

Improving Acid Mine Drainage Treatment through Electrocoagulation: Effect of Time, Electrode Distance, and Electrode Types

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Abstract. This study explores the feasibility of employing electrocoagulation technology to manage Acid Mine Drainage (AMD) wastewater, focusing on reducing heavy metal concentrations, particularly iron (Fe) and manganese (Mn). Samples of AMD liquid waste from PT Lhoong Setia Mining in Aceh Province, Indonesia, underwent electrocoagulation using Al-Zn and Al-Fe electrodes with Direct Current (DC). The investigation considered various parameters, including contact time (ranging from 0 to 45 minutes), electrode distance (2, 2.5, and 3 cm), and electrode type (Al-Fe and Al-Zn). The study revealed that prolonged electrocoagulation increased the reduction of Fe and Mn metals due to enhanced $\text{Al}(\text{OH})_3$ formation. While Al-Zn electrodes exhibited rapid coagulant formation initially, Al-Fe electrodes sustained effectiveness throughout the process. Optimal reduction of Fe and Mn concentrations occurred at different electrode distances, emphasizing the critical role of spacing in electrocoagulation efficiency. Furthermore, the electrocoagulation process successfully elevated pH levels within acceptable limits and effectively reduced Total Suspended Solids (TSS) in AMD waste, aligning with regulatory standards. This research underscores the potential for electrocoagulation as a viable technology for mitigating the environmental impact of AMD and addresses knowledge gaps related to efficient pollutant removal in mining wastewater treatment. Future studies should explore parameter optimization and consider transitioning to continuous operation for increased effectiveness, particularly in remote mining locations.

1 Introduction

Indonesia, strategically situated in the tropics and home to active volcanoes, boasts abundant mineral and coal reserves. Over the past few decades, mineral mining has made a significant contribution to the country's economy [6]. Globally, minerals, especially coal as a major energy source, play a pivotal role in shaping the geopolitical landscape. In this context, precious minerals like gold also wield significant influence in the global economic dynamics [8].

Nevertheless, despite its economic advantages, mineral mining activities give rise to a host of challenges. The mineral oxidation process that occurs during mining generates hazardous waste, often tainted with heavy metals such as manganese and iron [4]. This waste takes the form of corrosive mine leachate, commonly known as Acid Mine Drainage (AMD), which poses a potential threat to the local ecosystem and human well-being [3]. Elevated levels of heavy metal contamination and acidity in mining waste have detrimental effects on both the land and water, including

surface and groundwater, ultimately impacting plants, animals, and human beings [10].

Wastewater treatment employs various conventional methods encompassing physical, chemical, biological processes, or their amalgamation. The utilization of chemicals in wastewater treatment often generates substantial sludge, previously tainted by these chemicals. This, however, fails to address the environmental issues associated with contamination.

The microbiological treatment system, on the other hand, necessitates a considerable land area and entails relatively lengthy processing times. Despite its impracticality for handling organic pollutants and nutrients in wastewater, the prevailing approach for eliminating persistent inorganic constituents, primarily metals, from acid mine wastewater remains electrocoagulation.

Considering these concerns, this research seeks to evaluate the feasibility of employing electrocoagulation technology for managing acid mine drainage wastewater, with a specific emphasis on reducing levels of heavy metals such as iron (Fe) and manganese (Mn). The selection of this technology is based on its efficacy

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in the electrolyte separation process, wherein electrical energy is converted into chemical energy through an electrolytic cell [3].

To accomplish this objective, the study utilizes samples of acid mine drainage liquid waste collected from PT Lhoong Setia Mining, situated in the Aceh Besar District of Aceh Province, Indonesia. During this process, Al-Zn and Al-Fe electrodes are employed in conjunction with Direct Current (DC) to expedite the coagulation of colloid particles serving as pollutants. Notably, this study differs from previous research where Al-Al electrodes were used [1].

