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Lithological Controls on Acid Mine Drainage Formation: An Integrated Rock Characterization of AMD Sources in the Sungai Seluang Area, East Kalimantan, Indonesia

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Abstract

Acid Mine Drainage (AMD) represents a critical environmental challenge in coal-mining regions, particularly due to its long-term impacts on surface water quality and surrounding ecosystems. This study investigates the lithological controls on AMD formation in the Sungai Seluang area, East Kalimantan, Indonesia, through an integrated rock characterization approach. The novelty of this research lies in linking detailed lithological attributes and pyrite micro-morphology with AMD generation potential and its implications for riverine water systems. Macroscopic lithological observations were combined with standardized pH testing (SNI 6989.11:2019) and Scanning Electron Microscopy (SEM) to evaluate the acid-generation characteristics of representative rock units. The results indicate that 92% of the analyzed samples are classified as Potentially Acid Forming (PAF), while only 8% are Non-Acid Forming (NAF). The study area is lithologically dominated by claystone (42%), sandstone (31%), and shale (27%), all of which commonly exhibit intense oxidative staining, pervasive fracturing, and weathering features that significantly enhance sulfide exposure to oxygen and water. SEM analyses reveal the presence of both euhedral and framboidal pyrite, with framboidal pyrite identified as particularly reactive and influential in accelerating acid production. Measured pH values are predominantly acidic (<6), indicating a high AMD potential that poses a serious threat to the Sungai Seluang system through acidification and metal mobilization. These findings demonstrate that lithology and micro-scale mineralogical characteristics play a decisive role in controlling AMD formation and its environmental consequences. The integrated approach adopted in this study provides a robust framework for early AMD source identification and supports the development of more effective geochemical management strategies aimed at protecting water quality and minimizing long-term environmental degradation in coal-mining areas.

Keywords: acid mine drainage, lithological control, pyrite morphology, water quality, environmental impact, coal mining

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INTRODUCTION

Acid mine drainage (AMD) is widely recognized as one of the most severe and persistent environmental problems associated with coal mining activities worldwide. It is primarily generated through the oxidation of sulfide minerals, especially pyrite (FeS_2), when exposed to oxygen and water during mining and post-mining processes. This oxidation produces sulfuric acid and mobilizes potentially toxic metals, which can significantly degrade surface water and groundwater quality, disrupt aquatic ecosystems, and pose long-term risks to human health and environmental sustainability (Acharya and Kharel, 2020). Once initiated, AMD generation may persist for decades or even centuries, making it a critical challenge for mine closure planning and watershed-scale environmental management.

The formation and severity of AMD are not uniform across mining regions but are strongly controlled by lithology, mineralogical composition, and the physical and microstructural characteristics of host rocks. Lithology governs the distribution and abundance of sulfide minerals as well as the presence of acid-neutralizing components such as carbonates and silicates. In coal-bearing successions, lithological units including coal seams, mudstone, claystone, siltstone, sandstone, and carbonaceous shale exhibit markedly different acid-generating and buffering capacities (Druschel et al., 2024). Consequently, understanding lithological controls is fundamental to identifying AMD source rocks and predicting spatial variability in AMD generation within mining-impacted catchments.

Among sulfide minerals, pyrite plays a dominant role in AMD generation due to its widespread occurrence in coal measures and its high reactivity under oxidizing conditions. However, pyrite reactivity is not solely determined by its bulk abundance. Micro-scale characteristics, such as grain size, morphology, surface area, crystallinity, and textural relationships with surrounding minerals, exert a decisive influence on oxidation kinetics (Qureshi et al., 2016; Adnyano et al., 2022). For example, finely disseminated or framboidal pyrite typically exhibits a much higher reactive surface area than coarse, euhedral crystals, leading to faster acid production rates. These microtextural factors are often overlooked in conventional AMD prediction methods.

Standard approaches for evaluating AMD potential, such as acid–base accounting (ABA), net acid generation (NAG) tests, and bulk geochemical analyses, provide valuable first-order assessments of acid-forming potential. Nevertheless, these methods may fail to capture lithology-specific controls and microstructural features that regulate sulfide oxidation processes, particularly in heterogeneous coal-bearing sequences (Acharya and Kharel, 2020). As a result, AMD risk may be underestimated or mischaracterized, especially in complex geological settings where reactive sulfides are unevenly distributed among lithological units.

Scanning Electron Microscopy (SEM), commonly coupled with energy-dispersive X-ray spectroscopy (EDS), has emerged as a powerful tool for bridging this gap by enabling direct visualization and characterization of sulfide minerals at the micro-scale. SEM-based analyses allow detailed examination of pyrite morphology, grain size, surface alteration features, and mineral associations within different lithologies (Castendyk et al., 2015; González et al., 2018). Numerous studies have demonstrated that framboidal, porous, or microcrystalline pyrite exhibits significantly higher oxidation rates compared to massive or well-crystallized euhedral pyrite. Therefore, integrating SEM observations with lithological and geochemical data provides a more robust framework for identifying AMD source rocks and understanding the mechanisms driving AMD generation.

The importance of lithological controls on AMD formation is further amplified in tropical environments. Regions such as East Kalimantan are characterized by high annual rainfall, elevated temperatures, and intense chemical weathering, all of which accelerate sulfide oxidation and metal leaching processes (Umar et al., 2022). Frequent rainfall enhances water–rock interaction and oxygen transport, while warm temperatures promote microbial activity that can catalyze sulfide oxidation. In addition, dense river networks facilitate the rapid transport of acidic and metal-rich drainage from mine sites into downstream aquatic systems, extending the environmental impact beyond the immediate mining area.

Despite extensive global research on AMD, studies that explicitly link lithology, pyrite microtexture, and AMD generation in tropical coal-bearing basins remain relatively limited. Many investigations focus on geochemical water quality assessments or bulk rock chemistry, with less emphasis on lithology-specific source identification at the catchment scale (Banerjee, 2014; Anawar et al., 2020). This knowledge gap is particularly significant in Indonesia, one of the world's largest coal producers, where open-pit mining in tropical settings poses substantial risks to riverine environments and downstream communities.

The Sungai Seluang area in East Kalimantan represents a typical tropical coal-mining catchment where diverse lithologies are exposed through mining and natural erosion processes. Coal measures in this region are frequently intersected by surface water and shallow groundwater systems, creating favorable conditions for AMD generation and transport. However, systematic studies that integrate field-based lithological characterization, standardized geochemical testing, and SEM-based pyrite analysis to identify AMD sources in the Sungai Seluang catchment are still scarce. A comprehensive understanding of lithology-controlled AMD processes in this area is therefore essential for effective mine water management and environmental protection (Sabara et al., 2022a).

