ZIBELINE INTERNATIONAL™ PUBLISHING

Water Conservation & Management (WCM) *DOI: http://doi.org/10.26480/wcm.04.2025.653.665*

ISSN: 2523-5664 (Print)
ISSN: 2523-5672 (Online)
CODEN: WCMABD

CrossMark

RESEARCH ARTICLE

LEACHING COLUMN SIMULATION OF ACID MINE DRAINAGE POTENTIAL FROM OVERBURDEN ROCKS OF THE SAWAHLUNTO FORMATION OMBILIN BASIN AND NEUTRALIZATION STUDY USING VERTICAL PASSIVE SYSTEM

Heri Prabowo*, Arif Algifari, Fitri Nauli, Wahyuda Pratama, Aisya Amini

Mining Engineering Department, Faculty of Engineering Universitas Negeri Padang, Indonesia
**Corresponding Author Email: heri.19782000@ft.unp.ac.id*

Article History:

Received 11 August 2025
Revised 21 September 2025
Accepted 17 October 2025
Available online 12 November 2025

ABSTRACT

Acid Mine Drainage (AMD) is a persistent environmental issue in coal mining regions, characterized by high acidity and elevated dissolved metal concentrations. Overburden materials play a key role in AMD generation, particularly in the coal-bearing Sawahlunto Formation of the Ombilin Basin, West Sumatra. This study aimed to evaluate the AMD potential of various overburden rock samples through column leaching tests and to assess the neutralization performance of a vertical passive fixed-bed system using different alkaline materials. Leaching tests classified the overburdens of Kandi, Batu Tanjung, and Sikalang as Non-Acid Forming (NAF) with Net Acid Producing Potential (NAPP) values of −0.49, −3.74, and −0.04 kg H_2SO_4/ton, respectively. In contrast, the overburdens of Salak 1, Salak 2, and Salak 3 were Potentially Acid Forming (PAF) with NAPP values of 8.87, 0.25, and 0.76 kg H_2SO_4/ton. Column leaching experiments using selected samples packed in a fixed bed and fed with water at pH 8.5 yielded average effluent pH values of 6.26 (Kandi), 3.54 (Salak 1), and 6.10 (Batu Tanjung), with corresponding total dissolved solids of 442 ppm, 731.4 ppm, and 149 ppm. Neutralization tests using CaO and Silungkang and Kubang limestones produced effluent pH values ranging from 5 to 12.4, with calcium conversions of 23.98%, 47.4%, and 27.77%, respectively. The results indicate that AMD generation is strongly influenced by the mineralogical composition of the overburden, while neutralization performance varies with the type and reactivity of the alkaline medium. System design optimization considering bed height, particle size, and flow rate is recommended to achieve effective AMD control. Further scaling-up studies are essential to ensure the sustainable application of passive neutralization systems in coal mining operations, particularly in sump water treatment.

KEYWORDS

Acid Mine Drainage, Column Leach Test, PAF, NAF, Passive Neutralization.

1. INTRODUCTION

During the past years, The Ombilin Basin, located in West Sumatra, Indonesia, is one of the country's historically significant coal mining regions, active today through both underground and open-pit methods. Geographically, it lies in the western part of the Central Sumatra Basin, approximately 90 km northeast of Padang City and is accessible by land routes. The coal deposits in this area originate from the Sawahlunto Formation which contains three major coal seams with relatively wide distribution (Algifari et al., 2023). Open-pit mining operations, in particular, expose overburden and interburden layers composed of sandstone, claystone, and shale with brown to greenish-gray coloration. The excavation and exposure of these coal and overburden to the atmosphere may lead to several environmental impacts, which poses major concerns in the Sawahlunto coalfield.

One of the major environmental concerns associated with these mining activities is the potential formation of Acid Mine Drainage (AMD). AMD is not only a chemical problem but also a hydrogeological one, as its generation, transport, and dispersion are closely linked to the site's hydrological and hydrogeological conditions. The interaction between rainfall, surface runoff, and groundwater flow determines how oxygen and water infiltrate sulfide-bearing rocks, influencing both the rate and extent of pyrite oxidation. Once formed, acidic water can migrate through fractures and permeable strata, contaminating nearby streams, groundwater, and surrounding ecosystems.

When rock layers containing sulfide minerals primarily pyrite FeS_2 are exposed to atmospheric oxygen and water during excavation (Maltrana and Morales, 2023). The oxidation of sulfide minerals produces sulfuric acid H_2SO_4 and ferric hydroxide $Fe(OH)_3$ precipitates (Algifari et al., 2024), as represented by the following reactions:

$$FeS_2 + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$

$$Fe^{2+} + 0.25O_2 + H^+ \rightarrow Fe^{3+} + 0.5H_2O$$

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3\,H^+$$

$$FeS_2 + 3.75O_2 + 3.5\,H_2O \rightarrow Fe(OH)_3 + 2SO4^{2-} + 4H^+$$

The oxidation of pyrite into $Fe(OH)_3$ and H_2SO_4 is an exothermic and spontaneous process, as the energy released from FeS_2 and Fe^{2+} oxidation,

Quick Response Code	Access this article online	
	Website: www.watconman.org	**DOI:** 10.26480/wcm.04.2025.653.665

Cite The Article: Heri Prabowo, Arif Algifari, Fitri Nauli, Wahyuda Pratama, Aisya Amini (2025). Leaching Column Simulation Of Acid Mine Drainage Potential From Overburden Rocks Of The Sawahlunto Formation Ombilin Basin And Neutralization Study Using Vertical Passive System. Water Conservation & Management, 9(4): 653-665.

along with $Fe(OH)_3$ precipitation, decreases the system's free energy. This reaction leads to the generation of highly acidic water with a pH typically ranging from 3 to 4, as reported by Har et al. In their study of AMD in the Sawahlunto area (Har et al., 2025). The problem intensifies during heavy rainfall, which accelerates the leaching of oxidation products and increases the rate of AMD formation.

The overburden and interburden in Sawahlunto underground and open-pit mining, may particularly contained sulfide minerals such as pyrite, are reactive when exposed to air and water. Continuous mining activities and tropical climatic conditions with high rainfall make Sawahlunto particularly vulnerable to AMD generation and subsequent contamination of surface and groundwater systems. Therefore, studying AMD formation in Sawahlunto is important, not only to understand the acid-producing potential of its overburden rocks but also to develop effective neutralization and mitigation strategies tailored to the local geological and hydrological conditions. The findings will contribute to sustainable mine water management and the long-term environmental protection of the Ombilin Basin.

This study emphasizes the importance of identifying Potentially Acid Forming (PAF) and Non-Acid Forming (NAF) rocks at multiple mining sites surrounding the Sawahlunto Formation. Such assessment, based on the Net Acid Producing Potential (NAPP) method to estimates AMD generation potential by comparing the acid-producing capacity derived from total sulfur content (Binnemans and Tom, 2023; X. Li et al., 2020). This against the neutralization potential contributed by calcium and magnesium-bearing minerals (Hamanaka et al., 2024). Rocks are categorized as PAF when their acid-producing potential exceeds their neutralizing capacity, and as NAF when the reverse condition occurs (Kusi et al., 2024). This classification provides essential baseline data for predicting AMD risks and for designing appropriate passive treatment and prevention strategies in the Sawahlunto coalfield.

To date, AMD neutralization has generally been conducted using batch methods, as demonstrated by Fadhilah et al. Where fly ash, bottom ash, and lime were added directly into acidic water and subsequently mixed (Fadhilah et al., 2022). However, this approach presents limitations in terms of mixing uniformity and efficiency. As an alternative, Rusli developed a passive treatment system with a horizontal configuration at a 5–9° slope, utilizing media such as zeolite, limestone ($CaCO_3$), fly ash, lime, and sand. In this system, acid water is introduced from the upper end, flows through the interstitial spaces between the neutralizing materials, and exits as neutralized water at the lower end (Har et al., 2025). In addition, previous studies employing constructed wetland methods have successfully reduced Fe and Mn concentrations, increased pH, and lowered TSS levels, resulting in treated water that meets wastewater quality standards (Prabowo et al., 2019).

The success of these passive treatment technologies provides a strong basis for further development of passive AMD neutralization systems. However, most previous studies have focused on horizontal-flow or batch configurations, while the performance of vertical-flow systems remain underexplored. Building upon this gap, the present study introduces a vertical-flow passive neutralization system, in which acid water percolates downward through a packed bed of neutralizing materials such as CaO and limestone sourced from the Silungkang and Tuhur Formations the lowermost stratigraphic units of the Ombilin Basin. The effluent is collected at the bottom, where gravity-driven vertical percolation is expected to enhance the contact between water and neutralizing media, thereby improving treatment effectiveness.

A channel filled with limestone enables acid water to come into contact with calcite and quictlime, thereby increasing pH naturally. The passive open limestone and CaO channel method, one of the approaches for managing acid mine drainage, utilizes limestone and CaO as the neutralizing medium. Limestone and CaO is placed along the channel, where it dissolves upon contact with acid water and contributes alkalinity, which is essential for raising the water's pH (Ananda, 2024). The reaction between CaO or $CaCO_3$ and H_2SO_4 produces $CaSO_4$, CO_2, and H_2O is both exothermic and spontaneous due to the formation of sulfate salts and water accompanied by heat release (Algifari et al., 2024).

$$CaO + H_2SO_4 \rightarrow CaSO_4 + H_2O$$

$$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + CO_2 + H_2O$$

However, despite the widespread use of limestone-based systems for AMD treatment, the specific leaching and neutralization behavior of overburden rocks from the Sawahlunto Formation has not been comprehensively studied, particularly under realistic flow and rainfall conditions. The typical characteristics of PAF and NAF from Sawahlunto's overburden and interburden rocks have not yet been clearly identified, and the properties of the acid water generated during leaching remain poorly understood, especially in relation to leaching rates that reflect the average rainfall over the past five years in the region. Another critical knowledge gap lies in determining the minimum water flow required for efficient neutralization within passive beds using CaO and local limestones from the Silungkang and Tuhur Formations. Furthermore, the actual design parameters such as bed mass and flow capacity needed to effectively treat acid water at the sump inlet have not been accurately estimated using site-specific hydrological data from mining operations. Therefore, this study aims to evaluate the AMD generation potential of overburden rocks from the Sawahlunto Formation and to assess the neutralization performance of vertical passive systems using CaO and locally sourced limestones. The specific objectives are to (1) characterize the acid-forming potential of overburden rocks through NAPP, Maximum Potential Acidity (MPA), and Acid Neutralizing Capacity (ANC) analyses to classify them as PAF or NAF; (2) simulate AMD generation using leaching column experiments under controlled flow and pH conditions that represent natural rainfall scenarios; (3) evaluate the neutralization efficiency of CaO and limestones from the Silungkang and Tuhur Formations under varying flow rates; and (4) estimate the required material quantities for scaling up the vertical passive system to field-level applications in the Sawahlunto open-pit coal mines. This integrated approach bridges laboratory-scale characterization with practical design considerations, providing a strong scientific basis for developing sustainable AMD mitigation strategies tailored to the geological and hydrological conditions of the Ombilin Basin.