Compared with Al-Fe, Fe-Al, and Fe-Fe, previous research has proved that Al-Al configuration exhibited the highest effectiveness, particularly in decreasing both Chemical Oxygen Demand (COD) and total suspended solids (TSS) [2]. Al electrodes also have removal efficiencies of 75% for Cu^{2+} and 65% for Zn^{2+} after 60 minutes of experimentation, using specific conditions such as a voltage of 15 V, an electrode distance of 3 cm, and an initial pH of 5.4 [11]. The reduction in COD and Biochemical Oxygen Demand (BOD) at this condition were 36% and 35%, respectively [11]. However, Al electrodes might experience mass loss in both anode and cathode compared to Zn and Fe with only on the anode despite having significant loss [13]. Therefore, in this paper, for different alternatives as well as to try on different condition, the study focused on Al-Zn and Al-Fe configurations.

Previous studies also have illuminated the adverse impacts of mining, particularly acid mine drainage, on the environment and local communities [4]. Nevertheless, a knowledge gap persists regarding effective technologies to address this issue.

Hence, this research endeavors to bridge this gap by examining the potential application of electrocoagulation technology in treating acid mine drainage wastewater, particularly with the variation of time, electrode distance, and electrode type. The study adheres to the test parameters outlined in Indonesian Minister of Environment Regulation Number 21 of 2009, which addresses Wastewater Quality Standards for Mineral Mining Businesses or Activities. It is anticipated that this study will mitigate the environmental repercussions of acid mine drainage.

2 Methodology

In this study, the considered variables were categorized into two groups: constant and variable parameters. The constants encompass the volume of acid mine drainage wastewater (1 liter), the dimensions of the aluminum and iron plates (300 x 150 x 2 mm), and the voltage level (18 volts). The variables encompass the contact time (0, 15, 30, and 45 minutes), the distance between electrodes (2, 2.5, and 3 cm), and the electrode type variations (Al-Fe and Al-Zn).

The research methodology involved the preparation of a 1-liter liquid waste sample, which was placed within a batch system container. The effectiveness of different electrode variations, electrode distances, and electrocoagulation process durations in treating acid mine drainage was then evaluated using the electrocoagulation method. Illustration for the methodology is presented as in Fig. 1.

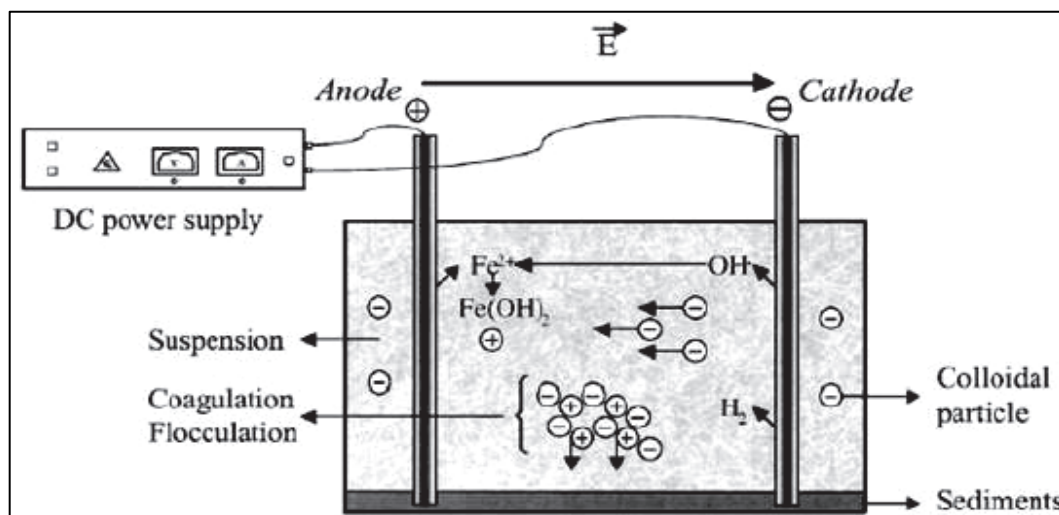


Fig.1. Influence of Electrocoagulation Time on the Reduction of Fe Metal Concentration with Electrode Variation.

