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Review Article

A Comprehensive Framework for Drainage, Dewatering and Treatment Technologies in Acid Mine Drainage Control

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Abstract

Acid mine drainage (AMD) represents a long-term environmental challenge originating from the oxidation of sulfide minerals and mobilization of dissolved metals into surrounding water systems. This study developed a comprehensive framework for AMD control that integrates drainage prevention strategies, hydraulic engineering, active and passive treatment technologies, monitoring systems, and sustainability principles into a unified approach. The framework synthesizes advances in geochemical mine planning, diversion and dewatering systems, hybrid chemical–biological treatment processes, and emerging technologies, including microbial electrochemical systems, selective metal recovery, and digital twins. A life cycle assessment was applied to evaluate environmental and economic trade-offs, emphasizing the potential for circular economy strategies that convert AMD byproducts into valuable resources. This review highlights the importance of adaptive management supported by real-time monitoring, stakeholder involvement, and robust regulatory structures. By connecting technological innovation with policy and ecological restoration objectives, the proposed framework supports resilient AMD control over the entire mine lifecycle and contributes to sustainable post-closure water management.

Keywords: Acid mine drainage; adaptive management: hybrid treatment systems; lifecycle assessment; resource recovery

1. Introduction

Acidic mine drainage (AMD) is one of the most critical and persistent environmental challenges associated with coal and metal mining (Mukherjee et al., 2024). It originates from the oxidation of sulfide minerals exposed during excavation and generates acidic drainage enriched with dissolved metals and sulfates (Wibowo et al., 2022). Once discharged into the surrounding environment, AMD severely degrades water quality, mobilizes toxic elements such as Fe, Al, Cu, Zn, Mn, and As, and induces long-term ecological impacts (Hogsden and Harding, 2012; Lin et al., 2007; RoyChowdhury et al., 2015). These impacts often persist for decades or centuries after mining activities have ceased. The global distribution of AMD is well documented across operating and abandoned mines in North America, Europe, South Africa, China, Indonesia, and Australia (Ashby and Van Etten, 2021; Farooki, 2012; Rajaram et al., 2005), where the environmental liabilities associated with remediation and long-term monitoring reach billions of dollars each year.

Despite decades of research, significant scientific and technological challenges remain in the field of AMD control. The generation of AMD is governed by complex geochemical pathways of sulfide oxidation, coupled with microbial catalysis and hydrogeological conditions that regulate the water flow and contaminant transport. Environmental dynamics, such as rainfall, groundwater recharge, mineralogical heterogeneity, and microbial community evolution, create large variability in AMD composition over space and time. These conditions complicate the design of stable and cost-effective treatment systems for wastewater. Although numerous technologies are available, many existing solutions focus on downstream remediation rather than preventing AMD generation at the source, resulting in fragmented engineering practices and high operational costs.

Current AMD management approaches include chemical neutralization, high-density sludge processes, constructed wetlands, sulfate-reducing bioreactors, membrane filtration, adsorption, and electrochemical methods (Mapukata et al., 2024; Tong et al., 2021; Wei et al., 2018). Although these technologies have demonstrated high removal efficiency in controlled environments, their performance often declines under field conditions owing to fluctuating water chemistry, seasonal hydraulic loads, and maintenance limitations. In addition, there is limited quantitative evaluation of critical factors such as capital expenditure, operational costs, energy demand, sludge handling, and opportunities for resource recovery. Most existing reviews address treatment technologies separately, without integrating mine drainage design, dewatering engineering, and treatment processes into a unified strategy for AMD management.

This gap highlights the need for a holistic and systematic framework that connects the mechanisms of AMD formation, hydraulic and dewatering control strategies, treatment technologies, and resource valorization potential. The objective of this study is to develop a comprehensive framework that integrates drainage design, mine dewatering, and treatment technologies into a coherent management architecture. The framework provides guidance for technology selection based on hydrogeological conditions, water chemistry, sustainability indicators and economic feasibility. It also incorporates circular economy principles by highlighting the potential recovery of metals, sulfates, and rare earth elements from AMD streams. This study advances current knowledge by linking source prevention, hydraulic control, and downstream remediation into one consistent strategy. It introduces a decision hierarchy and sustainability assessment model that can support more informed engineering design, policy development and long-term planning. To the best of our knowledge, this is the first review to systematically integrate AMD formation mechanisms, dewatering and drainage control, treatment approaches, and circular resource recovery into an interdisciplinary and performance-based framework for sustainable mine water management.