Wastewater, including acid mine drainage, must comply with environmental quality standards before being discharged into water bodies or the surrounding environment. One of the main requirements is that the acidity level must fall within a safe range, with a minimum pH of 6.5 according to WHO standards to prevent acidic conditions that could damage aquatic ecosystems (Saalidong et al., 2022). In addition, WHO specifies that the concentration of total dissolved solids should not exceed 500 ppm to avoid negative impacts on both groundwater and surface water quality (Mohammed et al., 2020). The treated water must also be odorless, tasteless, and colorless to ensure it is environmentally safe and does not disrupt biotic life or human activities nearby. Meeting these standards serves as a key indicator of the effectiveness of wastewater treatment processes before discharge into the environment. Therefore, understanding and investigating appropriate treatment methods for acid mine drainage is crucial to ensure that effluent water meets these quality thresholds, safeguarding environmental sustainability and compliance with regulatory standards.

2. Material And Methods

2.1 Research Design and Location

This study combines laboratory simulation and field data analysis to evaluate the AMD generation potential of overburden rocks and to assess the performance of a vertical passive neutralization system using quicklime and local limestones from the Silungkang and Tuhur Formations. The research was conducted at the Chemistry Laboratory, Department of Mining Engineering, Universitas Negeri Padang, while field data and rock samples were obtained from coal mining areas in Sawahlunto, West Sumatra located approximately 90 km northeast of Padang City, within the western part of the Central Sumatra Basin.

2.2 Materials and Sampling

Nine rock samples were collected, including six overburden samples from the Sawahlunto Formation and three neutralizing materials are CaO, Silungkang limestone, and Kubang limestone. Overburden samples were taken from Kandi, Batu Tanjung, Sikalang, and Salak areas, as shown in Figure 1. Limestones were obtained from Silungkang Subdistrict and Kubang Tengah, Lembah Segar Subdistrict, while CaO was sourced commercially. The overburden were crushed and sieved to a particle size below 6.3 mm following ASTM D5744-18 for laboratory weathering simulation (Uni et al., 2024).

2.3 Acid-Forming Potential Analysis

Each sample was analyzed using X-Ray Fluorescence to determine its elemental composition. The Net Acid Producing Potential was calculated empirically using the formula (Hamanaka et al., 2024):

$$NAPP = MPA - ANC$$

where Fe and S represent acid-forming components Maximum Potential Acidity, and Ca and Mg represent neutralizing components or Acid

Neutralizing Capacity. Samples were classified as Potentially Acid Forming if MPA > ANC, or Non-Acid Forming if ANC > MPA (Kusi et al., 2024).

2.4 Leaching Column Simulation

To simulate AMD generation under rainfall conditions, a leaching column experiment was performed. The columns were made of 14 cm PVC cylinders and 28 cm height (see Figure 13) equipped with bottom drainage outlets and a leachate collection container. Artificial rainwater (pH ≈ 8.5) was sprinkled onto the columns three times daily to simulate the average rainfall intensity of the Sawahlunto area over the past five years. The applied discharge was calculated using:

$$Q = A \times I$$

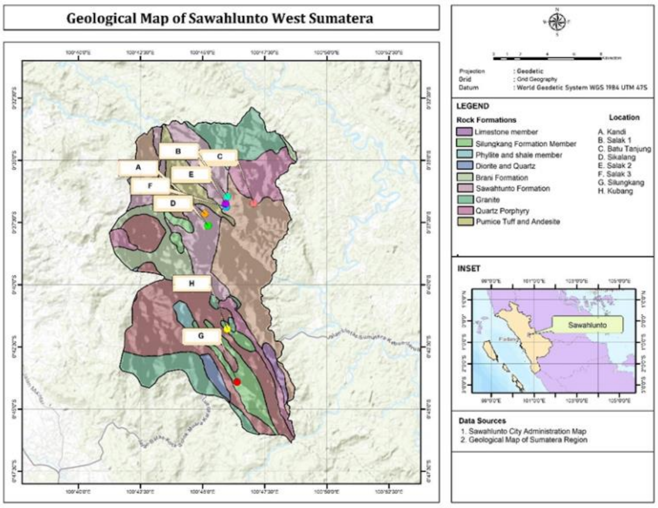


Figure 1: Geological map of research in Sawahlunto West Sumatera

The calculation of water discharge in the leaching experiment of sulfide-bearing overburden rocks was based on rainfall data for Sawahlunto over the past five years, as reported by Atanay (Septelina Naomi Kamano Atanay, 2024). The discharge of rainfall applied to the leaching column was determined using the equation Q = A × I, where A is the catchment area and I is the rainfall intensity. Based on this calculation, the discharge was obtained as 154 cm^2 × 0.826 cm/h = 127 cm^3/h, which is equivalent to 127 mL/h. In this case, the catchment area of 154 cm^2 represented the cross-sectional area of the leaching column, while the value of 0.826 cm/h was derived from secondary rainfall intensity data. The leachate was then analyzed for several key parameters. Chemical parameters included pH measurement using a digital pH meter to determine acidity levels, and analysis of Total Dissolved Solids to quantify dissolved solids content. Additional analyses were conducted using X-Ray Fluorescence before and after leaching to identify changes in elemental composition, expressed as leaching conversion for sulphur, iron, and calcium. Moreover, physical parameters such as ambient temperature were also recorded as supporting factors in the interpretation of leaching results. The conversion percentage of each element was calculated as:

$$\%\ \text{Component conversion} = \left(\frac{\%\ \text{Initial grade} - \%\ \text{final grade}}{\%\ \text{Initial grade}}\right) \times 100\%.$$

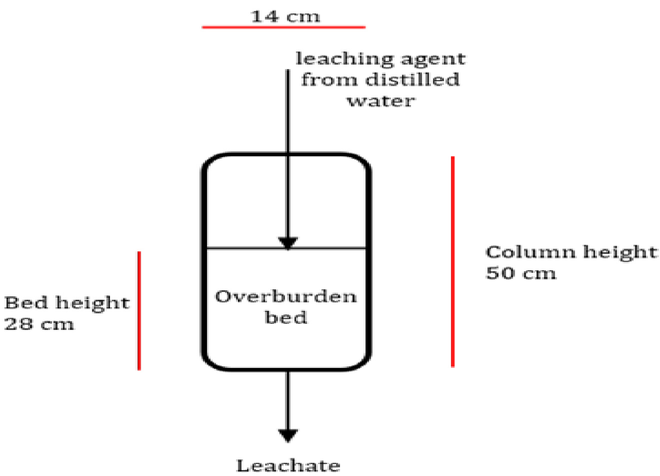


Figure 2: Schematic of column leaching test equipment

2.5 Passive Neutralization Simulation

Following the leaching test, neutralization experiments were conducted using a vertical fixed-bed system (Figure 3). The setup consisted of a separatory funnel regulating the inflow of acidic water, which then passed downward through a packed bed of neutralizing material are CaO, Silungkang limestone, or Kubang limestone contained in a glass funnel. The effluent was collected in a beaker for measurement. Each run used 10 g of neutralizing material with six successive feedings of 100 mL synthetic acidic water contained H2SO4 (pH ≈ 4) under low, medium, high flow rates, yielding nine total trials. Effluent pH and TDS were monitored for each condition, and XRF analysis of the solid media before and after the experiment was conducted to assess Ca and Mg depletion.

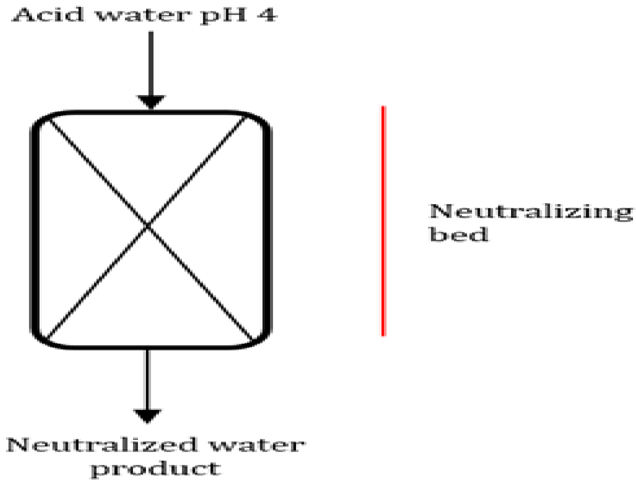


Figure 3: Schematic of passive neutralization fixed-bed for acid mine drainage treatment

2.6 Scale-Up and Simulation to Field Conditions

A scaling simulation was then performed to estimate the material requirements for treating actual mine water at Sawahlunto's open-pit sump, which discharges approximately 496.8 m^3/h h (Septelina Naomi Kamano Atanay, 2024). Based on laboratory results, regression analysis was applied to determine the minimum neutralization flow rate and the corresponding material mass required for effective pH adjustment and compliance with wastewater standards. The estimated material needs were calculated for CaO and both limestone sources to guide field-scale passive system design.

3. Results

3.1 Characterization of Overburden and Neutralizing Rocks

In the context of mining, overburden refers to the layer of soil or rock that directly covers mineral resources such as coal, metallic ores, or other valuable minerals, and must be removed prior to extraction (Qin et al., 2024). In other words, direct overburden rock is the covering material located immediately above the targeted mineral deposit. Overburden rocks from the Sawahlunto Formation, collected from the Kandi, Salak, Sikalang, and Batu Tanjung areas, generally exhibit similar physical characteristics, consisting of claystone with a greenish-gray color. This coloration indicates the presence of clay silicate materials commonly found in coal overburden layers within the Ombilin Basin. In contrast, overburden rocks from the Salak area display distinct features in the form of layered metasedimentary shale with a yellowish-brown color, suggesting more advanced alteration or weathering processes and a potentially higher sulfide content due to mineralogical transformations during geological processes.

In the coal mining process, soil excavation is carried out to access the coal seams. The first layer removed prior to the overburden is the topsoil, which is stockpiled in soil banks for reclamation purposes. The overburden material is then stripped and either deposited in disposal areas or used for backfilling mined-out pits. Overburden may contain sulfide minerals, which, when exposed to air and water, can generate acidic conditions through the oxidation of sulfide compounds (Algifari et al., 2024). For acid mine drainage neutralization, neutralizing rocks from the Silungkang Formation consist predominantly of calcite and metacalcite, exhibiting a whitish-yellow color and occurring within grayish karst formations. These karst rocks are presumed to be eroded andesite and granite subsequently infilled by calcite veins.