The research procedure was divided into two principal stages: material preparation and the electrocoagulation process. Initially, acid mine drainage wastewater samples were procured from the mining site and subjected to electrocoagulation techniques to determine the most efficient electrode variation. Subsequently, the electrocoagulation process was

conducted using Al-Zn and Al-Fe electrodes, which have been properly cleaned and positioned at a specified distance. This process operated at a fixed voltage of 18 volts, with samples collected at defined time intervals to assess pH levels and measure heavy metal ions (Fe and Mn).

The parameter tests comprised pH measurements before and after the electrocoagulation process, performed using a pH meter. Additionally, Atomic Absorption Spectroscopy (AAS) analysis was employed to quantify the concentration of metal components in the samples, while Total Suspended Solid testing was conducted to evaluate the turbidity of the mine waste samples. The outcomes of these tests were anticipated to conform to the quality standards set for mine waste.

3 Result and Discussion

3.1 The Effect of Electrocoagulation Time on the Reduction of Fe Metal Concentration in the Electrocoagulation Process with Al-Zn and Al-Fe Electrode Variations

As depicted in Fig. 2, the efficacy of reducing the concentration of Fe metal exhibits a positive correlation with the duration of electrocoagulation. In practical terms, this signifies that as the electrocoagulation duration extends, the iron (Fe) content in the mine wastewater decreases proportionally. This observed increment can be elucidated by the progressive dissolution of aluminum over an extended period, consequently leading to an amplified generation of $\text{Al}(\text{OH})_3$. This phenomenon aligns with findings from prior research [7], which underscore that an augmented formation of complexes, such as $\text{Al}(\text{OH})_3$, during the process contributes to the enhanced efficiency of pollutant reduction.

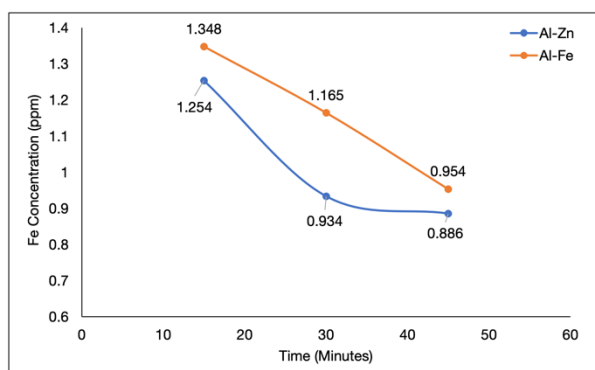


Fig. 2. Influence of Electrocoagulation Time on the Reduction of Fe Metal Concentration with Electrode Variation.

The formation of $\text{Al}(\text{OH})_3$ arises from the reduction process of aluminum (Al) metal at the anode, resulting in the production of Al^{3+} ions. Subsequently, these Al^{3+} ions combine with OH^- ions to give rise to $\text{Al}(\text{OH})_3$. This compound acts as a coagulant, facilitating the removal of iron (Fe) metal from the solution. Therefore, it is evident that the duration of electrocoagulation directly influences the efficiency of Fe metal concentration reduction. In simpler terms, a longer electrocoagulation period yields a greater quantity of $\text{Al}(\text{OH})_3$, which, in turn, proves more effective in diminishing the Fe metal concentration in acid mine water.

These findings signify the impact of varying contact times on the efficiency of iron removal. With an extended electrocoagulation contact time, the electrolysis process endures for a longer duration, allowing for the occurrence of reduction and oxidation reactions at the cathode. This observation aligns with Faraday's first law, which posits that the mass of a substance produced at the electrode during electrolysis is directly proportional to the number of moles of electrons transferred to the electrode.