2. Materials and Methods

2.1 Study Design and Review Approach

This study employed a structured narrative review combined with a framework development approach to synthesize current knowledge on acid mine drainage (AMD) control across prevention, drainage and dewatering engineering, treatment technologies, monitoring systems, sustainability assessments, and governance mechanisms. The objective was not only to summarize existing technologies but also to construct an integrated, lifecycle-based decision framework that connects geochemical understanding with engineering design, resource recovery, and long-term stewardship. The review followed four sequential stages (Figure 1), as follows:

Figure 1. Stage in review method

2.2 Literature Search Strategy

A comprehensive literature search was conducted using major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. The search covered peer-reviewed journal articles, review papers, conference proceedings, technical guidelines, and international best-practice documents published primarily between 2000 and 2025, with selected earlier foundational works included where relevant. Search keywords were structured using Boolean combinations, including: "acid mine drainage" OR "acid rock drainage"; "AMD prevention" OR "sulfide oxidation control"; "mine drainage" AND "dewatering"; "passive treatment" OR "active treatment"; "sulfate-reducing bacteria" OR "constructed wetlands"; "membrane treatment" OR "electrochemical AMD"; "resource recovery" AND "circular economy"; "life cycle assessment" AND "mine water"; "digital twin" OR "AI in AMD monitoring." Studies were included if they Addressed AMD formation mechanisms, hydraulic control, treatment, monitoring, sustainability, or policy aspects; reported quantitative or mechanistic findings; provided case studies or applied field-scale evidence; or contributed to decision support, lifecycle, or circular economy integration. Publications not directly related to mining-derived acidic drainage or lacking technical relevance were excluded from the study.

3. Result and Discussion

3.1 Fundamentals of Acid Mine Drainage Formation

The formation of acid mine drainage is primarily driven by the oxidation of sulfide minerals, such as pyrite, pyrrhotite, and chalcopyrite, which become exposed to oxygen and water during mining operations (Evangelou and Zhang, 1995; Parbhakar-Fox and Lottermoser, 2017). Figure 2 shows an illustration of AMD generation. When these minerals undergo oxidation, sulfur is converted to sulfate, and ferrous iron is released into the solution, which subsequently oxidizes to ferric iron. Ferric iron acts as a strong oxidizing agent and further propagates sulfide oxidation even in the absence of molecular oxygen, creating a self-sustaining cycle of acid generation in the mine tailings. This process produces protons, which decrease the pH and mobilize metals that were previously immobilized in the mineral matrix. The combined effects of mineralogical composition, reactive surface area, and environmental exposure strongly influence the rate and severity of AMD generation (Figure 3).

Microbial activity plays a significant role in accelerating the AMD formation. Acidophilic microorganisms, such as *Acidithiobacillus ferrooxidans*, catalyze the oxidation of ferrous to ferric iron and enhance sulfide oxidation under acidic conditions (Baker and Banfield, 2003; Bhandari and Choudhary, 2022). These microorganisms thrive in low pH environments established during the early stages of AMD generation, creating a positive feedback loop that intensifies acid production. The metabolic activity of such microbes can increase reaction rates by several orders of magnitude compared with abiotic oxidation processes.

Consequently, sites with favorable microbial communities and abundant sulfide minerals tend to develop AMD rapidly and sustain acid generation over long periods, even after mining operations cease.