3.1.1 Overburden from Kandi Area

The overburden in the Sawahlunto Formation within the Kandi area is dominated by claystone, which is physically characterized by its greenish-gray color, fine texture, and distinct layered structure. Outcrops of this rock are exposed on road cuts near a former coal mine reclamation area, making them easily accessible and identifiable directly in the field.

Figure 4: Overburden rock sampling at Kandi area

3.1.2 Overburden from Salak 1 Area

The overburden in the Sawahlunto Formation, Salak 1 area, is dominated by shale, characterized by its fine-grained texture and laminated structure. In the field, this rock commonly appears yellowish to brown in color. However, upon closer inspection, a grayish hue the original color of shale can be observed. The yellow to brown coloration on the surface results from iron oxide coating the rock. A shale sample used in this study from the Kandi area was collected at the edge of a former open-pit mine in Salak.

Figure 5: Overburden rock sampling at Salak 1 area

3.1.3 Overburden from Batu Tanjung Area

The overburden in the Sawahlunto Formation at Batu Tanjung exhibits characteristics similar to that of the Kandi area, being dominated by claystone with physical features of grayish green color, fine texture, and well laminated structure. The overburden sample from Batu Tanjung was collected from a drainage ditch located along the mine access road leading to the Parambahan area. This ditch functions as a surface water channel, which generally remains dry during the dry season but fills with water during the rainy season. Such conditions suggest that natural leaching by rainwater has already occurred, resulting in the mobilization of metals and the partial depletion of acid-forming potential within the rock.

Figure 6: Overburden rock sampling at Batu Tanjung area

3.1.4 Overburden from Sikalang Area

The overburden identified at the periphery of the open-pit mine in the Sikalang-Kandi area is predominantly composed of shale. This lithology is characterized by its gray coloration, well-laminated structure, and a distinctive tendency to fracture easily into thin plates.

Figure 7: Overburden rock sampling at Sikalang area

3.1.5 Overburden from Salak 2 Area

The overburden rock sampled from the Salak 2 site, Sawahlunto, is located at the edge of the open-pit mining area in Salak. This rock is classified as clay with a fine texture, characterized by its friable nature and dark gray color.

Figure 8: Overburden rock at the Salak 2 area

3.1.6 Overburden from Salak 3 Area

The overburden rock collected from the Salak 3 site in Sawahlunto, located at the edge of the open-pit area, is classified as clay with a fine texture. It is characterized by its friable nature and a grayish-green color.

3.1.7 Limestone from Silungkang

Silungkang limestone was obtained from Batu Runcing in the Silungkang area, which belongs to the Silungkang Formation, the Permian volcanics rock (Algifari et al., 2023). This formation represents one of the lowermost stratigraphic units, overlying the Kuantan Formation, and serves as part of the basement of the Ombilin Basin. Based on geological studies, the Silungkang Formation was deposited on igneous rocks consisting of granite and andesite. Due to marine sedimentation processes, significant calcium carbonate deposits were formed, as evidenced by the presence of calcium carbonate infilling fractures within the igneous rocks and the discovery of several shell fossils. In this study, Silungkang limestone samples were collected from surface fragments that had already detached and were used as one of the neutralizing materials for acid mine water. Macroscopically, the rock appears white to gray in its fresh state, whereas weathered samples exhibit a cream to brownish coloration, likely due to surface weathering and contamination with soil. Silungkang limestone is characterized by its very hard, coarse texture and resistance to breakage.

Figure 9: Overburden rock sampling at Salak 3 area

Figure 10: Silungkang limestone

3.1.9 Limestone from Kubang

The Kubang limestone was obtained from the Kubang area, Sawahlunto, and belongs to the Tuhur Formation were intruded by granites and granodiorites with quartzites and slates/argirite, which is located adjacent to the Silungkang Formation. This formation of Triassic sedimentary stata contains a high proportion of calcium carbonate and was deposited in a marine environment, as evidenced by the presence of shell fossils found at several research sites. In this study, Kubang limestone samples were collected and used as one of the materials for neutralizing acid mine water. Macroscopically, the Kubang limestone is bluish-gray in color, has a coarse texture, and is very hard, making it difficult to break. In weathered sections, the rock exhibits a reddish-brown coloration, while loose rock samples display a brownish hue as a result of the weathering process.

Figure 11: Kubang limestone

3.1.10 Quicklime

Quicklime is a naturally occurring material, typically white in color, formed from sedimentary rocks with a fine texture. Chemically, quicklime is composed of CaO. In this study, the quicklime used was a commercial product labeled MERC and served as one of the materials for neutralizing acid mine drainage. A detailed depiction of the characteristics of this limestone is presented in the following figure.

Figure 12: Quicklime

3.2 Composition of Overburden and Neutralizing Rock

Based on XRF data, the overburden in Sawahlunto on Kandi, Salak, Batu Tanjung, and Sikalang shows a dominance of silicate minerals with Al contents of 7–12% and Si 22–28%, low to moderate Fe 0.66–4.18%, very low S 0.03–0.29%, Ca 0.01-0.19%, and almost Mg. As a result, its acid-neutralizing capacity is low, and it has the potential to generate acid mine drainage, particularly in samples with higher S contents. In contrast, limestone from Silungkang and Kubang contains high Ca, at 12.91% and 32.89% respectively, with low or negligible Mg, moderate Fe, and low Si, confirming the dominance of carbonates and their effectiveness as acid-neutralizing agents. Commercial quicklime, with 66.35% Ca, represents the purest and most optimal CaO source for neutralization. Other minor elements such as Ti, V, Cr, Mn, and Co are present in very low concentrations and have no significant effect on the rock's chemical properties or on the leaching and neutralization processes.

Table 1: Major elemental composition of overburden and neutralizing rocks determined by XRF analysis

Rock samples	Grades of Component (%wt)										
	Al	Si	S	Fe	Mg	Ca	Ti	V	Cr	Mn	Co
Kandi	7.47	22.15	0.04	2.91	0	0.07	0.41	0	0.01	0.01	0
Salak 1	7.04	25.82	0.29	0.66	0	0	0.48	0	0.01	0.00	0
Batu Tanjung	9.56	22.92	0.03	4.18	0	0.19	0.38	0	0.01	0.03	0
Sikalang	10.55	24.92	0.03	2.63	0	0.04	0.56	0.02	0.01	0.02	0.01
Salak 2	11.89	27.43	0.05	2.74	0	0.01	0.56	0.02	0.01	0.02	0.01
Salak 3	12.39	28.53	0.05	2.84	0	0.03	0.57	0	0.01	0.03	0.01
Gamping Silungkang	5.64	13.21	0	4.49	1.36	12.91	0.31	0	0.01	0.07	0
Gamping Kubang	3.12	4.09	0.05	2.92	0	32.89	0.25	0	0.01	0.08	0
Quicklime	0.20	0.29	0	0.10	0	66.35	0.16	0	0.01	0.02	0

3.3 Leaching Column Test

Leaching tests were carried out following the ASTM D5744-18 reference method using three assembled leaching columns, as seen on Figure 13, each with a diameter of 14 cm and a bed height of 28 cm, filled with overburden samples from Kandi, Salak 1, and Batu Tanjung, with particle sizes smaller than 6.3 mm. Distilled water with an initial pH of 8.5 and TDS of 8 ppm was used as the leachant. The leaching water flow rate was adjusted to the average rainfall of the past five years in Sawahlunto is 8.26 mm/h, with a catchment area equivalent to a circle of 14 cm in diameter, resulting in a leachant flow rate of approximately 127 mL/h. The experiment was conducted for 7 days, with a water application scheme of 127 mL/h for one hour on the first and second days, and 3 × 127 mL for three hours per day on the third to seventh days. The effluent was collected daily, and its pH and TDS were measured.

After the leaching tests, XRF and XRD analyses were performed on the rock samples before and after leaching to observe the decrease in Fe, S, Ca, and Mg contents as a basis for leaching conversion calculations. XRD was used to monitor mineralogical changes, particularly the reduction in pyrite intensity and possible transformations of other mineral phases during the leaching process. Based on the leachate pH of PAF rocks and reference data of acid mine drainage pH in Sawahlunto, a subsequent passive vertical neutralization test was carried out. Acid water with a pH of 4, prepared by diluting commercial H_2SO_4, was applied vertically amount of 100 mL onto a stationary bed of neutralizing material with a size of 10 mesh, after which the pH and TDS of the effluent were measured. Data analysis of Fe, S, Mg, and Ca contents before and after leaching was conducted to determine the percentage of leaching conversion.

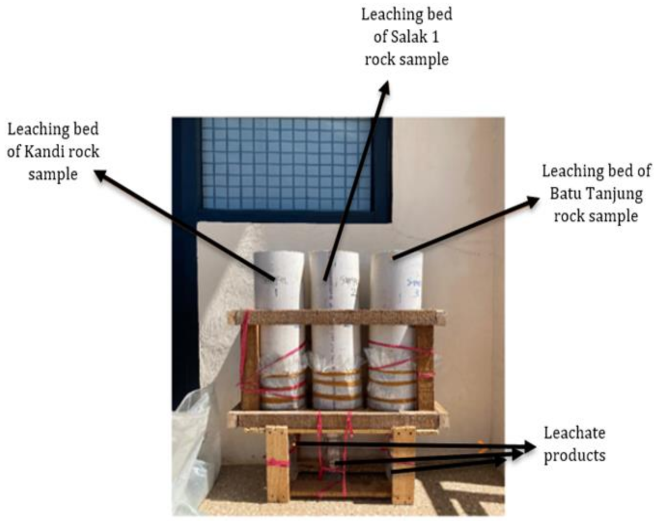


Figure 13: Experimental set up of the column leach test

The leaching columns were constructed from PVC pipe components serving as leaching tubes. At the bottom of each column, a plastic sheet secured with rubber bands was installed to retain the rock samples and prevent them from being flushed out during water feeding. Column 1 was filled with overburden from the Kandi site, Column 2 with samples from Salak 1, and Column 3 with samples from Batu Tanjung. Measurement of pH commenced on Day 3, as all rock samples had been fully wetted by water application during Days 1 and 2 is 1 × 127 mL/day, which facilitated subsequent water infiltration. From Day 3 to Day 7, the leaching rate was increased to 3 × 127 mL/day, resulting in the collection of leachate. As presented in Table 3, 4 and 5, the leachate pH decreased over time, which may be attributed to sulfide oxidation reactions occurring during leaching, as indicated by the observed reductions in sulphur, iron, and calcium contents. The daily leachate pH data from Day 3 to Day 7 are in Figure 16. Meanwhile, the measured leachate volume at Table 2 varied due to evaporation and showed an increasing trend up to Day 7, suggesting that the leaching bed had reached a saturated condition at the end of the experiment.

