its laboratory scale and limited variables. More complex field conditions may produce different responses to the electrocoagulation system. Additionally, other parameters such as pH, current, and reaction time have not been fully optimized. For future research, pilot-scale testing and optimization of operational parameters are recommended. Furthermore, exploring other electrode combinations and integrating electrocoagulation with other treatment technologies may enhance overall system performance. Overall, the results of this study indicate that electrocoagulation is an effective and promising technology for Mn removal in AMD, with the Fe–Al electrode combination as the optimal configuration from both technical and economic perspectives.

## CONCLUSION

This study shows that the electrocoagulation method is an effective technology for reducing manganese (Mn) concentrations in acid mine drainage (AMD) at the Air Laya Mine, PT Bukit Asam. The initial Mn concentration, which ranged from 5.89 to 6.68 mg/L, was successfully reduced significantly to below the regulatory standard ($\leq$ 4 mg/L) through all electrocoagulation treatments, in contrast to the control method (sedimentation), which did not demonstrate adequate effectiveness. From a technical perspective, Fe electrodes exhibited better performance than Al electrodes, with an Mn removal efficiency of 82.78% compared to 77.94%. This indicates that oxidation mechanisms and iron-based floc formation play an important role in the Mn removal process. However, the Fe–Al electrode combination produced the most optimal results, achieving the highest efficiency of 85.62% and a final Mn concentration of 0.91 mg/L. These results demonstrate a synergistic effect between oxidation by Fe and adsorption by Al in enhancing the efficiency of the electrocoagulation process.

From an economic standpoint, the differences in operational costs among treatments were relatively small, with costs of Rp312.240/$m^3$ for Fe, Rp316.550/$m^3$ for Al, and Rp313.100/$m^3$ for the Fe–Al combination. Although Fe electrodes had the lowest cost, the Fe–Al combination showed the best cost-effectiveness value, as it provided the highest efficiency with only a marginal cost difference. This confirms that the selection of treatment technology should consider not only cost but also the technical performance achieved. Overall, this study concludes that the Fe–Al electrode combination is the most optimal configuration for acid mine drainage treatment, as it provides the best balance between technical effectiveness and economic efficiency. These findings contribute significantly to the development of more effective, applicable, and sustainable AMD treatment strategies, particularly in the context of the coal mining industry in Indonesia.

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