Potential continuous electrocoagulation for the treatment of coal mine water containing colloidal clays

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Abstract

As a country with high rainfall (average 2,900 mm/a in 2021), Indonesia has serious problems with the quantity and quality of coal mining wastewater. By adopting an open pit mining system, wastewater can reach a discharge of 2000 L/s at its worst, with the main quality problem being high turbidity caused by colloidal clays/suspended solids. The total colloidal clays found in the wastewater reach 15,000 mg/L. Chemical coagulation has been carried out, but the amount of chemicals used is a problem due to the high discharge that needs to be treated. The electrocoagulation system with batch method shows promising potential to be an alternative to chemical coagulation with a removal percentage of up to 99.58%. However, with the problem of large discharge, further electrocoagulation research is needed using continuous operation. This study conducted continuous electrocoagulation research using a reactor with 15 L of working volume. The electrodes used were 39 (21 anodes and 18 cathodes), mounted monopolarly and arranged parallelly. Discharge variations of 0.3, 0.5, and 0.7 LPM (L/min) with current densities of 16.3, 19, and 21.7 A/m^2 were conducted as the initial stage of the continuous flow study. It was found that the results with the highest removal were in the variation of discharge of 0.3 L/min and current density of 16.3 A/m^2. In this variation, colloidal clay was removed by 99.87% from the initial concentration of 15,000 mg/L to 17 mg/L. In addition, total iron (Fe) removal in the electrocoagulation process was studied and resulted in 93% of removal. Conventional chemical coagulation was also conducted using the jar test method compared with electrocoagulation. The coagulants used were $Al_2(SO_4)_3$, Poly Aluminium Chloride, and Polyacrylamide, with a 400–700 mg/L dosage range. The highest removal of colloidal clays occurred using 700 mg/L of $Al_2(SO_4)_3$, 700 mg/L of Poly Aluminium Chloride, or 400 mg/L of Polyacrylamide, with each removal percentage reaching up to 99%. This research is expected to be a key step in determining the design criteria of electrocoagulation to develop scale-up efforts in the field.

Keywords: Colloidal clay, electrocoagulation, continuous operation, mine water, open pit mining

Introduction

Surface runoff is caused by rainfall exceeding the infiltration rate, and when it occurs, small depressions on the surface begin to store water (Qiao et al., 2023). The production of surface runoff is affected by the physical properties of the soil (Kirkby, 2002). Soils consist of clay and have a high swelling potential, which can cause a high run-off potential (Neitsch et al., 2011). The quantity of surface runoff is also influenced by rainfall; as rain intensity increases, so does the amount of surface runoff (Yao et al., 2021). The climate in Indonesia is characterized by two seasons – a dry season and a wet season due to the Asian-Australian monsoon system (Nur'utami & Hayasaka, 2022). It has been known for some time that Indonesia has high levels of rainfall, up to 2,900 mm/a, by 2021 (Badan Pusat Statistik Republik Indonesia, 2022). The variability and high levels of rainfall in Indonesia are influenced by the El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Madden-Julian Oscillation (MJO) (Lestari et al., 2019). In addition to quantity issues, the quality of surface runoff produced is influenced by slope steepness and slope length conditions, where a steeper slope angle causes higher runoff velocity and leads to soil erosion. In addition, excessive tillage leads to a closer arrangement of the soil particles, a lower overall porosity, a lower permeability, and the stability of the soil aggregates is reduced, resulting in increased run-off and sediment production (Jourgholami et al., 2018; Keesstra et al., 2016). The surface runoff produced can carry colloidal clay particles (< 2 µm) and fine particles (< 20 µm) that are small and stable. These particles have characteristics of high specific surface area and charge density. This increases the absorption potential for iron (Fe) and other organic pollutants. These particles also cause high Total Suspended Solids (TSS) concentrations in surface runoff (Li et al., 2023).

Coal mining is a process of excavation and transportation of relatively large quantities of overburden material. Open-pit mining activities can also alter topography and land cover (Abfertiawan et al., 2016), making surface runoff a severe concern at coal mining sites using the open-pit method. Under these conditions, mine water management is one of the challenges of mining environmental management. Surface runoff with quality problems and huge volumes must be treated before entering the water bodies. The aim is to avoid environmental issues, particularly regarding the aquatic biota in the recipient water bodies. Currently, water that is difficult to settle is treated by adding positively charged chemicals such as $Al_2(SO_4)_3$ or poly aluminium chloride to aid the coagulation process. Nevertheless, the amount of chemicals used is a problem due to the high discharge that needs to be treated. An electrocoagulation system with a batch method shows promising potential to be an alternative to chemical coagulation with a removal percentage of up to 99.58% (Abfertiawan et al., 2023). However, with the problem of large discharge, further electrocoagulation research is needed using continuous operation.