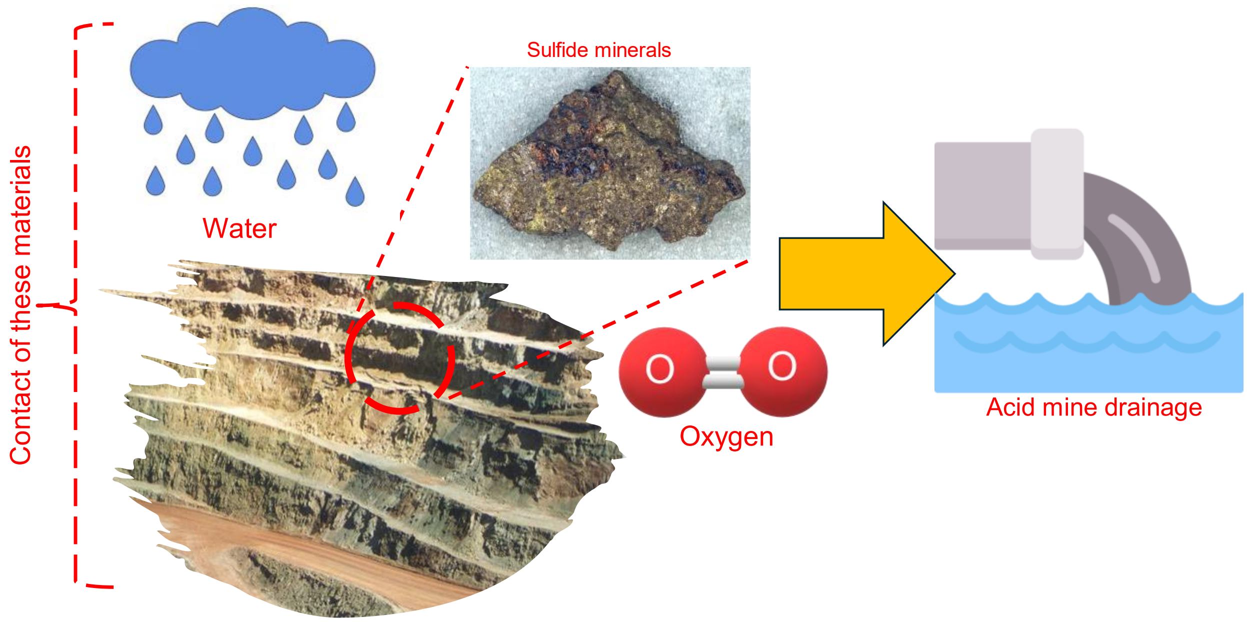

Figure 2. Acid mine drainage generation

Hydrogeological conditions exert significant control over the pathways of water movement and the availability of oxygen required for the oxidation of sulfide. Groundwater recharge, rainfall infiltration, and mine geometry define how water interacts with ore bodies and waste rock piles. In open pits and underground mine voids, stagnant water zones often facilitate prolonged contact between oxidized mineral surfaces and circulating water, promoting the continuous leaching of metals and acidity. Fractured rock networks and mine tunnels create preferential flow paths, allowing oxygen-rich water to penetrate deeper into sulfide-bearing rocks. Seasonal patterns, such as monsoons or snowmelt, can further alter hydraulic gradients and accelerate AMD release. These dynamics highlight the need to understand local hydrogeological settings when designing AMD prevention strategies for long-term sustainability.

The geochemical complexity of AMD is amplified by the presence of secondary minerals and precipitation reactions that occur once acidic water mobilizes metals and sulfate. Iron hydroxides, jarosites, and other secondary precipitates can temporarily immobilize contaminants, releasing them later when environmental conditions change (Cruells and Roca, 2022; Zhang et al., 2023). This transient metal storage creates delayed pollution and complicates predictions of long-term AMD behavior. Therefore, modeling AMD generation requires the integration of mineralogical data with kinetic reaction rates, redox potential, temperature, and microbial activity patterns. A growing body of research applies reactive transport modeling to simulate AMD evolution, but field validation remains challenging because of parameter uncertainty and spatial variability in mine environments. Understanding the fundamentals of AMD formation is essential for designing effective control strategies. Prevention requires minimizing the exposure of sulfide minerals to oxidizing conditions, whereas treatment systems must address the diverse range of metals and low pH conditions in AMD effluents. Insights into geochemical drivers, microbial acceleration, and hydrogeological controls allow engineers to target interventions at critical points where acid generation occurs. By characterizing these mechanisms, it is possible to evaluate the likelihood and future trajectory of AMD at specific sites, prioritize mitigation actions, and support the selection of drainage, dewatering, and treatment technologies within a comprehensive management framework.

3.2 Conceptual Framework for Acid Mine Drainage Control

Developing a comprehensive framework for AMD control requires the integration of prevention, hydraulic management, and treatment into a unified strategy rather than addressing each aspect in isolation. Historically, AMD management has relied on downstream remediation technologies that treat water after contamination, which mitigates symptoms rather than root causes (Skousen et al., 2019). Modern approaches emphasize prevention-first strategies that minimize sulfide mineral exposure and manage hydrological pathways to restrict the transport of contaminants (Wibowo et al., 2023; Yang et al., 2023). This integrated philosophy aligns with sustainable mine water management principles that combine source control, hydraulic design and treatment optimization.