This study addresses these gaps by investigating the effects of lithology on AMD formation through an integrated rock characterization approach. Field-scale lithological observations are combined with standardized pH measurements (SNI 6989.11:2019) and detailed SEM analyses to assess the acid-generation potential of different rock units exposed in the Sungai Seluang area. By linking macroscopic lithological features with micro-scale pyrite characteristics, this research provides new insights into the mechanisms controlling AMD generation in tropical coal-mining environments. The outcomes of this study are expected to support improved prediction of AMD-prone lithologies and contribute to the development of more targeted and effective mitigation strategies for protecting water quality and environmental sustainability in mining-impacted catchments (Sabara et al., 2022b).

Geological setting

The Sungai Seluang area is located in the eastern part of Kalimantan within the Kutai Basin, one of the largest and most prolific Tertiary sedimentary basins in Indonesia. The Kutai Basin developed primarily as a Cenozoic extensional basin and was subsequently modified by thermal subsidence and regional tectonic deformation associated with the complex interaction among the Eurasian, Indo-Australian, and Philippine Sea plates (Paterson et al., 1997; Jamaluddin et al., 2024a–b) **(Figure 1A)**. This prolonged tectonic evolution played a fundamental role in controlling basin architecture, sediment accommodation, and the distribution of coal-bearing sequences across eastern Kalimantan.

As a result of this tectono-sedimentary history, the Kutai Basin hosts thick siliciclastic successions that contain extensive and economically significant coal deposits (Allen, 1970; Cloke et al., 1997). Stratigraphically, the Sungai Seluang area is dominated by Paleogene to Neogene sedimentary sequences composed predominantly of interbedded coal seams, mudstone, claystone, siltstone, sandstone, and carbonaceous shale **(Figure 1B)**. These lithological units were deposited in fluvio-deltaic to coastal plain environments under humid tropical conditions, reflecting repeated shifts in sediment supply, relative sea level, and depositional energy. Such depositional settings favored the accumulation of organic-rich sediments and the development of reducing conditions conducive to sulfide mineral formation.

The coal-bearing units exposed in the Sungai Seluang area belong to formations that are widely developed throughout the Kutai Basin and are characterized by high organic matter content and variable abundances of sulfide minerals, particularly pyrite. Pyrite commonly occurs as disseminated grains, nodules, and framboidal aggregates within coal seams and associated fine-grained sedimentary rocks. The heterogeneous distribution of these sulfide minerals among different lithologies exerts a strong control on the acid-generating potential of the rock units. Conversely, the presence or absence of acid-neutralizing minerals, such as carbonates and certain silicate phases, determines the buffering capacity of each lithology. This lithological variability is therefore a critical factor governing the spatial distribution and intensity of acid mine drainage (AMD) generation in the area (Satyana et al., 1999; Jamaluddin et al., 2024a).

Structurally, the Sungai Seluang area is characterized by gentle folding and minor faulting related to basin inversion and regional tectonic reactivation during the late Cenozoic. Although deformation intensity is relatively low, these structures significantly influence stratigraphic exposure and subsurface fluid flow patterns. Faults, fractures, and bedding planes act as preferential pathways for the infiltration of oxygenated meteoric water into sulfide-bearing lithologies. This enhanced permeability increases water–rock interaction and accelerates sulfide oxidation processes, thereby promoting the initiation and propagation of AMD, particularly in areas where reactive lithologies are intersected by surface water and shallow groundwater systems.

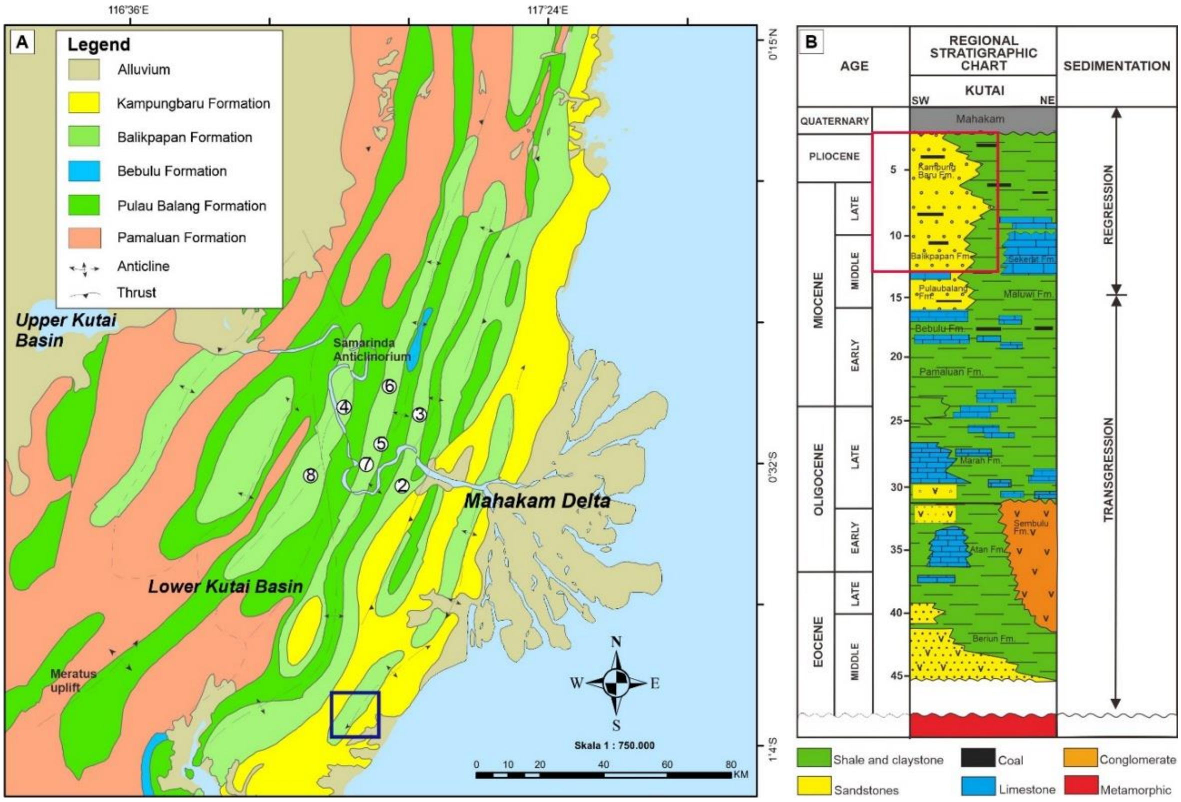

Figure 1. The Sungai Seluang area is located in the eastern part of Kalimantan within the Kutai Basin, one of the largest and most prolific tertiary sedimentary basins (Satyana et al., 1999; Jamaluddin et al., 2024a)

Climatically, the region experiences a humid tropical climate characterized by high annual rainfall and persistently warm temperatures. These conditions promote intense chemical weathering, rapid oxidation of sulfide minerals, and efficient leaching of acidic and metal-rich solutions from exposed rock units. River systems, including the Sungai Seluang, function as the primary drainage networks that collect and transport weathering products from coal-bearing formations into downstream environments. The close hydrological connectivity between exposed lithologies and the Sungai Seluang area enhances the potential for AMD to directly impact surface water quality. The combined effects of sulfide-rich lithologies, structural permeability, and tropical climatic conditions create a highly favorable setting for AMD generation and propagation in the Sungai Seluang area. Understanding this geological and environmental framework is essential for identifying lithological sources of AMD and for developing effective management and mitigation strategies aimed at protecting riverine ecosystems and water resources in mining-impacted regions of East Kalimantan.