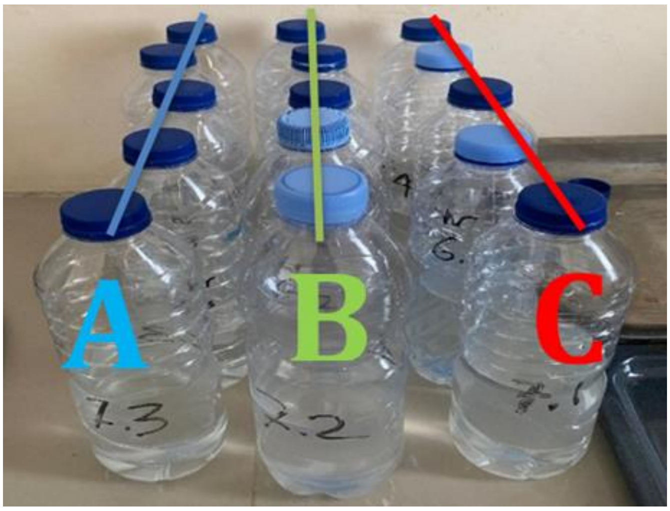


Figure 14: Leachate products: (a) leachate from Kandi overburden, (b) leachate from Salak 1 overburden, and (c) leachate from Batu Tanjung overburden.

The leaching results indicated that the Salak 1 sample was classified as PAF, whereas the Kandi and Batu Tanjung samples were classified as NAF, consistent with the NAPP predictions. This classification is supported by the data in Table 3, 4 and 5, where the leachate pH of the Salak sample ranged between 3 and 4, reflecting the acidic conditions typical of PAF materials. XRF compositional analysis revealed the conversion of Fe, S, and Ca during leaching, indicating the release of these elements into solution. However, certain conversion calculations yielded invalid values, particularly for the Kandi and Batu Tanjung samples, likely due to increased concentrations observed after leaching.

Table 2: Volume of leachate collected from day 1 to day 7.

Days	Inlet water flow Rates	Leachate product volume of Kandi's overburden (ml)	Leachate product volume of Salak 1's overburden (ml)	Leachate product volume of Batu Tanjung's overburden (ml)
1	1x127ml/h/day	-	-	-
2	3x127ml/3h/day	-	-	-
3	3x127ml/3h/day	90	150	90
4	3x127ml/3h/day	190	220	198
5	3x127ml/3h/day	190	200	185
6	3x127ml/3h/day	315	320	310
7	3x127ml/3h/day	310	280	295

The leaching results indicated that the Salak 1 sample was classified as PAF, whereas the Kandi and Batu Tanjung samples were classified as NAF, consistent with the NAPP predictions. This classification is supported by the data in Table 3, 4 and 5, where the leachate pH of the Salak sample ranged between 3 and 4, reflecting the acidic conditions typical of PAF materials. XRF compositional analysis revealed the conversion of Fe, S, and Ca during leaching, indicating the release of these elements into solution. However, certain conversion calculations yielded invalid values, particularly for the Kandi and Batu Tanjung samples, likely due to increased concentrations observed after leaching. This phenomenon may be attributed to sampling inaccuracies or heterogeneity of the materials analyzed by XRF, leading to anomalous increases in the concentration of certain minerals that theoretically should have decreased. Overall, the observed trends in pH and elemental conversion support the PAF/NAF characterization; nevertheless, the reliability of some conversion values requires further attention regarding sampling procedures and repeated measurements.

Table 3: Leaching data for overburden rock sample from Kandi area

Days	Ambient temperature (°C)	Feed water pH	Product water pH	TDS (ppm)	Initial Fe in bed (%)	Final Fe in bed (%)	Fe Conversion (%)	Initial S in bed (%)	Final S in bed (%)	S Conversion (%)	Initial Ca in bed (%)	Final Ca in bed (%)	Ca Conversion (%)
1	31.1		-	-									
2	30.7		-	-									
3	33.7		6.6	767									
4	31.7	8.5	6.4	537	2.91	3.39	*	0.04	0.02	39.51	0.07	0.06	12.16
5	31.1		6.2	342									
6	31.2		6.1	323									
7	30		6	241									

*invalid

Table 4: Leaching data for overburden rock sample from Salak 1 Area

Days	Ambient temperature (°C)	Feed water pH	Product water pH	TDS (ppm)	Initial Fe in bed (%)	Final Fe in bed (%)	Fe Conversion (%)	Initial S in bed (%)	Final S in bed (%)	S Conversion (%)	Initial Ca in bed (%)	Final Ca in bed (%)	Ca Conversion (%)
1	31.1		-	-									
2	30.7		-	-									
3	33.7		4	754									
4	31.7	8.5	3.7	877	0.66	0.63	4.27	0.29	0.12	58.3	0	0	0
5	31.1		3.5	839									
6	31.2		3.3	692									
7	30		3.2	495									

Table 5: Leaching data for overburden rock sample from Batu Tanjung

Days	Ambient temperature (°C)	Feed water pH	Product water pH	TDS (ppm)	Initial Fe in bed (%)	Final Fe in bed (%)	Fe Conversion (%)	Initial S in bed (%)	Final S in bed (%)	S Conversion (%)	Initial Ca in bed (%)	Final Ca in bed (%)	Ca Conversion (%)
1	31.1		-	-									
2	30.7		-	-									
3	33.7		7	682									
4	31.7	8.5	6.7	298	4.18	3.4	18.63	0.03	0.04	*	0.19	0.26	*
5	31.1		6.5	222									
6	31.2		6.3	216									
7	30		6.1	149									

*invalid

3.4 Vertical Passive Neutralization of Acid Mine Drainage

The acidic water used in this study had a pH of 4, prepared from laboratory-grade sulphuric acid, with the selected pH value referring to the work of HAR et al. (Har et al., 2025). Each type of neutralizing rock sample was tested in triplicate under different flow rate variations. The passive vertical fixed-bed neutralization process, in Figure 15, required supporting equipment consisting of a retort stand to hold both a separatory funnel and a glass column. The separatory funnel functioned to regulate the flow rate of acidic water onto the neutralizing rock bed, while the glass column served as the container for the stationary neutralizing material, positioned directly beneath the funnel.

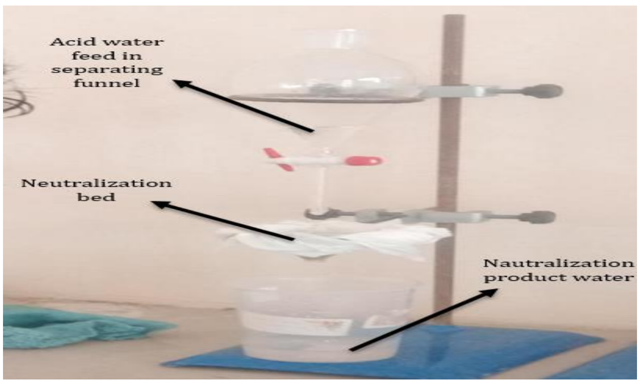


Figure 15: Configuration set up of vertical fixed-bed passive neutralization

During each experiment, 100 mL of acidic water of pH 4 was introduced into the fixed-bed system at different flow rates, corresponding to variations in weight hourly space velocity (WHSV). The effluent was collected in beakers beneath the glass column, and its pH and TDS were measured immediately using a calibrated pH meter and a digital TDS meter to minimize artifacts caused by atmospheric exposure or secondary reactions. Each condition was tested in triplicate, and the averaged values were used for interpretation. The neutralization performance of the three tested materials CaO, Silungkang limestone, and Kubang limestone demonstrated clear differences in efficiency as seen on Table 6. CaO exhibited the strongest neutralizing effect among the tested materials, raising the effluent pH from 4 to as high as 12.4–12.5 under varying flow rates. Calcium conversion ranged from 17.3% to 24.0%, with higher conversions observed at lower WHSV, indicating improved reaction efficiency under longer contact times (Pocaan et al., 2025). However, despite the high pH, the effluent still exceeded the recommended limits for wastewater discharge according to WHO standards, primarily due to excessively high TDS levels 2650–3540 ppm resulting from the significant dissolution of Ca-bearing phases. These results suggest that, while CaO is highly reactive, using a low feed flow rate is insufficient to produce effluent that meets regulatory requirements. To achieve acceptable effluent quality, it is necessary to increase the feed flow rate.

Silungkang limestone, despite containing only 12.91% Ca, showed the highest Ca conversion rates 36.1–47.5%. However, the resulting effluent pH values were more moderate 5–7, suggesting that although a larger proportion of Ca was mobilized, the absolute neutralizing capacity was limited by the lower initial Ca content. TDS values remained low 245–285 ppm, consistent with the relatively small amount of dissolved solids released into solution. Kubang limestone demonstrated intermediate behavior between CaO and Silungkang limestone. With an initial Ca content of 32.89%, its effluent pH values stabilized between 6.6 and 7.0, and Ca conversion ranged from 24.3% to 27.8%. Effluent TDS levels were moderate 256–275 ppm. These results suggest that Kubang limestone combines a relatively high Ca content with moderate reactivity, producing stable neutralization performance.

The data confirm that neutralization efficiency depends not only on bulk Ca content but also on mineral reactivity and dissolution kinetics. CaO, as a highly reactive oxide, provided the strongest neutralization effect but with lower relative conversion due to its high initial Ca concentration. Silungkang limestone, while less rich in Ca, achieved high conversion percentages but limited pH buffering. Kubang limestone offered balanced performance, achieving near-neutral effluent pH with consistent Ca utilization. The observed trends also highlight the role of WHSV, lower WHSV or longer contact times consistently improved both pH outcomes and Ca conversion, underscoring the importance of hydraulic conditions in passive neutralization systems.