Under optimal conditions, the most substantial reduction in Fe metal concentration occurs at an electrocoagulation time of 45 minutes and the use of Al-Zn electrodes. Zinc has a higher standard reduction potential than iron. This means that zinc is more electrochemically reactive and prone to undergo reduction reactions compared to iron.

In the context of electrocoagulation, this higher reactivity allows Al-Zn electrodes to efficiently facilitate the reduction of iron ions, leading to the formation of iron hydroxide ($\text{Fe}(\text{OH})_3$) coagulants. This is particularly beneficial when rapid coagulation and removal of iron are desired, as is often the case in wastewater treatment processes. Under certain conditions, the reactivity of zinc may also be more suitable for efficient iron removal.

3.2 The Effect of Electrocoagulation Time on the Reduction of Mn Metal Concentration in the Electrocoagulation Process with Al-Zn and Al-Fe Electrode Variations

Referring to Fig. 3, it is evident that the effectiveness of reducing the concentration of manganese (Mn) metal in mine wastewater improves with the prolongation of electrocoagulation time. As the electrocoagulation process extends, the Mn level decreases correspondingly. This decline is intricately linked to a mechanism in which hydroxide compounds bind with pollutants, resulting in the formation of aggregates. Simultaneously, hydrogen gas produced in the process lifts these aggregates towards the surface of the reactor. This continuous process leads to the gradual accumulation of aggregates over time, causing them to collide with one another and enhancing the mass's density. Eventually, a portion of this denser mass settles to the bottom of the reactor, forming sludge [7].

This relationship is closely intertwined with the duration of the electrocoagulation process. As the process extends, a larger quantity of dissolved metal, such as $\text{Al}(\text{OH})_3$, forms, leading to a reduction in manganese (Mn) concentration. In simpler terms, as the treatment time lengthens, the concentrations of both Fe and Mn in the water decrease due to the formation of $\text{Al}(\text{OH})_3$. The correlation between the increasingly lower levels of Fe and Mn in the treated water and the duration of contact time is direct and notable. Hence, contact time emerges as a pivotal parameter in the electrocoagulation process.

Under ideal conditions, the most effective reduction in Mn metal concentration was achieved at an

electrocoagulation time of 45 minutes, employing Al-Zn electrodes. In this scenario, the Mn metal concentration reached 0.912 ppm, which was slightly higher than the concentration achieved using Al-Fe electrodes, at 0.925 ppm.

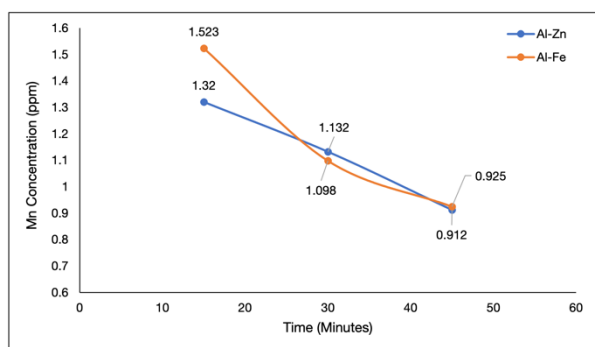


Fig. 3. Influence of Electrocoagulation Time on the Reduction of Mn Metal Concentration with Electrode Variation.

However, it is worth noting that Al-Zn electrodes exhibited more pronounced results within the initial 10 minutes compared to Al-Fe electrodes. This then became almost similar in for the next 10 to 20 minutes. During the first 10 minutes of electrocoagulation, rapid coagulation and contaminant removal are crucial. Zinc (Zn) has a higher standard reduction potential than iron (Fe), indicating greater electrochemical reactivity. This higher reactivity allows Al-Zn electrodes to expedite the formation of coagulants, particularly iron hydroxide ($\text{Fe}(\text{OH})_3$), which play a critical role in removing manganese ions from the wastewater. As a result, Al-Zn electrodes are more efficient in reducing Mn concentration during this initial phase.