METHOD

Study Design and Data Collection

This study employed an integrated field–laboratory approach to identify lithological sources of acid mine drainage (AMD) in the Sungai Seluang area, East Kalimantan, Indonesia. A total of 63 rock samples were collected, comprising 33 samples from in situ mine-wall exposures and 30 samples from mine disposal materials. Sampling focused on representative lithologies within coal-bearing successions, including sandstone, claystone, and shale, selected to capture the variability of potential acid-generating materials **(Figure 2)**.

Rock Acidity Testing and AMD Classification

Laboratory analyses were performed to evaluate the acid-generation potential of rock samples using pH measurements in accordance with the Indonesian National Standard SNI 6989.11:2019. Each sample was crushed to a representative grain size and measured using a calibrated pH meter. The resulting pH values were used as a primary indicator to classify samples into Potentially Acid Forming (PAF) and Non-Acid Forming (NAF) categories. Samples exhibiting acidic pH values were interpreted as having elevated acid-generating potential, whereas samples with near-neutral to alkaline pH values were classified as non-acid forming. This approach provides a rapid and effective screening tool for identifying AMD-prone lithologies in coal mining environments.

Scanning Electron Microscope (SEM) Analysis

Representative rock samples from different lithological units and acidity classes were selected for microtextural and mineralogical analysis using Scanning Electron Microscopy (SEM). Samples were cut and polished to obtain flat, smooth surfaces and coated with a thin carbon layer to ensure electrical conductivity and minimize charging effects. SEM observations were conducted using an Inspect S-50 instrument operated at an accelerating voltage of 12.5 kV. Secondary Electron (SE) imaging was employed to examine surface textures, while Energy-Dispersive X-ray Spectroscopy (EDS) facilitated elemental characterization. Electron Backscatter Diffraction (EBSD) analysis was applied to obtain crystallographic information and confirm mineral phases and crystal structures. All SEM analyses were performed at the University of Vienna, Austria, ensuring high-resolution imaging and robust mineral identification.

Data Integration and Interpretation

Results from lithological mapping, pH-based acidity classification, and SEM microtextural analyses were systematically integrated to elucidate lithology-controlled mechanisms of acid mine drainage (AMD) generation within the Sungai Seluang catchment. The integration of macroscopic, geochemical, and micro-scale datasets provides a comprehensive framework for identifying AMD source rocks and understanding the processes governing acid production in this tropical coal-mining environment. Quantitative evaluation of sample classifications reveals a pronounced dominance of Potentially Acid Forming (PAF) materials over Non-Acid Forming (NAF) units, indicating that AMD generation in the study area is strongly governed by the underlying geological framework rather than by isolated geochemical conditions (Sadjab et al., 2020).

Among the investigated lithologies, sandstone and claystone–shale units exhibit the highest proportions of PAF classification. These lithologies are characterized by pervasive fracturing, advanced weathering, and elevated sulfide mineral contents, all of which enhance exposure of reactive minerals to oxygen and water. Field observations indicate that such physical characteristics increase permeability and promote prolonged water–rock interaction, thereby accelerating sulfide oxidation processes. In contrast, lithologies displaying more massive textures and limited structural discontinuities tend to exhibit lower degrees of weathering and reduced acid-generation potential. A strong correlation is observed between measured pH values and SEM-derived mineralogical characteristics. Samples yielding low pH values are consistently associated with high abundances of sulfide minerals, particularly pyrite occurring as framboidal and euhedral aggregates (Gautama and Hartaji, 2004). Framboidal pyrite, which is predominantly hosted within fine-grained claystone and shale units, exhibits a high specific surface area and enhanced reactivity, making it especially susceptible to rapid oxidation and acid generation. Euhedral pyrite, although less reactive than framboidal forms, also contributes to sustained acid production where it occurs in fractured and weathered rock matrices.

Conversely, samples classified as NAF typically show limited sulfide occurrence or contain sulfide minerals encapsulated within more competent rock fabrics, resulting in near-neutral pH values. This multi-scale integration of lithological, geochemical, and microtextural evidence enables robust identification of primary AMD source rocks within the Sungai Seluang area. The findings clearly demonstrate that lithological characteristics exert a first-order control on AMD generation and propagation. From a practical perspective, this integrated interpretation provides a strong geological basis for targeted AMD management, highlighting the importance of prioritizing mitigation measures on PAF-dominated lithologies during mine planning, waste rock handling, and post-mining rehabilitation to minimize long-term impacts on riverine water quality and the surrounding environment.