Table 6: Neutralization performance of acidic water using CaO, Silungkang limestone, and Kubang limestone

Acid-neutralizing rock	pH of acid water	Acid water flow rate (ml/min)	Bed mass 9gr)	WHSV (min^{-1})	pH of water product	TDS of water product (ppm)	Initial Ca in bed (%)	Final Ca in bed (%)	Ca Conversion (%)
CaO	4	10.6	10	0.94	12.4	3420	66.35	50.44	23.98
	4	17.95	10	0.56	12.5	3540	66.35	52.05	21.55
	4	49.49	10	0.2	12.2	2650	66.35	54.86	17.33
Silungkang Limestone	4	14.26	10	0.7	7	245	12.91	6.78	47.46
	4	16.66	10	0.6	6	250	12.91	7.51	41.85
	4	40.77	10	0.25	5	285	12.91	8.25	36.11
Kubang Limestone	4	6.21	10	1.61	7	256	32.89	23.76	27.77
	4	18.35	10	0.55	6.8	275	32.89	24.68	24.96
	4	30.74	10	0.33	6.6	265	32.89	24.89	24.31

4. DISCUSSION

4.1 PAF and NAF Estimation for Overburdens

Geochemical characterization of overburden rock is a method used to assess the potential for acid mine drainage in mining activities through a series of static tests, including Net Acid Production Potential, NAPP (Tuheteru et al., 2023) and Net Acid Generation, NAG (Lemos et al., 2021). The difference between Maximum Potential Acidity, MPA and Acid Neutralizing Capacity, ANC is referred to as the Net Acid Producing Potential. Materials are classified as Potentially Acid Forming if the NAG pH is below 4.5 and NAPP is greater than zero, and as Non-Acid Forming if the NAG pH is above 4.5 (Lemos et al., 2021). NAPP is less than zero (Hamanaka et al., 2024).

The ANC parameter measures a sample's capacity to neutralize acid and is typically determined analytically using the Acid-Base Accounting method (Kusi et al., 2024). In this study, however, ANC was estimated stoichiometrically based on empirical data from the neutralizing material, using the calcium carbonate content in the rock expressed in units of kg H_2SO_4 per ton of rock (Hamanaka et al., 2024). The MPA was calculated as the product of total sulphur content and 30.6, with units of kg H_2SO_4 per ton of rock (Kusi et al., 2024). The use of total sulphur represents a conservative approach, as some sulphur may occur in forms other than pyrite. Empirical estimation of PAF and NAF using the NAPP method is presented in Table 7.

Table 7: Estimation of net acid producing potential for overburden rocks

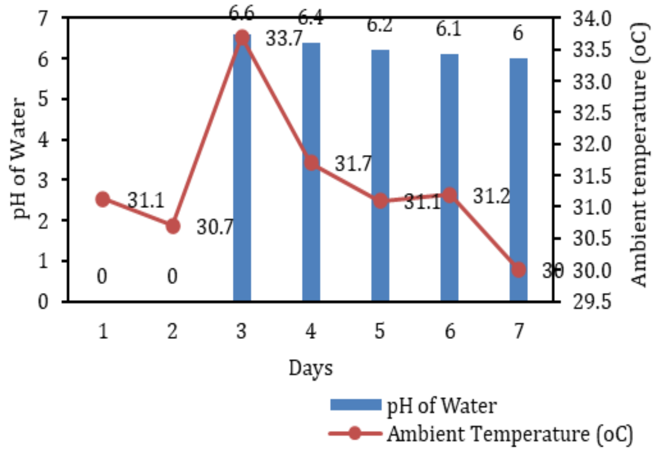
Overburden rocks	MPA (kg H_2SO_4/Ton) =%S x 30.6	ANC (kg H_2SO_4/ton) based on stoichiometric calculation	NAPP	Categories
Kandi	0,04 x 30,6= 1,22	1.71	-0.49	NAF
Salak 1	0,29 x 30,6= 8,87	0	8.87	PAF
Batu Tanjung	0,03 x 30,6= 0,91	4.65	-3.74	NAF
Sikalang	0.035 x 30.6 =1.07	1.1	-0.04	NAF
Salak 2	0.048 x30.6 = 1.46	1.21	0.25	PAF
Salak 3	0.049 x 30.6 = 1.49	0.73	0.76	PAF

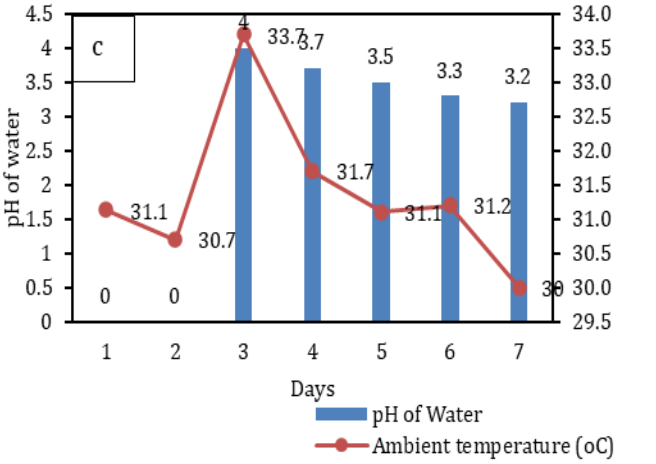
The calculation of Acid Neutralizing Capacity for several overburden samples from Sawahlunto shows significant variation across locations. At the Kandi site, the dominant neutralization reaction can be expressed as $CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + CO_2 + H_2O$, with a Maximum Potential Acidity of 1.22 kg H_2SO_4/ton. The calcium content of 0.07% corresponds to 0.7 g Ca/kg rock, equivalent to 0.0175 mol $CaCO_3$. This amount can neutralize 1.715 kg H_2SO_4/ton, giving an ANC value of 1.71 and a Net Acid Producing Potential of –0.49 kg H_2SO_4/ton, which classifies Kandi as NAF. In contrast, the Salak 1 sample contained no measurable Ca, resulting in ANC = 0. With an MPA of 8.87 kg H_2SO_4/ton, the NAPP was 8.87, categorizing this sample as PAF (Potentially Acid Forming). For Batu Tanjung, the Ca content of 0.19%. 1.9 g Ca/kg rock, equivalent to 0.0475 mol $CaCO_3$ corresponds to 4.65 kg H_2SO_4/ton neutralization capacity. Given its MPA of 0.91, the resulting NAPP was –3.74, again classifying the sample as NAF. Further comparisons are summarized in Table 7, where the Sikalang sample also falls into the NAF category with NAPP –0.04, whereas Salak 2 and Salak 3 are classified as PAF with positive NAPP values of 0.25 and 0.76, respectively. Overall, these results confirm that the acid-forming potential of Sawahlunto Formation overburden is highly site-specific, governed by both sulphur content and available neutralizing minerals.

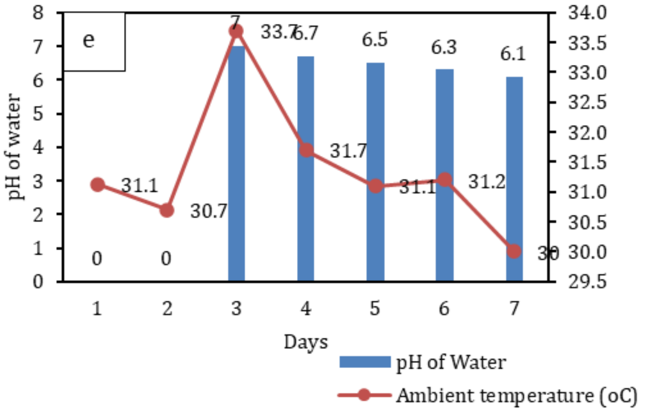
4.2 Analysis of Leachate pH and TDS Trends

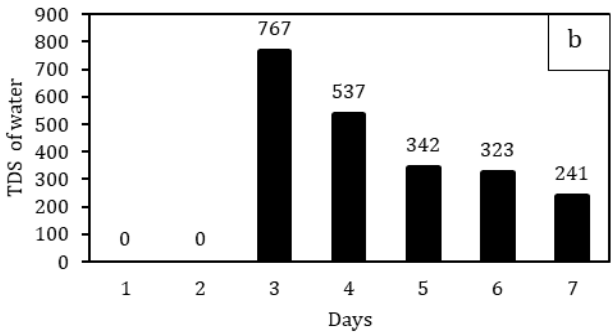
According to Abfertiawan et al, leachate from overburden samples exhibited distinct behaviors corresponding to their acid-forming potential (Abfertiawan et al., 2024). For Kandi and Batu Tanjung, classified as Non-Acid Forming, the average effluent pH values were 6.26 and 6.52, with Total Dissolved Solids of 442 ppm and 313.4 ppm, respectively. These near-neutral pH values and moderate TDS levels indicate limited acid generation, consistent with their low sulfur content and sufficient neutralizing capacity. In contrast, the Salak 1 sample, categorized as Potentially Acid Forming, produced leachate with an average pH of 3.54 and a higher TDS of 731.4 ppm, reflecting active acid generation and greater mobilization of dissolved solids due to higher sulfur content and negligible neutralizing minerals. From Day 3 to Day 7, pH and TDS gradually decreased across all samples, likely due to lower ambient temperatures, which reduce the rate of acid-generating reactions and ion mobility.

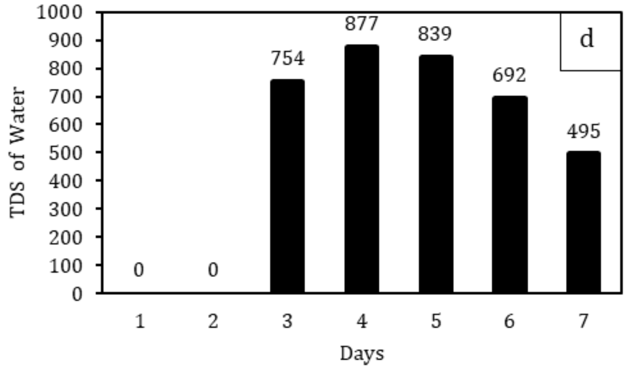
The observed trends in pH and TDS over the first five weeks can be explained by mineral hydrolysis and acid formation from decomposing organic matter. After the fifth week, pH tends to increase and TDS decrease, likely due to neutralization reactions between hydrogen ions and available neutralizing minerals. Similar trends have been reported in other studies, where leachate from active waste sites initially exhibits low pH and high TDS, then gradually stabilizes as chemical and biological processes progress. Overall, these findings confirm the predictive value of the PAF/NAF classification in determining leachate quality, with NAF samples producing near-neutral, lower-TDS water and PAF samples producing acidic, high-TDS effluent











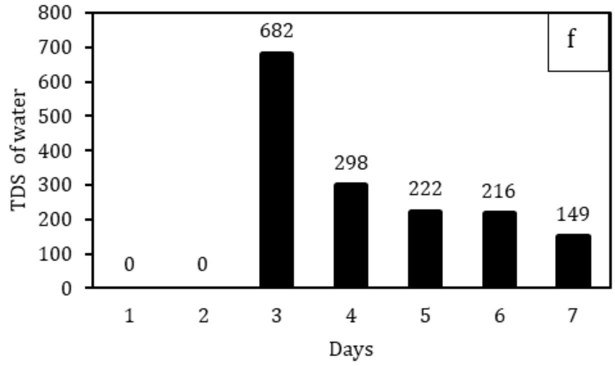


Figure 16: Trends of days versus leachate pH and ambient temperature for (a) Kandi overburden, (c) Salak 1 overburden, and (e) Batu Tanjung overburden; and trends of dasys versus leachate TDS for (b) Kandi overburden, (d) Salak 1 overburden, and (f) Batu Tanjung overburden.