In the subsequent 10 to 20 minutes, the advantage of Al-Zn electrodes persists but may become slightly less pronounced. The efficient formation of coagulants by Al-Zn electrodes continues to contribute to manganese removal. However, as the electrocoagulation process progresses, the dynamics of ion transport, electrode surface interactions, and the availability of metal ions can change. This may lead to a narrowing performance gap between Al-Zn and Al-Fe electrodes.

In essence, Al-Zn electrodes maintain their effectiveness for a longer duration due to their superior reactivity and ability to quickly generate coagulants. However, the specific conditions of the electrocoagulation process, including pH, initial metal concentrations, and water chemistry, can influence the relative performance of the two electrode materials. Consequently, the choice between Al-Zn and Al-Fe electrodes should consider these factors to optimize manganese removal efficiency throughout the entire electrocoagulation process.

3.3 The Effect of Electrode Distance on the Reduction of Fe Metal Concentration in the

Electrocoagulation Process with Al-Zn and Al-Fe Electrode Variations

As illustrated in Fig. 4, a shorter distance between the electrodes elevates the risk of encountering short circuits during the electrocoagulation process. In contrast, when the gap between the electrodes is expanded, the volume of water within the process reactor increases. Consequently, the presence of iron-contaminating binder particles on the aluminum surfaces diminishes. This occurrence is intricately tied to the inter-electrode distance's influence on the rate of electron transfer. Specifically, it governs the swiftness with which electrons travel from the anode, where they are received, to the cathode, where the reduction process unfolds. Moreover, the spacing between the electrodes exerts a tangible impact on the efficiency of iron reduction, consequently augmenting the production of $\text{Al}(\text{OH})_3$ coagulant—a crucial agent for binding Fe concentrations [6].

In the context of the electrocoagulation reaction, the formation of $\text{Al}(\text{OH})_3$ plays a pivotal role in both the coagulation process and the adsorption of organic substances and metal ions. This intricate chemical reaction involves the agglomeration of particles, their subsequent sedimentation, and their buoyancy alongside the release of H_2 gas. This collective action serves to effectively detach colloidal impurities from the solution, thereby leading to a substantial reduction in pollutant concentrations.

Nonetheless, it is crucial to maintain an appropriate distance between the electrodes to optimize this process. If the gap between the electrodes is too narrow, it results in an excessive generation of coagulant. However, this can be counterproductive as it may lead to disruptions in the system due to the occurrence of short circuits between the electrodes. Conversely, widening the gap between the electrodes can diminish process efficiency. This is attributable to the heightened resistance encountered by the electrical current, resulting in decreased overall conductivity of the system [8]. It is worth noting that this electrochemical process is contingent on various factors, including ion production concentration, electrode material, and reaction duration.

Under conditions optimized for effectiveness, the most substantial reduction in Fe metal concentration occurs at an electrode distance of 2.5 cm. At this specific configuration, the Fe metal concentration attains a value of 0.886 ppm for Al-Zn and 0.954 for Al-Fe electrodes. At a closer electrode distance of 2 cm, the superior reactivity of zinc (Zn) as compared to iron (Fe) may result in Al-Zn electrodes being significantly better at rapidly generating iron hydroxide ($\text{Fe}(\text{OH})_3$) coagulants. This quick coagulant formation leads to efficient iron removal. Meanwhile, when the distance was increased to 2.5 cm, both Al-Fe and Al-Zn electrodes remain effective, but the performance gap between them narrows. This can be attributed to the fact that the optimal conditions for Al-Fe electrodes still allow them to efficiently form coagulants, but the difference in

performance between the two electrode types becomes less pronounced.