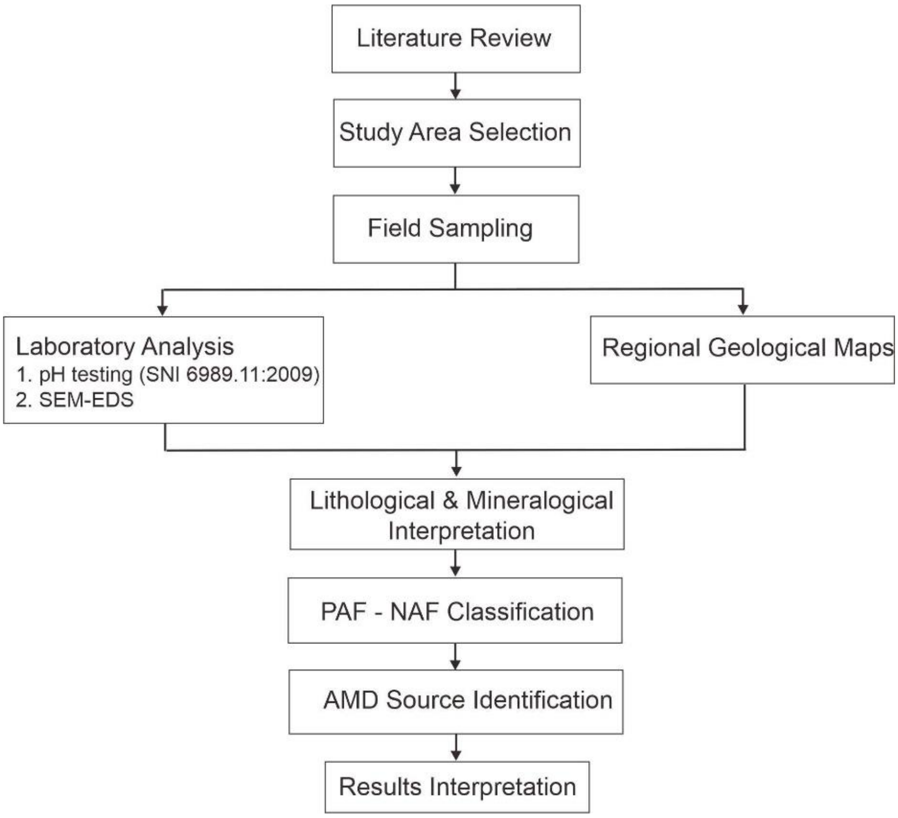

Figure 2. Research workflow illustrating the integrated approach used in this study, including lithological mapping and sampling, pH based rock acidity classification (PAF–NAF), and SEM microtextural and mineralogical analyses, leading to the identification of lithology-controlled acid mine drainage (AMD) source rocks in the Sungai Seluang area

RESULTS AND DISCUSSION

Lithological Characteristics of AMD-Related Rock Units

The lithological characteristics of AMD-related rock units in the Sungai Seluang area demonstrate a strong lithological control on acid mine drainage generation through the combined influence of mineralogical composition, rock texture, and structural features. Sampling focused on representative lithologies within coal-bearing successions, including sandstone, claystone, and shale, which collectively constitute the dominant host rocks associated with AMD development in the study area **(Figure 3)**. Claystone and shale units, characterized by fine grain size, laminated structures, and relatively low permeability under fresh conditions, commonly exhibit intense weathering and pervasive fracturing in exposed settings. These fractures and bedding-parallel partings serve as effective conduits for oxygenated meteoric water, significantly enhancing fluid–rock interaction and promoting sulfide oxidation. The frequent presence of yellowish to brownish oxidation products along fractures and interlayer surfaces provides clear macroscopic evidence of active chemical weathering processes linked to AMD formation.

Sandstone units display a contrasting but still significant AMD-related behavior. Although sandstones are generally more massive and mechanically competent, they are often intersected by irregular fracture networks that locally increase permeability and exposure of sulfide-bearing minerals to oxidizing conditions. Oxidation halos observed along fracture surfaces indicate ongoing chemical alteration of disseminated sulfides, contributing to localized acid generation. Compared to claystone and shale, sandstone typically contains lower sulfide concentrations; however, structural permeability and prolonged exposure to atmospheric and hydrological processes can substantially elevate its acid-generating potential.

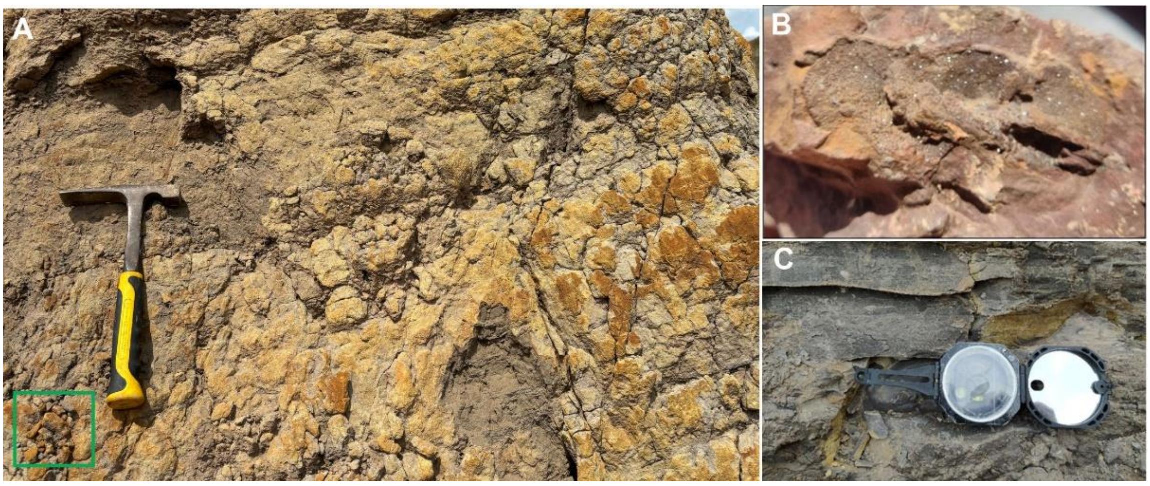

Figure 3. Representative lithological outcrops from the Sungai Seluang area showing sandstone, claystone, and shale units within coal-bearing successions, highlighting visible oxidation features and fracture networks associated with acid mine drainage (AMD) development

The integration of lithological observations with geochemical indicators highlights that AMD generation in the Sungai Seluang area is governed not solely by sulfide abundance but by the interplay between lithology, fracture architecture, and weathering intensity. Fine-grained claystone and shale represent the highest-risk lithologies due to their enhanced reactivity under weathered conditions, while sandstone contributes to AMD generation primarily where structural features amplify oxidation processes. This lithology-based interpretation provides a robust framework for identifying priority AMD source rocks and supports targeted management strategies in coal-mining environments (Prastowo et al., 2021).