Methods

Before entering the mine water treatment plant (sediment pond), water samples are taken and transferred to the laboratory via a 1,000 L Intermediate Bulk Container (IBC). The water sample characteristics are described in the table below.

Continuous electrocoagulation research was conducted using a reactor with 15 L of working volume. The electrodes used were 39 (21 anodes and 18 cathodes), mounted monopolarly and arranged parallelly. The electrodes were made of aluminum with dimensions of length and height of 12.5 × 20 cm with a thickness of 0.2 cm. The plate submerged in the solution was 14 cm (resulting in a total anode surface of 0.0175 m^2). The plates were arranged horizontally in the direction of mine water flow into the reactor. The plates were mounted in a frame with a distance of 3 cm. The DC electricity supply and measuring electricity equipment were the same as those used (Abfertiawan et al., 2023). Observations were made in beaker glass after 60 minutes of settling time. Discharge variations of 0.3, 0.5, and 0.7 L/min with current densities of 16.3, 19, and 21.7 A/m^2 were conducted as the initial stage of the continuous flow study.

***Table 1** Characteristics of the raw mine water*

Parameters	Value	Unit
pH	7.46	µS/cm
Conductivity	905	mV
ORP	-43.88	mg/L
Total Suspended Solid (TSS)	15,730	mg/L
Total Dissolved Solid (TDS)	440.3	mg/L
Total Iron (Fe)	14.65	mg/L

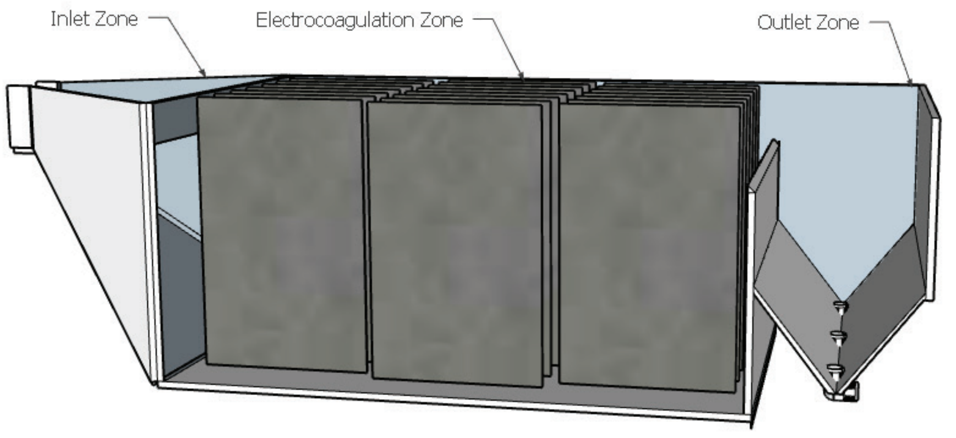

Figure 1 *Reactor Illustration in 3D*

Conventional chemical coagulation was also conducted using the jar test method as a comparison with electrocoagulation. The coagulants used were $Al_2(SO_4)_3$, Poly Aluminium Chloride, and Polyacrylamide, with a 400–700 mg/L dosage range. The total suspended solid parameter was analyzed after rapid mixing at 120 rpm for 1 minute and slow mixing at 60 rpm for 20 minutes. In this study, the total suspended solid was measured with a Total Suspended Solid (TSS) meter calibrated by the gravimetric method. In addition to Total Suspended Solid (TSS) parameter measurements, total Fe measurements were taken using Atomic Absorption Spectrophotometry (AAS). Before being tested using AAS, the sample was given a mixture of nitric acid and hydrochloric acid to dissolve all suspended solids.

Results and Discussion

In experiments with electrocoagulation, it was found that the results with the highest removal were in the variation of discharge 0.3 L/min and current density of 16.3 A/m^2. In this variation, colloidal clay was removed by 99.87% from the initial concentration of 15,000 mg/L to 17 mg/L. This occurs due to the Al^{3+} ions produced from the anode neutralize the charge of particles. In addition, Al^{3+} ions can bind with OH^- to form $Al(OH)_{3\,(s)}$ precipitates. This precipitate forms a sludge blanket and eventually entraps colloidal particles. This mechanism is also called sweep coagulation (Moussa et al., 2017).