The observed decrease in leachate pH and TDS from Day 3 to Day 7 can be attributed to a combination of environmental and system-specific factors. Firstly, ambient temperature plays a significant role in controlling the kinetics of chemical reactions within the bed. Lower temperatures during the later days of the experiment likely slowed the oxidation of sulfide minerals and the dissolution of neutralizing phases, resulting in reduced acid generation and a lower concentration of dissolved ions in the effluent. Secondly, the packed-bed characteristics of the overburden samples influenced the distribution and transport of the leachate. In the initial days, water percolation primarily interacts with easily accessible surfaces, causing higher pH fluctuations and TDS release. As the experiment progressed, the system approached a more saturated and homogeneous condition, with fewer readily soluble ions remaining, leading to a gradual decline in both pH and TDS. Thirdly, the system was approaching a quasi-steady state, wherein the rate of ion release from the rock matrix balanced with the flow of the leachate. In this phase, the effluent properties become more stable, reflecting the equilibrium between ongoing chemical reactions and hydrodynamic transport. Finally, the intrinsic mineralogical characteristics of the overburden contributed to the observed trends. For PAF samples, such as Salak 1, high sulfur content maintained a low pH despite decreasing TDS as initial reactive sulfides were depleted. Conversely, for NAF samples like Kandi and Batu Tanjung, the initial alkalinity from calcium-bearing minerals caused moderate pH values, but as easily dissolvable Ca was consumed, both pH and TDS gradually decreased. Temperature influences the leaching process by determining the forms of sulphur species that develop, where at lower temperatures sulfate species, which are more soluble, dominate, while at higher temperatures elemental sulphur or sulfide species may form, thereby affecting the rate and outcome of leaching (Lu et al., 2021).

4.3 Analysis of Overburden Rock Before and After Leaching

XRD analysis of the overburden samples revealed that pyrite (FeS_2) peaks were not observed either before or after leaching, despite the red markers on the diffractogram indicating the expected 2θ positions for pyrite. This absence suggests that pyrite content in the samples was very low, present in amorphous form, or composed of extremely fine particles, resulting in diffraction signals below the detection limit of XRD. In contrast, the major mineral peaks, including quartz SiO_2, marked as Q and kaolinite $Al_2Si_2O_5(OH)_4$, marked as K, exhibited increased intensity after leaching. The diffraction pattern shows a strong peak at a 2θ angle of around 26°, indicating the presence of quartz (Sriramoju et al., 2021). As well as peaks at approximately 33°, 37°, and 56°, which are characteristic of pyrite (X. Li et al., 2020). The presence of kaolinite is confirmed by peaks at around 12° and 25° (Y. Li et al., 2023). While calcite appears at around 29.4° (Prashanth et al., 2024). This phenomenon can be explained by the selective dissolution of more reactive minerals, such as carbonates or sulfides, during the leaching process, which effectively increased the relative proportion of chemically resistant minerals in the sample. Therefore, the observed changes in the diffractogram reflect not the formation of new minerals but rather the apparent enrichment of stable phases like quartz and kaolinite due to the removal of more soluble components. This interpretation aligns with chemical analysis data showing decreases in calcium and sulfur concentrations, further confirming that the leaching process preferentially removed reactive mineral phases.

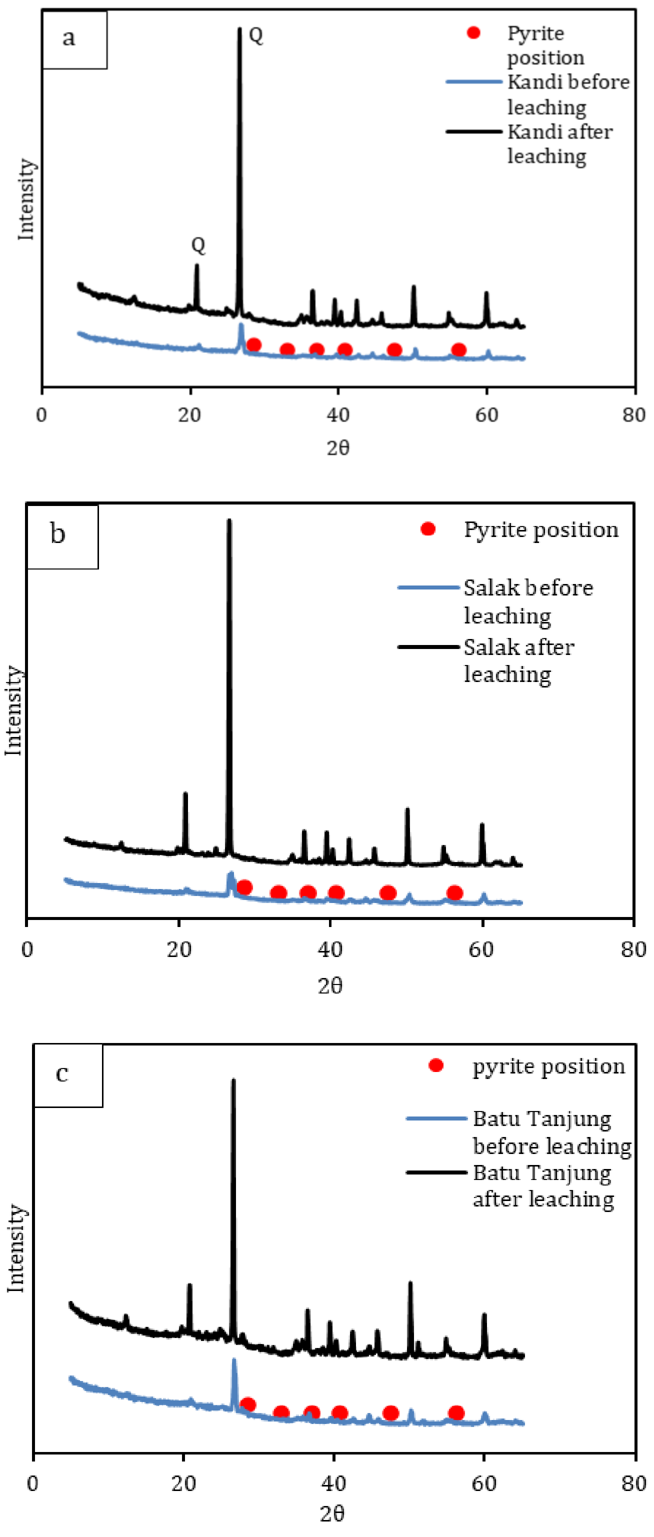


Figure 17: XRD patterns of overburden rock before and after leaching for Overburdens from: (a) Kandi, (b) Salak 1, and (c) Batu Tanjung.

4.4 Leaching Evaluation of AMD Neutralization Performance Using the Passive Fixed-Bed Neutralization Method

Based on the neutralization data, CaO exhibited very high reactivity, as evidenced by effluent pH values reaching 12–12.5 as seen on Figure 18 despite variations in flow rate, while calcium conversion remained relatively low 17–24% compared to its high initial content 66%. This behavior is attributed to the exothermic and unstable nature of CaO, which reacts with water to form $Ca(OH)_2$. The reaction generates significant heat, material expansion, and excessively high effluent pH. Such conditions make CaO less stable in a fixed bed and challenging to control without the risk of overheating or overly aggressive reactions. Acid neutralization using CaO proceeds via a two-step exothermic mechanism. The first step is hydration, where CaO reacts with water to form calcium hydroxide:

$$CaO + H_2O \rightarrow Ca(OH)_2$$

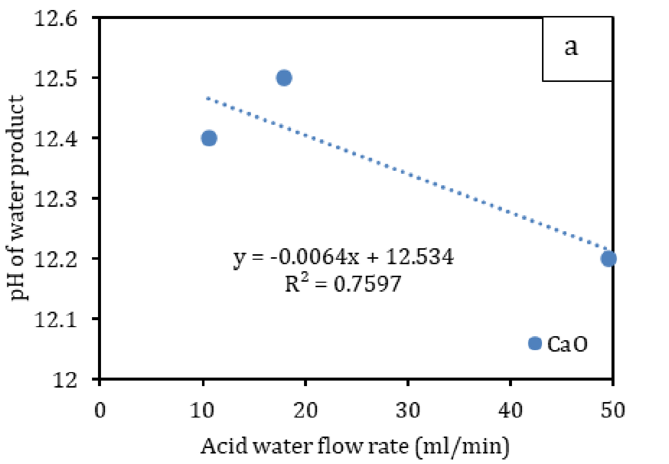
releasing considerable heat. In the second step, $Ca(OH)_2$ reacts with H^+ ions in acidic water (Fadhilah et al., 2022):

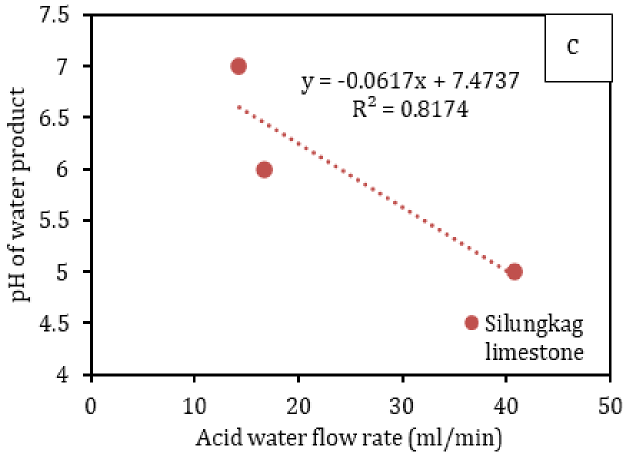
$$Ca(OH)_2 + 2H^+ \rightarrow Ca^{2+} + H_2O$$

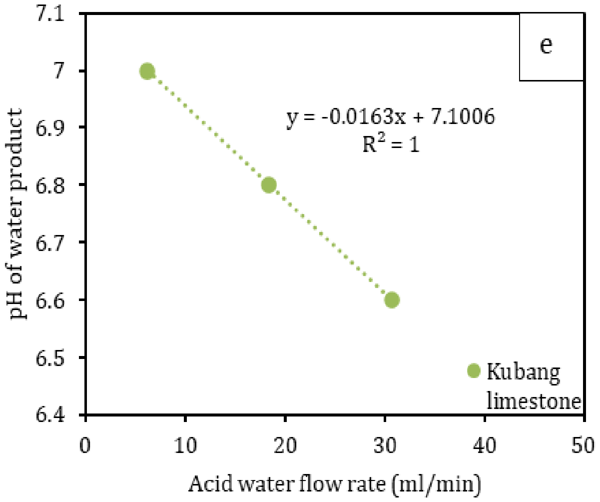
resulting in a sharp increase in pH. The combination of these two steps produces additional heat, making it importhan to carefully control the amount of CaO, flow rate, and residence time to safely achieve the target pH without excessive heating or overly alkaline effluent.

