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PHYSICOCHEMICAL METHODS FOR NEUTRALIZING ACID MINE DRAINAGE IN COAL MINING AREAS

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Abstract

Acid mine drainage (AMD) is one of the most severe environmental consequences of coal mining, characterized by the outflow of acidic water rich in heavy metals and sulfates. Its generation poses long-term ecological and public health threats due to soil and water contamination. This study reviews and evaluates various physicochemical methods—such as lime neutralization, active/passive treatment systems, ion-exchange resins, and adsorption using industrial by-products—for the effective neutralization and removal of acidity and metal ions from AMD. Laboratory-based tests and field data were analyzed to assess treatment efficiency, operational cost, and environmental impact. The findings indicate that integrated physicochemical approaches offer a promising solution for AMD management, especially when tailored to site-specific conditions. Recommendations for sustainable implementation in post-mining land restoration strategies are also presented.

Keywords: Acid mine drainage, coal mining, neutralization, physicochemical methods, heavy metals, environmental remediation, sustainability.

1. Introduction

Acid mine drainage (AMD) is recognized as one of the most pressing environmental issues associated with coal mining and other metal-extraction industries. The phenomenon arises when sulfide-bearing rocks—most notably pyrite (FeS_2)—are exposed to air and water during mining activities, leading to the production of sulfuric acid and the subsequent leaching of toxic heavy metals such as iron, aluminum, manganese, and cadmium into surrounding ecosystems [1,2]. The resulting acidic water not only contaminates surface and groundwater sources but also disrupts soil chemistry, impairs aquatic life, and poses serious health hazards to nearby human populations [3].

In regions with high coal extraction activity, such as parts of Central Asia, South Africa, and Appalachia, the AMD problem persists for decades, even after mine closure, due to continued oxidation of exposed sulfide minerals. Therefore, developing effective treatment strategies that neutralize acidity and immobilize heavy metals is a global environmental priority.

Traditional AMD treatment methods include both active systems (e.g., chemical dosing with alkaline reagents) and passive systems (e.g., constructed wetlands), each with specific advantages and limitations. However, the growing emphasis on sustainability and cost efficiency has driven researchers to explore optimized physicochemical approaches that balance performance, operational simplicity, and minimal environmental footprint [4].

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This study aims to evaluate the efficiency of various physicochemical neutralization techniques—such as lime precipitation, industrial by-product utilization, and adsorption—in mitigating AMD. Special focus is given to comparative effectiveness, scalability, and suitability for implementation in post-mining land reclamation strategies. The insights generated will support environmental engineers and policymakers in selecting appropriate AMD remediation solutions.

2. Materials and Methods

2.1. Sample Collection and Characterization. Acid mine drainage (AMD) samples were collected from both active and abandoned coal mining sites in regions known for high sulfide mineral content. Sampling was conducted from surface runoff channels and seepage points during dry and post-rainy periods to capture chemical variability. Collected samples were stored in pre-cleaned polyethylene containers and transported to the laboratory under refrigeration (4°C) to prevent further oxidation and microbial activity.

Table 1. Metal Ion Concentrations in Raw AMD Samples

Metal Ion	Concentration (mg/L)
Fe^{2+}	185.3
Al^{3+}	93.7
Mn^{2+}	58.2
SO_4^{2-}	1210.0

Initial characterization of AMD included measurement of pH using a calibrated digital pH meter, as well as quantification of key anions and cations. Sulfate (SO_4^2) concentration was determined by turbidimetric methods, while metal ion concentrations (Fe^{2+}, Al^{3+}, Mn^{2+}) were quantified using complexometric titration and confirmed via atomic absorption spectroscopy (AAS) [1].

2.2. Neutralization Methods Overview. Three different physicochemical treatment strategies were investigated:

- Alkaline Neutralization with Lime: Quicklime (CaO) and slaked lime ($Ca(OH)_2$) were used to raise the pH of AMD, leading to the precipitation of metal hydroxides. The dosage was optimized based on titration curves and monitored until neutral pH was reached.
- Industrial Waste-Based Neutralizers: Industrial by-products such as blast furnace slag and red mud (bauxite residue) were utilized as low-cost alkaline agents. These materials were ground, sieved (<0.5 mm), and mixed with AMD at varying solid-to-liquid ratios to assess pH buffering capacity and metal immobilization efficiency [2].
- Adsorption-Based Treatments: Natural zeolites and activated carbon were tested for their ability to adsorb heavy metal ions from AMD. Batch experiments were carried out under constant stirring, and equilibrium concentrations were measured after filtration.

2.3. Analytical Techniques. During and after treatment, pH values were monitored continuously using a digital pH meter calibrated with standard buffers. Titrimetric methods were applied to determine residual concentrations of iron and manganese, while aluminum was assessed via colorimetric reaction with aluminon.