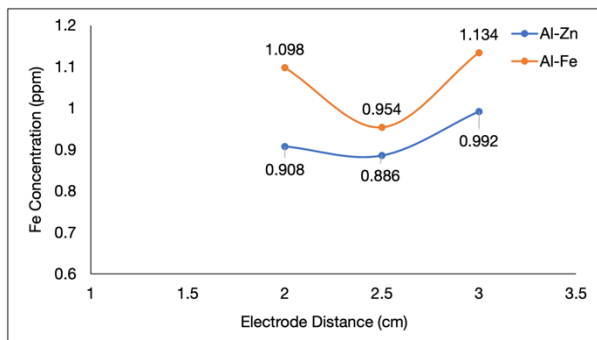


Fig. 4. Influence of Electrode Distance on the Reduction of Fe Metal Concentration with Electrode Variation.

At a greater distance of 3 cm, the advantage may shift in favor of Al-Zn electrodes. This is because, as the electrode distance increases, electrical resistance in the system rises. Al-Zn electrodes, with their higher standard reduction potential for zinc, may be better equipped to overcome this increased resistance and continue to form coagulants effectively. Meanwhile, the reactivity of Al-Fe electrodes may decrease, resulting in slightly reduced performance.

3.4 The Effect of Electrode Distance on the Reduction of Mn Metal Concentration in the Electrocoagulation Process with Al-Zn and Al-Fe Electrode Variations

As evident from Fig. 5, the proximity of the electrodes is directly linked to an escalated risk of short-circuiting. Conversely, when the electrode distance is expanded, it augments the volume of water within the reactor while diminishing the adhesion of particles to the aluminum surfaces. This has a tangible impact on the efficiency of pollutant reduction in wastewater. With the increasing separation between the electrodes, the interactions among the formed flocs weaken, rendering the formation of larger flocs more challenging. Simultaneously, the electrical current generated also wanes, resulting in a reduction in the dissolved aluminum's mass. This aligns with Faraday's law, which postulates that an increase in distance corresponds to a decrease in current, consequently leading to a diminished production of aluminum and hydroxyl ions.

The electrocoagulation process is governed by the fundamental principles of reduction and oxidation (redox) reactions. Within the coagulation cell, oxidation takes place at the anode (+) electrode, while reduction unfolds at the cathode (-). This intricate process involves the interaction of pollutants from the raw water with coagulants.

The separation distance between the electrodes assumes a pivotal role in regulating the rate of electron transfer between the anode and the cathode, where the reduction process transpires. An increased gap between the electrodes corresponds to a reduction in treatment efficiency, an elevation in current resistance, and a

decline in conductivity [12]. This process hinges on electrolysis, which, in turn, depends on ion concentration, electrode material characteristics, and reaction duration. When the electrodes are positioned too closely, an excessive accumulation of coagulant may occur, potentially leading to system disturbances stemming from short-circuits between the electrodes.

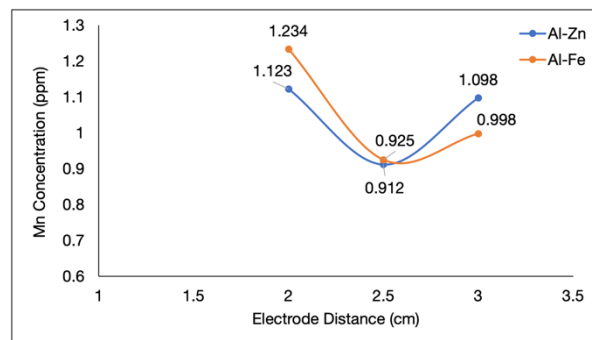


Fig. 5. Influence of Electrode Distance on the Reduction of Mn Metal Concentration with Electrode Variation.

In this study, the optimal reduction in manganese (Mn) metal concentration was achieved at an electrode distance of 2.5 cm, utilizing an Al-Zn electrode type, resulting in an Mn metal concentration of 0.912 ppm. As illustrated in Fig. 5, at a narrower electrode distance of 2 cm, the heightened reactivity of zinc (Zn) compared to iron (Fe) likely empowers Al-Zn electrodes to swiftly generate coagulants, a distinct advantage for the rapid removal of Mn ions. The proximity of the electrodes enhances electron transfer, thus facilitating efficient coagulant production.