Figure 4. Documentation of an acid mine drainage (AMD) pond in the Sungai Seluang area, illustrating acidic water accumulation and sedimentation associated with sulfide oxidation from surrounding coal-mine lithologies

The hydrogeochemical consequence of this lithological weathering is the formation of high-acidity ponds, as captured in the documentation of the Sungai Seluang site **(Figure 4)**. The observed water coloration, ranging from deep ochre/red **(Figure 4A)** to vivid greenish-yellow **(Figure 4B** and **Figure 4C)**, serves as a proxy for the evolving oxidation states of iron and the subsequent precipitation of metal hydroxides. The red hues indicate a dominance of ferric iron (Fe^{3+}) and the formation of oxyhydroxide sediments, while the greenish tints suggest transitional aqueous chemistry or the presence of ferrous iron (Fe^{2+}) and other dissolved metals. These ponds act as geochemical sinks where sedimentation associated with sulfide oxidation from the surrounding coal-mine lithologies occurs, illustrating the environmental footprint of lithologically-controlled acid generation. Ultimately, the integration of macro-scale oxidation features and basin-scale water accumulation confirms that AMD potential is governed not only by sulfide presence but by the synergistic effects of fracture density and weathering intensity (Kapugu et al., 2022).

pH-Based Classification of Acid-Forming Potential

The stratigraphic successions and associated geochemical datasets clearly demonstrate a pronounced dominance of Potentially Acid Forming (PAF) materials throughout the Sungai Seluang site, highlighting the inherently high acid-generating potential of the coal-bearing sequence in this area. This dominance reflects the combined influence of lithological composition, sulfide mineral distribution, and structural characteristics that collectively govern acid mine drainage (AMD) generation. Laboratory pH measurements obtained from representative rock samples exhibit a remarkably wide range, extending from extremely acidic conditions (as low as pH ~0.5) to near-neutral values approaching pH 8. Such variability underscores the strong heterogeneity in lithological properties and mineralogical controls across the stratigraphic profile.

Table 1. Summary of lithology, measured pH values, and AMD classification (PAF–NAF) for rock samples from the Sungai Seluang area

Station	Sample ID	Lithology	pH	Classification
SBJ 1	SBJ 1.1	Sandstone	4.8	PAF
	SBJ 1.2	Sandstone	2.3	PAF
	SBJ 1.4	Claystone	7.98	NAF
	SBJ 1.7	Claystone	1.7	PAF
SBJ 2	SBJ 2.1	Sandstone	7.2	NAF
	SBJ 2.2	Siltstone	3.4	PAF
	SBJ 2.3	Sandstone	4.5	PAF
	SBJ 2.4	Claystone	6.8	NAF
	SBJ 2.5	Claystone	6.8	NAF
	SBJ 2.6	Shale	6.8	NAF
	SBJ 2.8	Claystone	7.5	NAF
	SBJ 2.10	Claystone	1.2	PAF
	SBJ 2.12	Claystone	1.7	PAF
	SBJ 2.13	Claystone	2.6	PAF
	SBJ 2.14	Shale	1.7	PAF
	SBJ 2.15	Claystone	3.07	PAF
	SBJ 2.16	Sandstone	1.2	PAF
	SBJ 2.17	Shale	3.05	PAF
	SBJ 2.19	Sandstone	3.3	PAF
	SBJ 2.20	Shale	2.9	PAF
SBJ 3	SBJ 3.1	Claystone	4.3	PAF
	SBJ 3.3	Shale	3.3	PAF
	SBJ 3.4	Claystone	3.2	PAF
	SBJ 3.5	Shale	2.77	PAF
	SBJ 3.6	Claystone	3.68	PAF
	SBJ 3.8	Shale	2.93	PAF
STA 4	SBJ 4.1	Sandstone	4.7	PAF
	SBJ 4.2	Sandstone	2.9	PAF
	SBJ 4.3	Sandstone	5.42	PAF
	SBJ 4.4	Sandstone	2.2	PAF
	SBJ 4.5	Sandstone	1.78	PAF
	SBJ 4.6	Claystone	1.81	PAF
	SBJ 4.8	Shale	0.5	PAF

As summarized in **Table 1**, the majority of samples collected from stations SBJ 1 through SBJ 4 are classified as PAF, with only a limited number of samples identified as Non-Acid Forming (NAF). This distribution indicates that acid-generating lithologies are not confined to isolated horizons but are instead pervasive throughout the stratigraphic succession. The presence of extremely low pH values, particularly in shale and claystone samples, suggests active or advanced sulfide oxidation processes that have already produced significant acidity prior to or during sampling. Conversely, near-neutral pH values observed in a small number of samples reflect localized buffering effects, likely related to mineralogical variations or limited exposure of sulfides to oxidizing conditions. Sandstone units exhibit the broadest range of pH values, varying from strongly acidic (pH ~1.2) to near-neutral conditions (pH ~7.2). This wide variability can be attributed to the heterogeneous distribution of disseminated sulfide minerals within the sandstone matrix and along bedding planes, as well as differences in fracture density and connectivity. In sandstones where sulfide minerals are sparsely distributed or encapsulated within relatively competent rock fabrics, oxidation processes appear to be limited, resulting in higher pH values and occasional classification as NAF. In contrast, sandstones characterized by well-developed fractures, joints, and bedding-plane partings provide enhanced permeability, allowing greater ingress of oxygenated water. These conditions promote rapid sulfide oxidation, leading to the generation of acidic drainage and classification as PAF **(Figure 5; Table 1)**.

Fine-grained lithologies, including claystone, mudstone, and shale, display more consistently acidic geochemical behavior across the study area. Although some fine-grained units show limited buffering capacity through the dissolution of aluminosilicate minerals, this effect is generally insufficient to counterbalance the acidity produced by sulfide oxidation. A substantial proportion of these lithologies contain abundant framboidal pyrite, a sulfide morphology characterized by extremely high surface area and enhanced reactivity under oxidizing conditions. The presence of framboidal pyrite is particularly significant in claystone and shale units, where fine grain size and high porosity further facilitate water–rock interaction. As a result, many fine-grained samples yield strongly acidic pH values ranging from approximately 1.2 to 3.7, confirming their classification as dominant PAF lithologies. The stratigraphic distribution of pH values and AMD classifications reveals a systematic pattern when examined in relation to the stratigraphic column. Most sampled intervals, particularly those from sections SBJ 1 through SBJ 4, are consistently classified as PAF, as indicated by red markers in the stratigraphic profiles. These PAF-dominated intervals are laterally extensive and vertically continuous, suggesting that acid-generating conditions are widespread rather than localized. In contrast, NAF units, represented by blue markers, are relatively scarce and occur as discontinuous lenses or thin horizons within the stratigraphic succession. The limited spatial extent and poor continuity of NAF lithologies significantly reduce the overall neutralization capacity of the system.

This imbalance between PAF and NAF materials has important implications for AMD generation and propagation within the Sungai Seluang catchment. The scarcity of NAF lithologies means that there is minimal natural buffering available to neutralize acidity generated by sulfide oxidation. Consequently, acidic drainage produced within PAF-dominated strata can readily migrate into surface water and shallow groundwater systems, particularly where structural features such as fractures and bedding planes provide preferential flow paths. Once mobilized, acidic waters and dissolved metals can be transported downstream by the Sungai Seluang, posing risks to water quality and aquatic ecosystems.