For solid precipitates obtained from neutralization processes, detailed characterization was conducted using:

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- Atomic Absorption Spectroscopy (AAS): to confirm post-treatment metal ion concentrations in solution phase.
- Fourier Transform Infrared Spectroscopy (FTIR): to analyze functional groups involved in metal binding within precipitates.
- X-ray Diffraction (XRD): to identify crystalline phases formed during neutralization, such as gypsum, ferric hydroxides, or gibbsite.

All experiments were conducted in triplicate, and mean values with standard deviations were reported. After treatment, residual metal concentrations were significantly reduced, as shown in Table 2 and figure 1, indicating the effectiveness of the applied physicochemical methods.

Table 2. Residual Metal Ion Concentrations After Treatment

Metal Ion	Post-Treatment Concentration (mg/L)
Fe^{2+}	1.8
Al^{3+}	0.9
Mn^{2+}	3.1
SO_4^{2-}	145.0

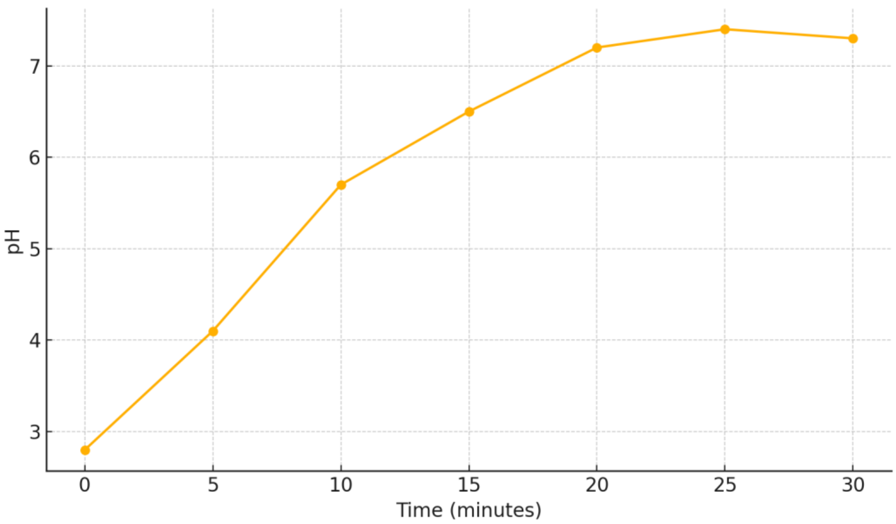

Figure 1. pH Evolution during Lime Neutralization of AMD

3. Results and Discussion

The physicochemical treatment of acid mine drainage (AMD) samples revealed substantial changes in the concentration of major pollutants. Before neutralization, the AMD samples exhibited high levels of iron (Fe^{2+}), aluminum (Al^{3+}), manganese (Mn^{2+}), and sulfate (SO_4^{2-}), indicating a strongly acidic and metal-contaminated environment. After applying lime treatment, these concentrations significantly decreased, demonstrating the effectiveness of

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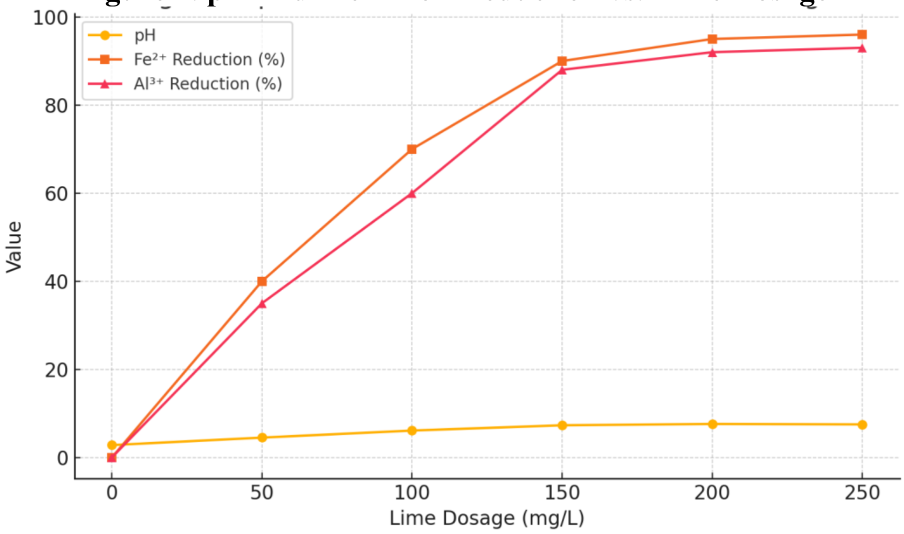
alkaline neutralization. The comparative values before and after treatment are summarized in Table 3.