Conversely, at an electrode distance of 2.5 cm, the performance differential between Al-Zn and Al-Fe electrodes diminishes. Both electrode types continue to exhibit effectiveness, but the disparity in performance becomes less pronounced. This observation may be attributed to the fact that the optimal conditions for Al-Fe electrodes still enable them to efficiently produce coagulants, thereby narrowing the performance gap.

Moving further to an increased distance of 3 cm, Al-Fe electrodes may begin to surpass Al-Zn electrodes in reducing Mn concentration. Despite the relatively similar performance gap observed at the 2 cm distance, the augmented electrode separation may affect the transport of metal ions, resulting in performance disparities. Al-Zn electrodes may encounter heightened resistance, while Al-Fe electrodes, with their lower reactivity, may be less susceptible to the influence of electrode distance.

3.5 The Effect of the Electrocoagulation Process on pH Value

Acid mine water harbors chemicals that pose a potential threat to soil and groundwater quality, particularly when it causes a significant reduction in water and soil pH levels. A sharp decline in pH enhances the solubility of heavy metals within this ecosystem. In a low pH environment, macronutrients become less

accessible as they become bound by metals, which, in turn, amplifies the solubility of essential nutrients [3]. The impact of the electrocoagulation process on pH values is visually depicted in Fig. 6.

Referring to Fig. 6, it becomes evident that the pH levels of the acid mine water undergo significant fluctuations. These pH variations align with the established standards for acid mine water originating from iron ore sources. Indonesian Ministerial Regulation Number 21 of 2009 stipulates a pH boundary standard for water within the range of 6-9. In the figure, all electrocoagulation treatments successfully comply with this standard. Notably, the treatment employing Al-Zn electrodes with an electrode distance of 2.5 cm and an electrocoagulation contact time of 45 minutes attains a pH value of 7.1. This shift in pH is attributed to the generation of OH⁻ ions at the cathode during the electrocoagulation process. The presence of an increased concentration of OH⁻ ions in the water leads to a rise in pH.

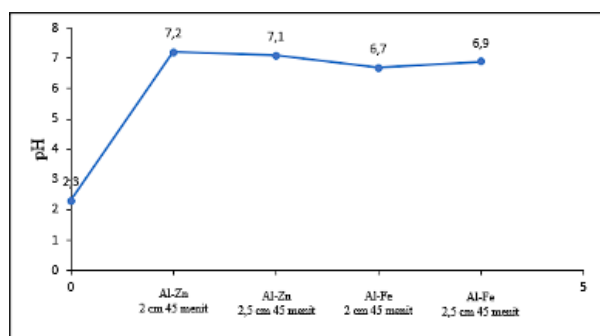


Fig. 6. Influence of Electrocoagulation Treatment on pH.

In the electrocoagulation process, the quantity of OH⁻ ions produced through water reduction at the cathode directly correlates with the alkalinity and pH of the treated water. The pH value experiences enhancement through several mechanisms inherent to electrocoagulation. Specifically, as the contact time with the sample prolongs, the pH value proportionally increases due to the greater generation of OH⁻ ions. During electrocoagulation, the pH of the solution ascends owing to the formation of OH⁻ gas and H₂ gas. The level of acidity profoundly impacts the efficiency of the process because pH influences the quantity of OH⁻ ions available at the cathode. These OH⁻ ions at the cathode interact with Al³⁺ ions at the anode, culminating in the formation of Al(OH)₃ [5].

3.6 The Effect of the Electrocoagulation Process on the Value of Total Suspended Solids (TSS)

Total Suspended Solids (TSS) represents the weight measurement, typically in milligrams per liter, of dry sludge particles found in waste processing. Assessing TSS serves as a valuable means to gauge the pollution extent in domestic wastewater and evaluate the performance of the water treatment system. The impact of electrocoagulation treatment on TSS values is visually depicted in Fig. 7.