Overall, the integrated stratigraphic and geochemical analysis demonstrates that AMD generation in the Sungai Seluang area is fundamentally controlled by lithological composition and the distribution of reactive sulfide minerals. The pervasive presence of PAF lithologies, coupled with limited buffering capacity, creates a geological setting that is highly susceptible to sustained AMD production. These findings emphasize the importance of lithology-based AMD assessment and highlight the need for targeted management strategies that prioritize PAF-dominated units during mine planning, waste rock segregation, and long-term environmental rehabilitation.

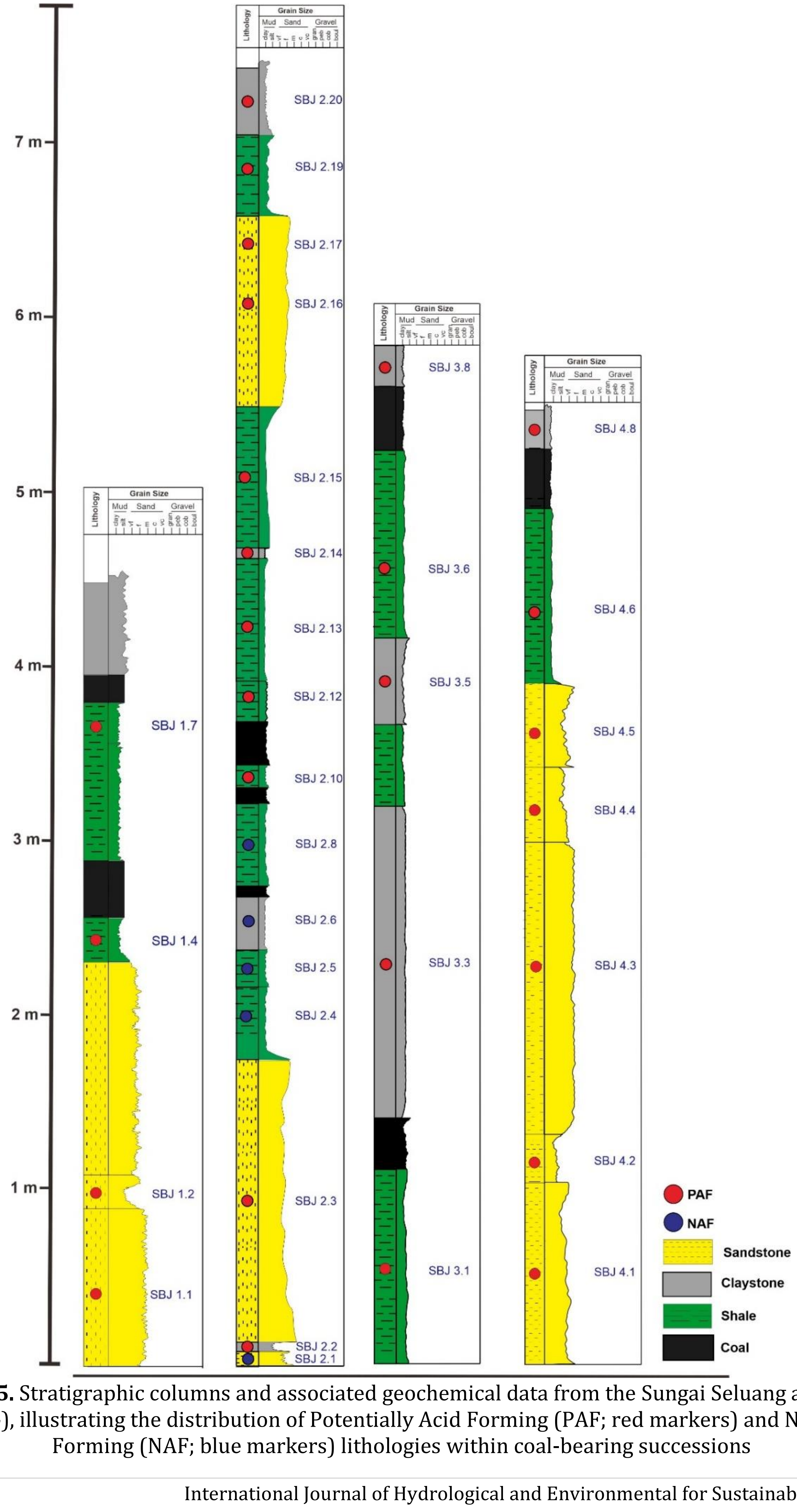

Figure 5. Stratigraphic columns and associated geochemical data from the Sungai Seluang area (SBJ 1–SBJ 4), illustrating the distribution of Potentially Acid Forming (PAF; red markers) and Non-Acid Forming (NAF; blue markers) lithologies within coal-bearing successions

The relationship between lithology, acidity, and acid mine drainage (AMD) potential in the Sungai Seluang area. **Figure 6A** shows that pH values vary systematically with lithology. Claystone exhibits the widest pH range, from strongly acidic to near-neutral conditions, indicating heterogeneous acid-generation behavior likely controlled by variable sulfide content and weathering intensity. Sandstone also displays a broad pH distribution, reflecting the influence of disseminated sulfides and fracture-controlled oxidation that can locally enhance acid generation. In contrast, shale samples show consistently low and narrowly distributed pH values, suggesting a more uniform and persistently acidic character, consistent with fine-grained textures that favor sulfide preservation and rapid oxidation. **Figure 6B** indicates that claystone is the dominant lithology (42%), followed by sandstone (31%) and shale (27%), highlighting the prevalence of lithologies susceptible to AMD development. **Figure 6C** further demonstrates that the study area is overwhelmingly dominated by Potentially Acid Forming (PAF) materials (92%), with only a minor proportion of Non-Acid Forming (NAF) units (8%). Together, these results confirm that lithology exerts a primary control on AMD generation, with fine-grained units representing the greatest and most persistent source of acidity, while sandstone contributes variably depending on its structural and mineralogical characteristics.