Discharge is closely related to the contact time between the water and the coagulants produced in situ by the electrodes. The longer

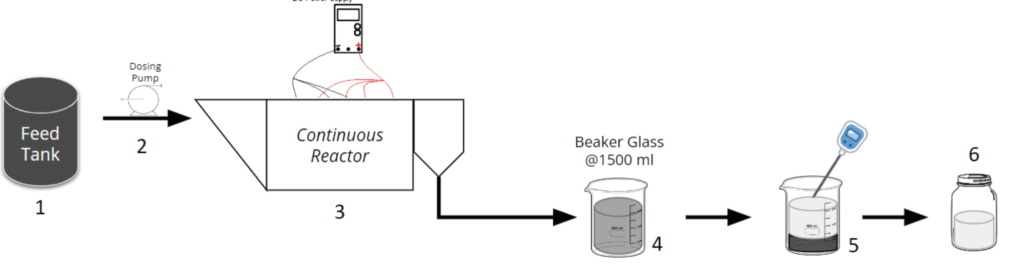

Figure 2 *Continuous Electrocoagulation Scheme (1) Feed tank; (2) Dosing pump; (3) Continuous reactor; (4) Beaker glass for settling process; (5) Measurement of Total Suspended Solid (TSS) Concentration after 60 minutes of settling time; (6) Supernatant was separated to measure total iron*

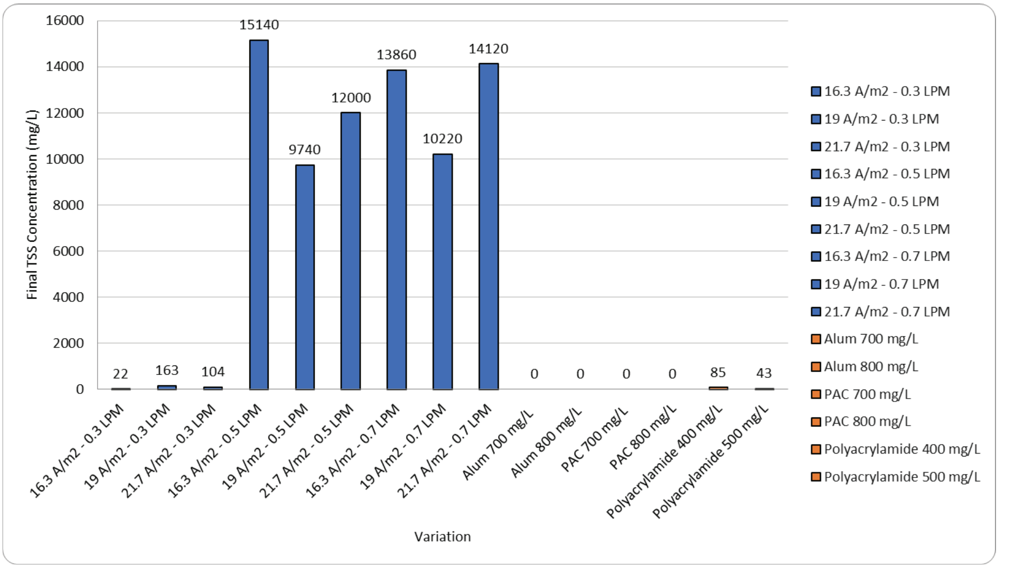

Figure 3 *Final Total Suspended Solid (TSS) Concentration (mg/L) with Electrocoagulation (blue bars) and Conventional Chemical Coagulation (orange bars) with initial Total Suspended Solid (TSS) Concentration of 15,000 mg/L*

the contact time, the better the coagulation (Moussavi et al., 2011). Based on Fig. 3, it is found that the variations of 0.5 and 0.7 L/min have not been able to remove colloidal clay. This is because the discharge entering the reactor is too much, so it does not provide sufficient time for the coagulation process. Furthermore, the electrodes are laid horizontally, creating the potential for short retention time. This results in a lack of contact time between the mine water and the coagulants, so coagulation cannot be maximized.

In removing total iron (Fe), the highest removal was in the variation of 0.3 L/min and a current density of 16.3 A/m². Total iron (Fe) was removed by 93% from 14.65 mg/L to 0.9 mg/L. In this study, it was found that iron removal is in line with colloidal clay removal. This proves that iron (Fe) contained in coal mine water has the characteristics of being contained in clay minerals and not dissolved in water. For conventional chemical coagulation. the highest removal of colloidal clays occurred using 700 mg/L of $Al_2(SO_4)_3$, 700 mg/L of Poly Aluminium Chloride, and 500 mg/L of Polyacrylamide, with each removal percentage reaching up to 99%. The conventional chemical coagulation process results can be the basis for future research on comparing operational cost analysis between conventional chemical coagulation and electrocoagulation for colloidal clay removal in mine water treatment plants.