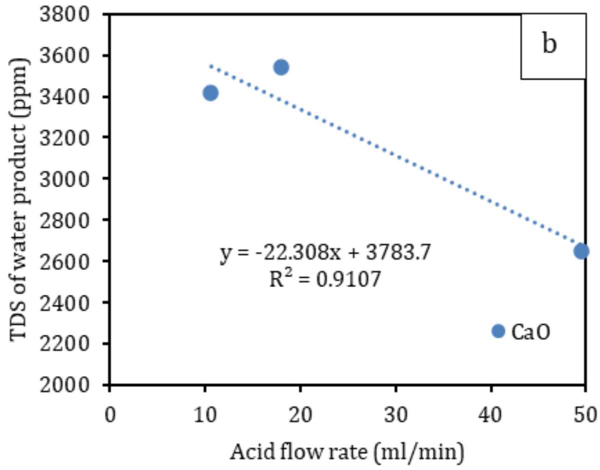
In contrast, limestones, including Silungkang and Kubang, demonstrated more controlled and stable neutralization performance. Effluent pH increased moderately to 5–7, while Ca conversion was higher for Silungkang Limestone 36–47% compared to Kubang Limestone 24–28% as seen on Figure 19, despite its lower initial Ca content. With the flow rates applied in this study, the use of Silungkang and Kubang limestones successfully met neutralization criteria, as both effluent pH and TDS remained below the WHO water quality threshold values. The fixed bed stability of limestone was significantly better than that of CaO, making it safer for practical applications. However, the relatively higher calcium conversion indicates that the neutralizing components in limestone could be consumed more quickly, potentially limiting its long-term performance if not replenished. Flow rate analysis also confirmed that limestone maintained controlled effluent characteristics, in contrast to CaO, where low flow rates could lead to excessively high pH and TDS due to aggressive exothermic reactions.

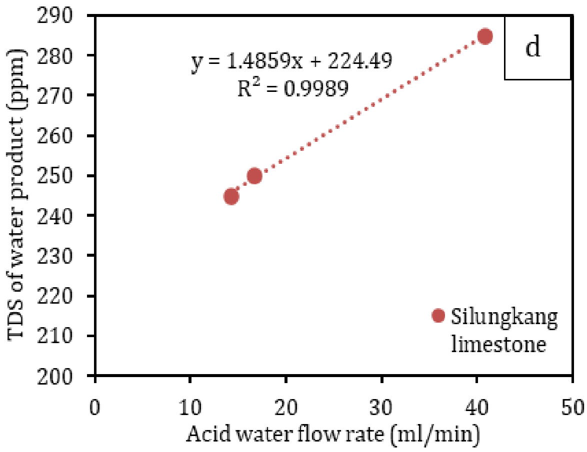
The acid neutralization mechanism of $CaCO_3$ differs from CaO due to its lower reactivity and more moderate heat release. When $CaCO_3$ reacts with H^+ ions, calcium dissolves into solution, water forms, and CO_2 gas is released (Getahun et al., 2021). The CO_2 evolution produces bubbling and slight expansion of the solution, but the reaction is far less exothermic than CaO hydration, resulting in a slower and more stable pH increase, typically reaching neutral or slightly alkaline conditions. Owing to its controlled behavior, $CaCO_3$ is safer to use in fixed beds or continuous neutralization systems, with a much lower risk of excessively high pH or overheating compared to CaO.











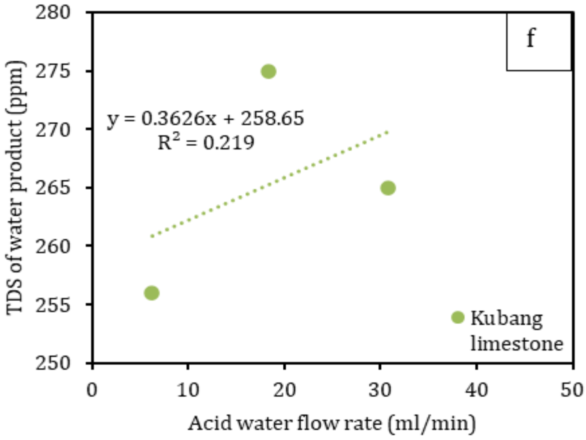


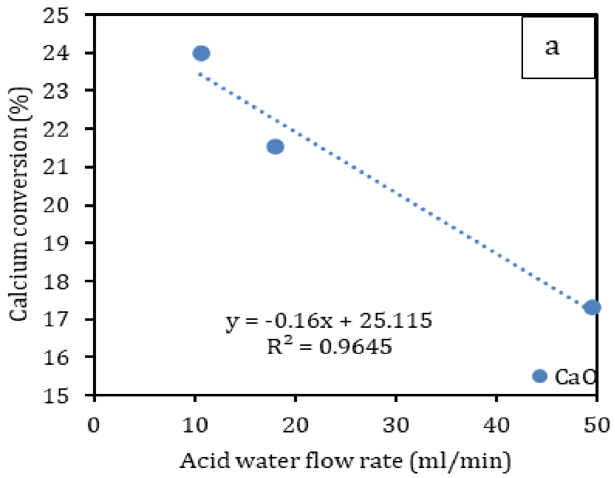
Figure 18: Correlation graph between the volumetric flow rate of acidic water and changes in effluent pH and TDS during neutralization with: (a)(b) CaO, (c)(d) Silungkang limestone, (e)(f) Kubang limestone

According to the wastewater quality standards of WHO, the effluent pH must be at least 6.5, and the TDS must not exceed 2000 ppm. Therefore, flow rate estimations were performed to determine the neutralization capacity of each material to meet these standards. For CaO, the linear regression between flow rate x, in mL/min and effluent pH y is given as $y=-0.0064x+12.53$. Solving for pH = 6.5 results in a maximum flow rate of 94.28 mL/min. For TDS, the regression $y=-22.308x+3783.7$ indicates that, to maintain a TDS target of 500 ppm, the corresponding flow rate is approximately 147.6 mL/min. This shows that, for CaO, pH control is the limiting factor in determining the maximum safe flow rate, even though the TDS would remain below the desired threshold at higher flows.

For Silungkang Limestone, the regression between flow rate and effluent pH is $y=-0.0617x+7.4737$, resulting in a maximum flow rate of 15.78 mL/min to achieve pH 6.5. Meanwhile, Kubang limestone shows a regression of $y=-0.0163x+7.1006$, which corresponds to a maximum flow rate of 36.84 mL/min for the same pH target. These results indicate that neutralization effectiveness varies significantly among the materials, with CaO providing the highest capacity to handle acidic water.

The number of acid additions required to maintain neutralization was also estimated to evaluate the durability of each material. For CaO, the regression between the number of additions x and effluent pH y is $y=-0.0657x+12.613$, yielding an estimated 93 additions for 100 mL of acidic water to reach pH 6.5. Silungkang Limestone requires approximately 6 additions $y=-0.2x+7.6$, while Kubang Limestone requires about 8 additions $y=-0.14x+7.6067$ to achieve the same pH.

These results demonstrate that the acid neutralization capacity differs among materials. CaO can maintain effective neutralization over more repetitions compared to Silungkang or Kubang limestones. However, due to its high reactivity, careful control of flow rate and contact time is essential to prevent excessively high pH or TDS in the effluent. In contrast, limestone provides more stable and controlled neutralization, with lower risk of overshooting pH or producing excessive TDS, although its neutralizing components can be consumed faster at higher calcium conversions.



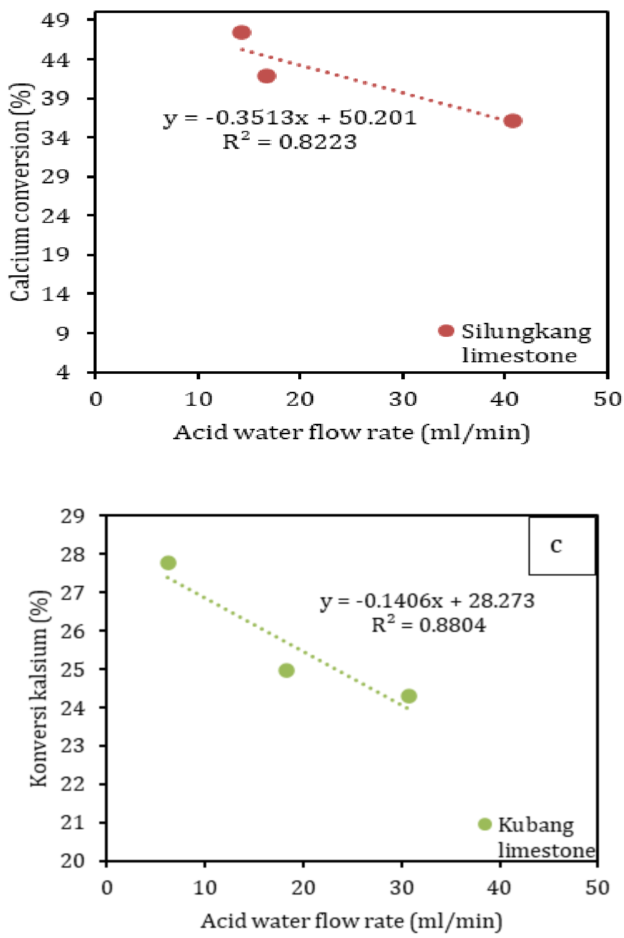


Figure 19: Correlation graph between the volumetric flow rate of acidic water and calcium conversion of neutralizing agents for (a) CaO, (b) Silungkang limestone, and (c) Kubang limestone.

4.5 Simulation of Acid Mine Water Neutralization in Coal Mining

An open-pit coal mining company in Sawahlunto experiences fluctuating inlet sump flow rates, as indicated by secondary data. This variability is closely related to mine water management, particularly in areas adjacent to road-edge slopes near reclaimed mine lands. The presence of these slopes indicates potential seepage that could affect both slope stability and sump capacity, highlighting the need for integrated water management to minimize environmental and operational impacts. Based on secondary data reported by Atanay, the average inflow rate is 8.28 mm/h, corresponding to a sump inflow of 496.8 m^3/h, or equivalently 8.28 × 10^6 mL/min (Septelina Naomi Kamano Atanay, 2024). Using this flow rate, the required mass of neutralizing material was estimated through a proportional scale-up approach based on laboratory-scale experiments. For CaO, based on a laboratory ratio of 10 g per 94.28 mL/min, the estimated mass required is approximately 0.87 tons. Silungkang Limestone, with a laboratory ratio of 10 g per 15.78 mL/min, requires an estimated 5.2 tons, while Kubang Limestone, at 10 g per 36.84 mL/min, requires about 2.2 tons. These results indicate that the required mass of neutralizing material varies significantly depending on the type of material. Silungkang limestone requires the largest quantity to neutralize the actual acid mine water inflow, whereas CaO is comparatively more efficient. The scale-up approach employed here is recommended for evaluating the key factors affecting the effectiveness of neutralization reactions under real, large-scale conditions, providing valuable guidance for operational planning and optimization of acid mine water treatment.