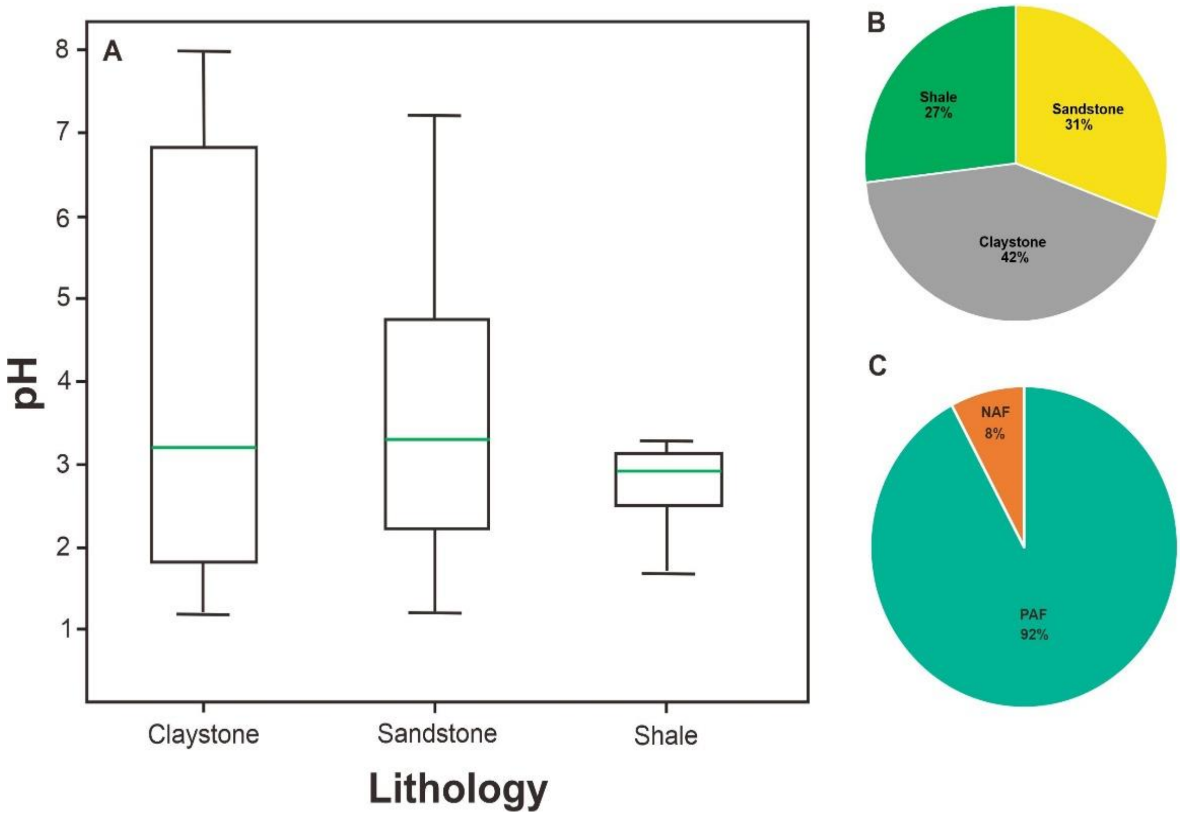

Figure 6. (A) Boxplots of pH values for claystone, sandstone, and shale, showing lithology-dependent acidity. (B) Proportional distribution of lithologies within the Sungai Seluang area. (C) Proportion of Potentially Acid Forming (PAF) and Non-Acid Forming (NAF) materials, highlighting the dominance of PAF lithologies

The disposal materials from the Sungai Seluang area are characterized by predominantly acidic conditions, with measured pH values ranging from extremely acidic (pH 0.23) to moderately acidic conditions (pH 6.53), indicating a strong dominance of Potentially Acid Forming (PAF) materials across all sampling stations (**Figure 7)**. Nearly all disposal samples are classified as PAF, with only a single sample identified as Non-Acid Forming (NAF), demonstrating the very limited inherent neutralization capacity of the disposed waste rocks. This pervasive acidity reflects advanced sulfide oxidation processes, suggesting that the disposal environments act as sustained and active sources of acid mine drainage (AMD). Spatial variations in acidity further highlight differences in waste composition and weathering intensity among stations. Disposal materials at STA 1 exhibit moderate to strong acidity, with pH values decreasing from near-neutral to highly acidic conditions. This variability likely reflects heterogeneity in the disposed materials, where localized buffering effects from carbonate- or clay-rich components may temporarily moderate acidity but are ultimately insufficient to offset the high acid-generating potential of sulfide-bearing lithologies. In contrast, disposal samples from STA 2 and STA 3 consistently display very low pH values, with several samples reaching extreme acidity (pH ≤ 1), indicative of advanced AMD development driven by intense pyrite oxidation. These conditions are commonly associated with increased reactive surface area and prolonged exposure to oxygen and meteoric water within loosely compacted waste rock. Similarly, disposal sites at STA 4 and STA 5 are dominated by strongly to extremely acidic samples, including pH values below 0.5, identifying these locations as persistent and highly active AMD sources. The absence of NAF materials at these stations suggests inadequate segregation of acid-forming and non-acid-forming rocks during disposal operations, thereby exacerbating long-term environmental risks.

Figure 7. Distribution of pH values and acid mine drainage (AMD) classification of disposal materials from the Sungai Seluang area

SEM Identification and Microtextural Characteristics of Sulfide Minerals

The SEM micrographs **(Figure 8)** reveal the occurrence of pyrite in both framboidal and euhedral morphologies across different lithological samples, providing critical insights into the mechanisms of acid mine drainage (AMD) generation in the Sungai Seluang area. **Figure 8A-C** show abundant framboidal pyrite aggregates, typically ranging from a few micrometers to ~10 μm in diameter, often occurring as clustered or disseminated forms within the fine-grained matrix. Framboidal pyrite is characterized by its high surface area and metastable structure, making it highly reactive under oxidizing conditions and a key driver of rapid acid generation. The close spatial association between framboidal and euhedral pyrite indicates multiple stages of sulfide mineral formation, where framboids represent early diagenetic products and euhedral crystals reflect later, more crystalline growth.

Figure 8D highlights euhedral pyrite crystals embedded within fractured host minerals, where microfractures enhance exposure to oxygenated fluids. This textural relationship suggests that structural discontinuities play a significant role in accelerating sulfide oxidation. Overall, the coexistence of highly reactive framboidal pyrite and structurally exposed euhedral pyrite confirms a strong mineralogical control on AMD generation, explaining the persistently low pH values observed in laboratory analyses and reinforcing the classification of these lithologies as dominant Potentially Acid Forming (PAF) materials.