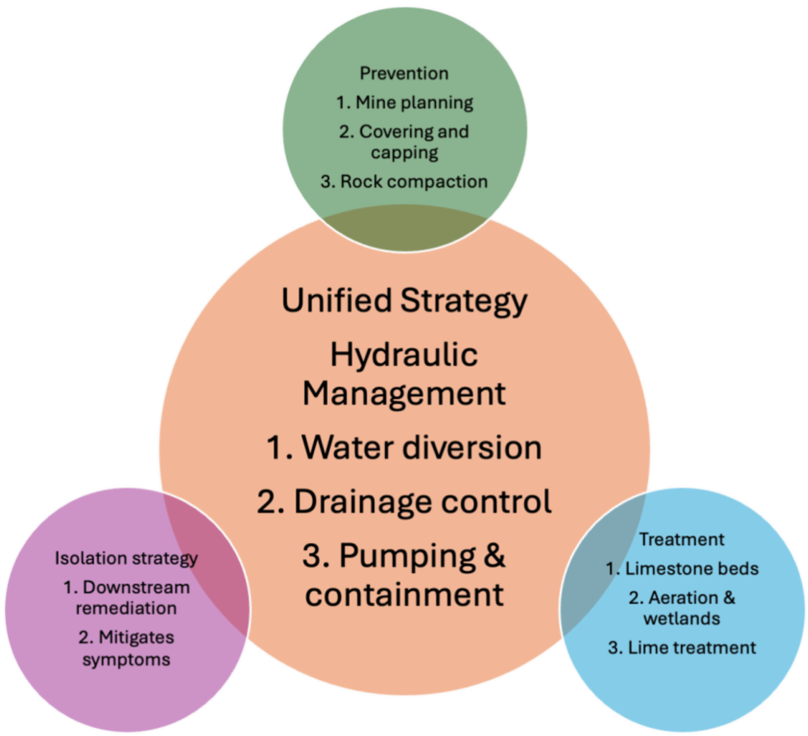

Figure 3. Holistic acid mine drainage control strategies

Because AMD generation is site-specific and influenced by geology, hydrology, and operational conditions, solutions must be tailored through structured decision frameworks that evaluate local mineralogy, water chemistry, and hydrogeology. Recent studies have highlighted that the accurate geochemical characterization of waste rock and predictive modeling of water flow are critical for preventing acid generation and prioritizing intervention points (Junaidi et al., 2024; Simate & Ndlovu, 2021). Bioremediation and passive treatment systems have also been recognized as effective long-term solutions, particularly when combined with preventive measures in mine closure planning (Martin et al., 2010; Younger, 2000).

Hydraulic control and dewatering strategies represent the second layer in this framework. The movement of water through mine workings is a primary driver of contaminant transport, and controlling the hydraulic pathways that deliver oxygen and leaching fluids to sulfide-bearing materials can significantly reduce AMD formation. In practice, hydraulic control techniques include groundwater barriers, interception wells, pumping systems, and engineered drainage networks that redirect surface runoff away from the reactive zones. Dewatering can also be applied within mine voids to prevent the accumulation of oxygen-rich water around the mineral surfaces (Zhang, 2024). By modifying hydrological conditions, these strategies help limit the exposure of sulfide minerals to oxidants and reduce the volumetric load of AMD requiring treatment. Importantly, hydraulic control is not a standalone solution but a critical component that reduces the reliance on energy- and reagent-intensive treatment processes.

The third layer of the framework focuses on treatment technologies that handle residual AMD that cannot be prevented at source. Treatment selection must balance the removal efficiency, operational cost, sludge management, and environmental sustainability. Chemical methods, such as neutralization and precipitation, remain the most widely used solutions because of their reliability (Kalin et al., 2006; Skousen 2014). However, they require continuous reagent inputs and generate large volumes of sludge that require safe disposal. Biological and passive systems, including constructed wetlands and sulfate-reducing bioreactors, offer lower operational costs and are suitable for long-term post-closure management, although they are sensitive to climatic conditions and influent variability (Neculita et al., 2007; Wang et al., 2024). Emerging technologies, such as membrane separation (Al-Zoubi et al., 2010), bioelectrochemical systems (Pozo et al., 2017), and hybrid processes, present new opportunities for improving metal recovery and reducing secondary waste streams (Gusti Wibowo et al., 2024); however, their scalability and cost profiles are still evolving. Within the integrated framework, treatment plays a supporting role and is optimized based on hydraulic control outcomes and source prevention measures.