5. Conclusion

The overburden rocks of the Sawahlunto Formation exhibit distinct acid-generating behaviors that directly influence the potential for acid mine drainage (AMD) formation. Based on NAPP, MPA, and ANC analyses, the Kandi, Batu Tanjung, and Sikalang samples were classified as Non-Acid Forming (NAF), while Salak 1, Salak 2, and Salak 3 were identified as Potentially Acid Forming (PAF). This classification aligns with the leaching column test results, where average leachate pH values were 6.26 for Kandi, 3.54 for Salak 1, and 6.10 for Batu Tanjung, indicating stronger acid generation in PAF samples and better buffering capacity in NAF samples. Neutralization studies revealed that CaO and limestones from Silungkang and Kubang exhibit varying effectiveness in AMD treatment, with calcium conversion rates of 23.98%, 47.40%, and 27.77%, respectively. Among them, Silungkang limestone achieved the best neutralization performance, producing effluent pH values up to 12.4. For an estimated mine drainage flow of 496.8 m^3/h, the required materials are 0.87 tons of CaO, 5.2 tons of Silungkang limestone, and 2.2 tons of Kubang limestone. Overall, this study demonstrates that the combination of leaching column simulation and passive neutralization testing provides a reliable approach for evaluating AMD potential and treatment strategies in coal mining areas. Future work should include more representative overburden sampling, repeated chemical analyses to improve reliability, and pilot-scale validation of vertical passive systems to ensure effective large-scale AMD mitigation in the Ombilin Basin.

Author Contributions

Heri Prabowo initiated the research on acid mine drainage and validated the procedures and data reliability. Arif Algifari designed the research and prepared the manuscript. Fitri Nauli validated the methodology and research procedures. Wahyuda Pratama conducted the research on acid mine drainage neutralization. Aisya Amini carried out the column leach test experiments.

Acknowledgement

The authors would like to thank the Department of Mining Engineering, Faculty of Engineering, Universitas Negeri Padang, for providing research facilities in Sawahlunto as well as access to the Chemistry Laboratory, Mining Laboratory, and Geology Laboratory. Special thanks are also extended to all members involved in this research and the owners of mining companies in Sawahlunto, West Sumatra, Indonesia, for their valuable support and cooperation.

References

Abfertiawan, M. S., Hasan, F., Palinggi, Y., and Pranoto, K. 2024. Comparative study of long-term laboratory and field kinetic test for potential acid forming (PAF) materials. E3S Web of Conferences, 485, Article 02014. https://doi.org/10.1051/e3sconf/202448502014

Algifari, A., Yanti, S. R., and Nauli, F. 2023. Studi review: Evaluasi batubara Formasi Sawahlunto sebagai batuan induk hidrokarbon. JUSTEK: Jurnal Sains dan Teknologi, 6(3), Pp. 308–322. https://doi.org/10.31764/justek.vXiY.ZZZ

Algifari, A., Yanti, S. R., Nauli, F., and Aisyah, S. 2024. Neutralization of acid mine drainage with calcium hydroxide in sand packed bed contactor. 9(2), Pp. 171–175.

Ananda, R. 2024. Penetralan pH air asam tambang menggunakan metode pasif open limestone channel dengan penambahan fly ash, zeolite, dan pasir silika pada pengujian .... Jurnal Geosains dan Teknologi, 7(September), Pp.75–82. https://doi.org/10.14710/jgt.7.1.2024.75-82

Binnemans, K., and Tom, P. 2023. The twelve principles of circular hydrometallurgy. Journal of Sustainable Metallurgy, 9(1), Pp. 1–25. https://doi.org/10.1007/s40831-022-00636-3

Fadhilah, F., Ramadhan, F., and Har, R. 2022. Treatment of acid mine drainage using fly ash, bottom ash, and lime mixed. JIPF (Jurnal Ilmu Pendidikan Fisika), 7(2), Pp. 168–176. https://doi.org/10.26737/jipf.v7i2.2660

Getahun, G. T., Etana, A., Munkholm, L. J., and Kirchmann, H. 2021. Liming with $CaCO_3$ or CaO affects aggregate stability and dissolved reactive phosphorus in a heavy clay subsoil. Soil and Tillage Research, 214, Article 105162. https://doi.org/10.1016/j.still.2021.105162

Hamanaka, A., Sasaoka, T., Shimada, H., Matsumoto, S., Kusuma, G. J., and Deni, M. C. N. 2024. Mitigation of acid mine drainage using blended waste rock in near-equatorial climates—Geochemical analysis and column leaching tests. Physchem, 4(4), Pp. 470–482. https://doi.org/10.3390/physchem404003

Har, R., Riam, M. A., Octova, A., Ichsan, I. B., Aulia, H. B., Anarta, R., Harizona, A. R., Rangga, A. P. H., Fadly, A., Maiyudi, R., and Ananda, R. 2025. Passive treatment of acid mine drainage (AMD) using an open limestone channel system prior to discharge into surface water bodies. Water Conservation and Management, 9(2), Pp. 257–268. https://doi.org/10.26480/wcm.02.2025.257.268

Kusi, J. K., Foli, G., Peasah, M. Y., and Akoto, O. 2024. Geochemical characterization of waste rock dump and its potential to predict acid mine drainage. Scientific African, 26, e02350. https://doi.org/10.1016/j.sciaf.2024.e02350

Lemos, M., Valente, T., Marinho Reis, P., Fonseca, R., Delbem, I., Ventura, J., and Magalhães, M. 2021. Mineralogical and geochemical characterization of gold mining tailings and their potential to generate acid mine drainage (Minas Gerais, Brazil). Minerals, 11(1), Pp. 1–16. https://doi.org/10.3390/min11010039

Li, X., Jin, Z., Bai, G., Wang, J., and Linghu, J., 2020. Experimental study of the influence of water on spontaneous combustion of coal containing pyrite. International Journal of Coal Preparation and Utilization, 40(1), Pp. 1–16. https://doi.org/10.1080/19392699.2020.1713766

Li, Y., Hou, D., Ding, X., Kang, X., and Liu, Q. 2023. Influence of coal-measure kaolinite with different types on the preparation of kaolinite nanotube. Applied Clay Science, 246, 107179. https://doi.org/10.1016/j.clay.2023.107179

Lu, J., Walder, I., & Leiviskä, T. 2021. Impact of temperature on the leaching of sulphate, Co, Fe, Mn, Ni and Zn from the Ballangen tailings deposit, Norway: A laboratory column experiment. Journal of Water and Climate Change, 12(8), Pp. 3558–3572. https://doi.org/10.2166/wcc.2021.058

Maltrana, V., and Morales, J. 2023. The use of acid leaching to recover metals from tailings: A review. Metals, 13(11), 1862. https://doi.org/10.3390/met13111862

Mohammed, A. I., Ahmed, A. A., and Dauda, T. E., 2020. Determination of levels of heavy metals and physicochemical parameters in waste water of Kasuwan Shanu abattoir, Maiduguri. J. Chem. Lett, 1, Pp. 84–88.

Pocaan, J. P., Bueno, B. G., Pagaduan, J. M., Capingian, J., Pablo, M. A. N., Louies, J., Paulo, R. W., Beltran, A. B., Orbecido, A. H., Tanhueco, R. M., Tabelin, C. B., Villacorte-Tabelin, M., Resabal, V. J. T., Dalona, I. M., Alonzo, D., Brito-Parada, P., Plancherel, Y., Armstrong, R., Jungblut, A. D., … Herrington, R. 2025. Limestone-based hybrid passive treatment for copper-rich acid mine drainage: From laboratory to field. 59, Pp. 1–25.

Prabowo, H., Amran, A., and Arbain, A. 2019. Decreasing level of heavy metals Fe and Mn using the wetland method at coal open mining PT Bukit Asam, South Sumatra Province. IOP Conference Series: Earth and Environmental Science, 314(1), 012023. https://doi.org/10.1088/ 1755-1315/314/1/012023

Prashanth, K. P., Rudresh, M., Venkatesh, N., Shivarathri, P. G., and Rajappa, S. 2024. Revolutionizing biodegradable and sustainable materials: Exploring the synergy of polylactic acid blends with sea shells. Journal of Renewable Materials, 12(12), Pp. 2115–2134. https://doi.org/10.32604/jrm.2024.055437

Qin, X., Yang, X., Liang, Z., Cao, H., and Xu, L., 2024. Study on the effect of the undercut area on the movement law of overburden rock layers in the block caving method. Applied Sciences, 14(11), 4704. https://doi.org/10.3390/app14114704

Saalidong, B. M., Aram, S. A., Otu, S., and Lartey, P. O. 2022. Examining the dynamics of the relationship between water pH and other water quality parameters in ground and surface water systems. PLoS ONE, 17(11), e0262117. https://doi.org/10.1371/journal.pone.0262117

Kamano Atanay, S. N., 2024. Perencanaan teknis mine dewatering dan mine drainage di Pit Timur PT Allied Indo Coal Jaya Parambanan, Desa Batu Tanjung, Kecamatan Talawi, Kota Sawahlunto, Provinsi Sumatra Barat [Skripsi, Universitas Jambi].

Sriramoju, S. K., Dash, P. S., and Majumdar, S., 2021. Extraction of clean coal from washery rejects and its effect on coking properties: An approach toward sustainable development. International Journal of Coal Preparation and Utilization, 00(00), Pp. 1–23. https://doi.org/10.1080/19392699.2021.195879

Tuheteru, E. J., Suhaila, S., Suliestyah, Hartami, P. N., and Yulianti, R., 2023. A preliminary study on the formation of acid mine drainage through rock geochemical test in the coal mining areas. IOP Conference Series: Earth and Environmental Science, 1263(1), 012044. https://doi.org/10.1088/1755-1315/1263/1/012044

Uni, S., Sci, J. N., and Öztürk, Ö. F. 2024. Characterization of acid mine drainage in tailings and ore stock areas of coal mine areas: Kinetic test moisture cell method (Kömür maden sahalarının atık ve maden stok alanlarında asit maden drenajının karakterizasyonu). Sinop Üniversitesi Fen Bilimleri Dergisi, 9(1), Pp. 96–113