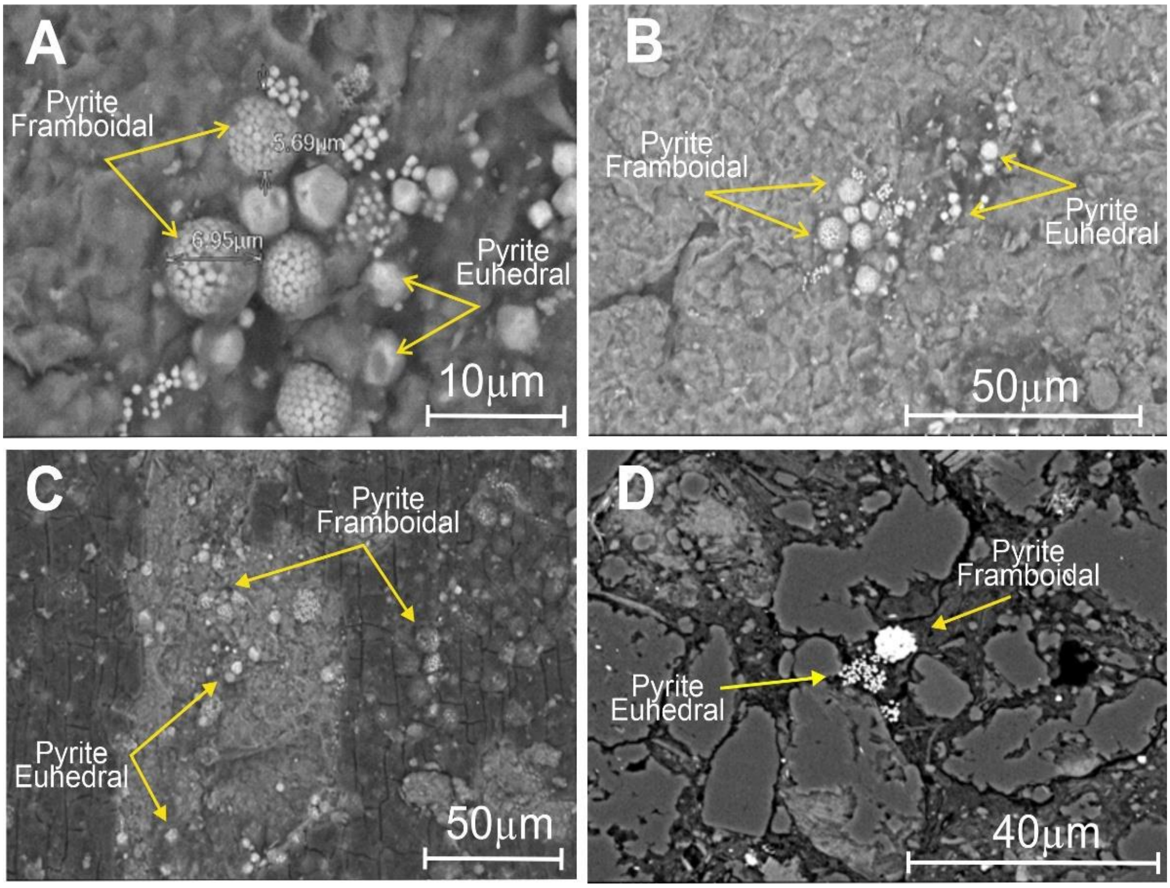

Figure 8. SEM micrographs showing pyrite morphologies in AMD related rock units from the Sungai Seluang area

Relationship Between Pyrite Microtexture and Acid Generation Potential

The relationship between pyrite microtexture and acid generation potential is a key factor controlling the intensity and persistence of acid mine drainage (AMD) in the Sungai Seluang area. Pyrite occurs in distinct microtextural forms, primarily as framboidal and euhedral crystals, each exhibiting different reactivities toward oxidation. Framboidal pyrite, composed of aggregates of microcrystalline pyrite spheres, possesses a very high specific surface area and abundant crystal defects. These characteristics make framboidal pyrite thermodynamically unstable and highly reactive when exposed to oxygenated water, resulting in rapid oxidation and accelerated acid production. SEM observations reveal that framboidal pyrite is particularly abundant within fine-grained lithologies such as claystone and shale, explaining the consistently low pH values and strong Potentially Acid Forming (PAF) classification of these units.

In contrast, euhedral pyrite crystals are generally more crystalline and structurally stable, leading to comparatively slower oxidation rates under similar environmental conditions. However, their acid-generating potential increases significantly when crystals are intersected by microfractures or exposed along grain boundaries. SEM images show that euhedral pyrite is commonly associated with fracture networks and bedding discontinuities, which enhance fluid penetration and oxygen diffusion, thereby sustaining long-term acid generation. The coexistence of framboidal and euhedral pyrite within the same lithological units suggests multiple stages of sulfide formation and implies both short-term intense acid release and prolonged AMD activity.

These microtextural characteristics demonstrate that AMD potential is not governed solely by total pyrite abundance but is strongly influenced by pyrite morphology, crystal size, and textural exposure. Framboidal pyrite drives rapid and severe acidification, while fractured euhedral pyrite contributes to sustained acid generation over extended periods. This microtextural control provides a mechanistic explanation for the extreme acidity observed in both in situ lithologies and disposal materials and highlights the importance of incorporating pyrite texture into AMD risk assessment and mine waste management strategies.

CONCLUSION

Acid mine drainage (AMD) generation in the Sungai Seluang area is primarily controlled by the lithological, mineralogical, and microstructural characteristics of coal-bearing rock units and associated mine waste materials. Integrated field observations, standardized pH measurements, and SEM-based microtextural analyses consistently demonstrate a dominance of Potentially Acid Forming (PAF) materials across both in situ lithologies and disposal sites. The widespread occurrence of low to extremely low pH values confirms that sulfide oxidation is pervasive and actively ongoing, posing a significant and long-term risk to surface water and groundwater systems within the catchment. Fine-grained lithologies, particularly claystone and shale, are identified as the main contributors to AMD generation due to their frequent enrichment in framboidal pyrite, a highly reactive sulfide morphology with a large specific surface area that promotes rapid oxidation under oxic conditions. SEM observations further indicate the coexistence of framboidal and euhedral pyrite, suggesting multiple stages of sulfide mineralization and a sustained acid-generating potential over time. The presence of microfractures and bedding-parallel discontinuities enhances permeability and facilitates oxygen and water ingress, thereby accelerating acid-producing reactions. Although sandstone units generally contain lower sulfide contents, they contribute significantly to AMD generation where fracture networks increase permeability and expose disseminated sulfides to weathering. Mine waste and disposal materials exhibit even higher AMD potential due to loose compaction, elevated surface area, and prolonged exposure to atmospheric conditions. The limited presence of Non-Acid Forming (NAF) materials, particularly within disposal areas, reflects inadequate waste segregation practices and severely restricts the natural neutralization capacity of the system. These findings highlight the importance of lithology-based AMD assessment for effective mitigation and long-term environmental protection in the Sungai Seluang catchment.

AUTHOR CONTRIBUTIONS

Conceptualization, J; methodology, J, EPU, and NM; software, J and MSQ; validation, J, EPU, and HR; formal analysis, J and NM; investigation, MSQ and ECAP; resources, EPU and MSQ; data curation, EPU and NM; writing—original draft preparation, MSQ and ECAP; writing—review and editing, J, HR, and EPU; visualization, MSQ and NM; supervision, J; project administration, EPU; funding acquisition, J.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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