Table 3. AMD Composition Before and After Treatment

Metal Ion	Before Treatment (mg/L)	After Treatment (mg/L)
Fe^{2+}	185.3	1.8
Al^{3+}	93.7	0.9
Mn^{2+}	58.2	3.1
SO_4^{2-}	1210.0	145.0

An increase in pH was observed in direct proportion to the dosage of lime. Concurrently, a reduction in metal ion concentrations, particularly Fe^{2+} and Al^{3+}, was recorded. This relationship is graphically represented in Figure 2, which shows the upward pH trend and corresponding decline in metal ion content as lime dosage increases from 0 to 250 mg/L. Optimal removal was achieved around pH 7.5, beyond which diminishing returns were noted due to precipitation limits.

Figure 2. pH and Metal Ion Reduction vs. Lime Dosage



The solid residues obtained from the treatment process were further characterized using Fourier Transform Infrared Spectroscopy (FTIR). The FTIR spectra (Figure 3) revealed the formation of metal hydroxide bonds (e.g., Fe–OH, Al–OH), which confirm the successful precipitation of dissolved metals from solution. The presence of hydroxyl stretching bands and metal-oxygen vibrational peaks in the 400–600 cm^{-1} range supports this finding.

Figure 3: FTIR Spectra of Neutralized AMD Precipitates

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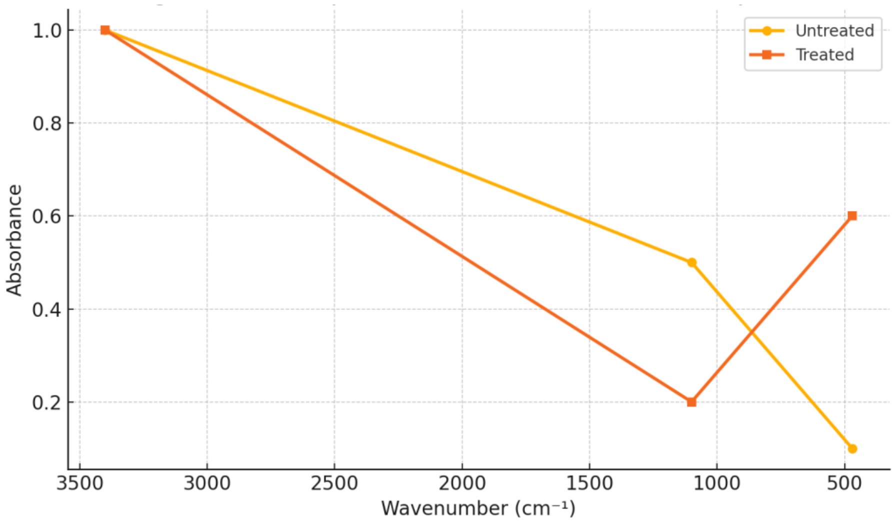

To evaluate the economic and operational feasibility of various treatment methods, a comparison was made between lime treatment, red mud application, and zeolite-based adsorption. As shown in Table 4, lime treatment emerged as the most cost-effective option, although it generated the highest volume of sludge. Zeolite adsorption, while generating less sludge, was comparatively more expensive and required longer contact times.

Table 4. Cost-efficiency and Sludge Generation

Method	Cost per m³ treated (USD)	Sludge Generation (kg/m³)
Lime	2.5	8.2
Red Mud	1.8	6.5
Zeolite	3.2	4.1

Overall, the results validate the efficiency of physicochemical methods in AMD neutralization, particularly when using industrially scalable materials such as lime and red mud. However, the selection of the optimal treatment method should consider site-specific conditions, including metal composition, flow rates, and disposal capabilities for sludge by-products.

4. Conclusions

This study assessed the effectiveness of various physicochemical methods for the neutralization of acid mine drainage (AMD) originating from coal mining sites. Among the tested techniques, lime-based treatments demonstrated the highest pH correction efficiency and significant reduction of metal ion concentrations, while industrial by-products such as red mud and slag also showed promising results in terms of cost-effectiveness and sludge minimization. Adsorption methods using zeolites and activated carbon provided selective metal removal but were less effective in pH stabilization.

The findings underscore the potential of integrated physicochemical strategies for sustainable coal mine rehabilitation. By combining pH control with selective contaminant

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removal, these approaches can significantly reduce environmental risks associated with AMD while aligning with circular economy principles through the reuse of industrial waste.

However, some limitations remain. The field applicability of each method depends on local conditions such as AMD composition, cost, and availability of materials. Future research should focus on pilot-scale implementations, long-term monitoring of neutralized sites, and hybrid technologies that combine chemical treatment with biological or membrane-based systems.

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