One of the factors affecting the electrocoagulation process is the reactor design (López-Guzmán et al., 2021). The electrocoagulation experiment in this study is shown in Fig. 5. There is a dead zone where the floc tends to settle in the continuous reactor tank. Dead zone causes mass transfer to be disrupted and the electrocoagulation process is not optimal. Further research is needed on cell geometry and reactor design suitable for mine water with high colloidal clay content. This research is expected to be a key step in determining the design criteria of electrocoagulation to develop scale-up efforts in the field.

Conclusions

Continuous electrocoagulation to remove colloidal clay in surface runoff is closely related to the discharge and current density. The discharge will affect the contact time of the mine water with the electrode. The longer the contact time, the coagulant can react

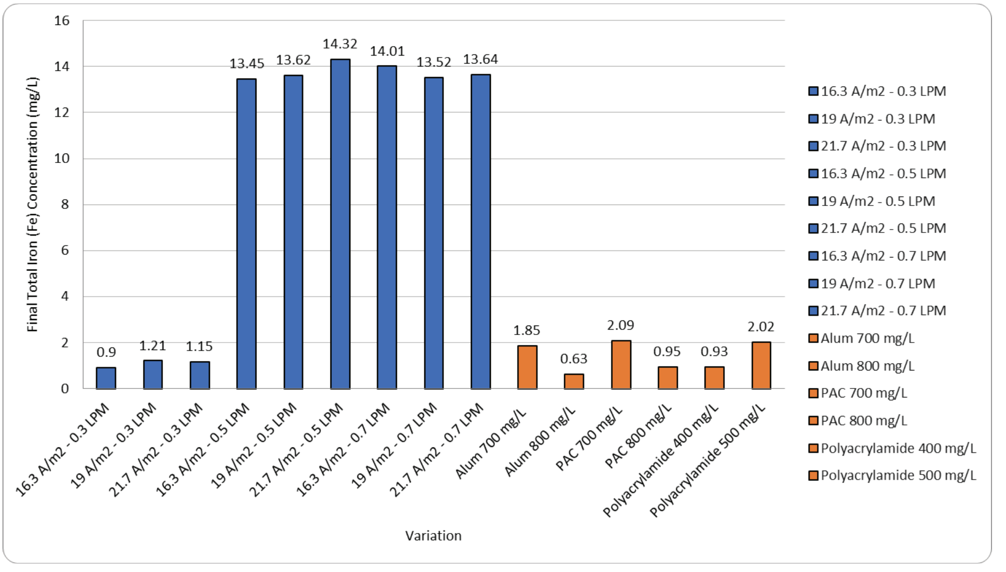

Figure 4 Final Total Iron (Fe) Concentration (mg/L) with Electrocoagulation (blue bars) and Conventional Chemical Coagulation (orange bars) with initial Total Iron (Fe) Concentration 14`.65 mg/L

perfectly with mine water. In this study, the largest removal was obtained in the variation of 0.3 L/min with a current density of 16.3 A/m^2. Colloidal clay that was removed was 99.87%. The removal of total iron (Fe) in this study is in line with the removal of colloidal clay/suspended solid, at the same variation the iron (Fe) removal obtained is 93% from 14.65 mg/L to 0.9 mg/L. Electrocoagulation technology in the removal of colloidal clay in mine water has the potential to be scaled up to field scale, but several design criteria issues need to be resolved such as cell geometry, reactor design, and cost analysis. Therefore, electrocoagulation research still requires exploration to find the optimum design to meet the challenges of scale-up in the field.

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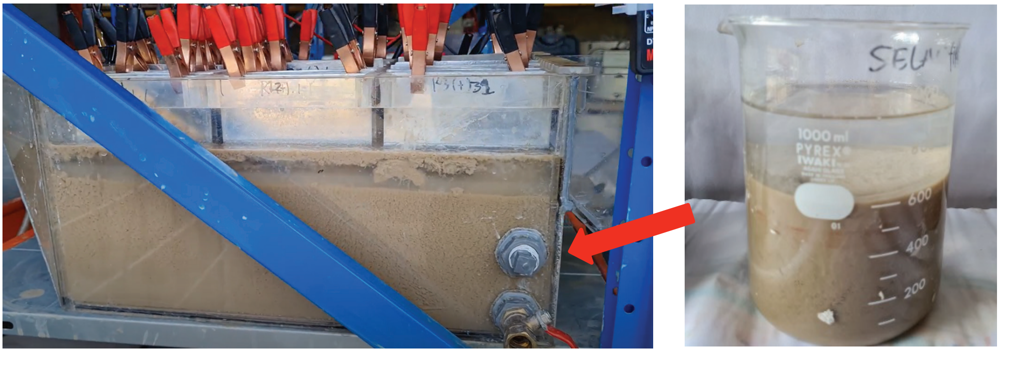