Analyzing Fig. 7, it becomes evident that there is a notable reduction in Total Suspended Solids (TSS) within the acid mine wastewater. This decrease aligns with the established standard for acid mine water originating from iron ore sources. Indonesia Ministerial Regulation Number 21 of 2009 designates a maximum permissible limit for Total Suspended Solids at 200 mg/L. In the figure, all electrocoagulation treatments consistently adhere to this standard. Notably, the treatment employing Al-Zn electrodes, with an electrode distance of 2.5 cm and a contact time of 45 minutes, yields a TSS value of 23.7 mg/L. Similarly, the treatment utilizing Al-Fe electrodes, featuring an electrode distance of 2.5 cm and a contact time of 45 minutes, produces a TSS value of 26.08 mg/L.

Total Suspended Solids (TSS) quantifies the quantity of suspended solids within a specified volume of water, serving as an indicator of solid concentration in a water sample [9]. The decline in TSS is attributed to the oxidation reaction of anions (negative ions) at the anode. The metal anode undergoes an oxidation process, forming Al(OH)₃. Simultaneously, the reduction reaction at the cathode generates hydrogen gas (H₂), which propels pollutant colloids to the water's surface. Some of these fragments settle, while others float. An elevation in TSS value may potentially result from increased turbidity in the waste sample solution. The heightened turbidity could be attributed to redox processes occurring at the electrode.

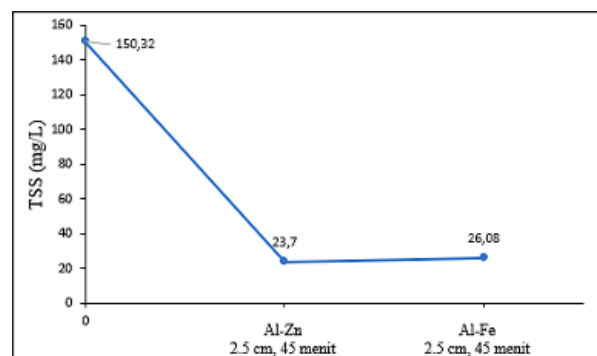


Fig. 7. Influence of Electrocoagulation Treatment on TSS.

4 Conclusion

In conclusion, this research has delved into the potential application of electrocoagulation technology for treating acid mine drainage wastewater, with a focus on exploring the effects of various parameters such as time, electrode distance, and electrode type. The research demonstrates a positive correlation between the duration of electrocoagulation and the reduction in Fe and Mn metal concentrations. Longer electrocoagulation times lead to more efficient removal of these metals due to increased Al(OH)₃ formation.

Al-Zn electrodes, with their higher reactivity, show an advantage in rapid coagulant formation and pollutant removal during the initial phase of electrocoagulation. Al-Fe electrodes remain effective but exhibit slightly reduced performance as the process

progresses. The separation distance between electrodes affects the process significantly. A closer electrode distance increases the risk of short-circuiting, while a wider gap improves water volume within the reactor and reduces particle adhesion to aluminum surfaces. Optimal conditions for reducing Fe and Mn concentrations are observed at different electrode distances.

Electrocoagulation treatment increases the pH of acid mine water by generating OH⁻ ions at the cathode. Compliance with pH standards for iron ore acid mine water was achieved across all treatments. TSS levels in acid mine water decrease significantly with electrocoagulation treatments, adhering to regulatory standards. Al-Zn electrodes at an electrode distance of 2.5 cm and a contact time of 45 minutes demonstrated an effective reduction in TSS.

Additional research efforts can be directed towards the optimization of various parameters, including electrode material, contact duration, and electrode spacing. This optimization aims to enhance the efficiency of pollutant removal while concurrently reducing energy consumption and operational expenses. This focus on optimization is especially pertinent in remote mining locations. Furthermore, transitioning the process from batch mode to continuous operation can be explored to further enhance contact times, thereby improving overall effectiveness.

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