Figure 5 Continuous Electrocoagulation Experiment (a) dead zones in reactor (b) Electrocoagulation after 60 min of settling time in 16.3 A/m^2 – 0.3 L/min

References

Abfertiawan, M. S., Gautama, R. S., Kusuma, S. B., & Notosiswoyo, S. (2016). Hydrology Simulation of Ukud River in Lati Coal Mine. Evergreen, 3(1), 21–31. https://doi.org/10.5109/1657737

Abfertiawan, M. S., Hasan, F., Handajani, M., Syafila, M., Gunawan, F., Djali, F., Stanley, P. (2023). High Total Suspended Solid (TSS) Removal for Coal Mining Water Using Electrocoagulation.

Badan Pusat Statistik Republik Indonesia. (2022). Statistical Yearbook of Indonesia 2022.

Jourgholami, M., Fathi, K., & Labelle, E. R. (2018). Effects of foliage and traffic intensity on runoff and sediment in skid trails after trafficking in a deciduous forest. European Journal of Forest Research, 137(2), 223–235. https://doi.org/10.1007/s10342-018-1102-7

Keesstra, S., Pereira, P., Novara, A., Brevik, E. C., Azorin-Molina, C., Parras-Alcántara, L., Jordán, A., & Cerdà, A. (2016). Effects of soil management techniques on soil water erosion in apricot orchards. Science of The Total Environment, 551–552, 357–366. https://doi.org/10.1016/j.scitotenv.2016.01.182

Kirkby, M. (2002). Modelling the interactions between soil surface properties and water erosion. CATENA, 46(2–3), 89–102. https://doi.org/10.1016/S0341-8162(01)00160-6

Lestari, S., King, A., Vincent, C., Karoly, D., & Protat, A. (2019). Seasonal dependence of rainfall extremes in and around Jakarta, Indonesia. Weather and Climate Extremes, 24, 100202. https://doi.org/10.1016/j.wace.2019.100202

Li, J., Luo, B., Wei, X., Ci, E., Ni, J., Wei, C., & Zhong, S. (2023). Transportation of fine particles controlled by particles flocculation is a key feature of soil erosion on gentle slope land. CATENA, 232, 107382. https://doi.org/10.1016/j.catena.2023.107382

López-Guzmán, M., Flores-Hidalgo, M. A., & Reynoso-Cuevas, L. (2021). Electrocoagulation Process: An Approach to Continuous Processes, Reactors Design, Pharmaceuticals Removal, and Hybrid Systems – A Review. Processes, 9(10), 1831. https://doi.org/10.3390/pr9101831

Moussa, D. T., El-Naas, M. H., Nasser, M., & Al-Marri, M. J. (2017). A comprehensive review of electrocoagulation for water treatment: Potentials and challenges. Journal of Environmental Management, 186, 24–41. https://doi.org/10.1016/j.jenvman.2016.10.032

Moussavi, G., Khosravi, R., & Farzadkia, M. (2011). Removal of petroleum hydrocarbons from contaminated groundwater using an electrocoagulation process: Batch and continuous experiments. Desalination, 278(1–3), 288–294. https://doi.org/10.1016/j.desal.2011.05.039

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). Soil and water assessment tool theoretical documentation version 2009. Texas Water Resources Institute.

Nur'utami, M. N., & Hayasaka, T. (2022). Interannual Variability of the Indonesian Rainfall and Air–Sea Interaction over the Indo–Pacific Associated with Interdecadal Pacific Oscillation Phases in the Dry Season. Journal of the Meteorological Society of Japan. Ser. II, 100(1), 2022–004. https://doi.org/10.2151/jmsj.2022-004

Qiao, P., Wang, S., Li, J., Zhao, Q., Wei, Y., Lei, M., Yang, J., & Zhang, Z. (2023). Process, influencing factors, and simulation of the lateral transport of heavy metals in surface runoff in a mining area driven by rainfall: A review. Science of The Total Environment, 857, 159119. https://doi.org/10.1016/j.scitotenv.2022.159119

Yao, Y., Dai, Q., Gao, R., Gan, Y., & Yi, X. (2021). Effects of rainfall intensity on runoff and nutrient loss of gently sloping farmland in a karst area of SW China. PLOS ONE, 16(3), e0246505. https://doi.org/10.1371/journal.pone.0246505