A key innovation of this framework is the incorporation of resource recovery and circular economy principles. Acid mine drainage contains valuable metals such as copper, zinc, and rare earth elements, as well as sulfate, which can be recovered as gypsum or other industrial products (Baloyi et al., 2023; Wibowo et al., 2025). By shifting the perspective from waste management to resource valorization, AMD can be transformed from an environmental liability to a potential economic resource. This approach encourages the integration of selective precipitation, solvent extraction, ion exchange, and membrane-based concentration processes that allow the recovery of valuable elements while purifying the water stream. Incorporating resource recovery into AMD control creates additional decision criteria related to product purity, market value, and potential for industrial reuse, which can influence the overall design of dewatering and treatment systems.

The final element of the framework is a decision hierarchy that guides engineers and policymakers from site characterization to strategy selection for site remediation. This hierarchy begins with the assessment of AMD generation potential, followed by the evaluation of hydraulic pathways and identification of feasible drainage and dewatering strategies. Treatment technologies are then selected based on the remaining contaminant loads, desired effluent quality, and opportunities for resource recovery. Economic and environmental sustainability metrics were applied at each decision point to ensure that the chosen approach delivered long-term benefits while minimizing operating costs and carbon footprint. By combining prevention, hydraulic control, treatment, and resource recovery into one coordinated architecture, the framework provides a structured basis for sustainable AMD management that can be adapted to different geological contexts and lifecycle stages of mining operations.

3.3 Drainage and Dewatering Strategies

Drainage and dewatering constitute a core layer within integrated AMD prevention frameworks, functioning as the primary hydraulic control mechanisms that regulate water movement through mine systems and limit the exposure of sulfide-bearing materials to oxidizing conditions. Effective design requires a detailed characterization of site hydrogeology, including aquifer structure, fracture networks, geochemical interactions, and surface–subsurface connectivity. This is particularly critical in hydrogeologically complex regions, such as karst environments, where preferential flow paths can rapidly transmit acidic drainage beyond the mine boundary. In such settings, zonal engineering strategies that integrate source control, drainage design, and downstream treatment have demonstrated improved containment performance compared to uncoordinated intervention practices (Hujun et al., 2024).

Consequently, drainage engineering is no longer treated as an auxiliary function but as a fundamental control element embedded within holistic AMD management systems consistent with international guidance, including the Global Acid Rock Drainage (GARD) framework (Verburg et al., 2009).

Dewatering strategies are broadly classified into active and passive systems based on energy demand, infrastructure complexity, and functional objectives of the system. Active dewatering relies on mechanical pumping from underground workings, pit floors, and interception wells to depress water levels and suppress hydraulic gradients in reactive zones. These systems are particularly critical in deep mines and high-recharge settings, where uncontrolled water ingress accelerates sulfide oxidation and structural instability. Chemically assisted dewatering through reagent dosing, typically using $Ca(OH)_2$ or NaOH, remains a widely adopted active treatment approach because of its rapid and predictable neutralization performance (Skousen et al., 2019; Zipper and Skousen, 2014). However, such systems are accompanied by high operational costs, continuous reagent demand, and sludge handling challenges, which restrict their sustainability in long-term postclosure scenarios. To enhance dewatering efficiency in high-moisture mine waste, mechanical–thermal dewatering (MTD) has been applied, particularly in lignite operations, where the removal of bound moisture reduces oxidative exposure and indirectly suppresses acid generation (Strauss et al., 2003).

Passive dewatering systems utilize gravity-driven flow pathways, such as adits, drainage galleries, and engineered channels, to evacuate mine water without mechanical intervention. These systems are generally implemented in parallel with cover systems and surface diversion structures to isolate reactive materials and redirect clean water away from exposed mine wastes. Passive technologies offer substantial advantages in post-closure contexts because of their low energy demand and long-term functional resilience. Constructed wetlands provide an additional passive control layer that exploits biological and geochemical processes mediated by plants and microbial communities to attenuate acidity and metal concentrations (Noor et al., 2021; Pat-Espadas et al., 2018). Dispersed alkaline substrate (DAS) systems further extend passive neutralization capacity by incorporating reactive materials within permeable matrices, although clogging from mineral precipitation remains a long-term limitation (Rötting et al., 2008).

Surface water management functions as a first-order control boundary that intercepts atmospheric inputs before they interact with the sulfide-bearing zones. Diversion channels, berm systems, contour drains, and slope grading practices are employed to minimize infiltration into waste rock and tailing deposits, significantly reducing the AMD generation potential (Galhardi and Soldera, 2018). Stormwater regulation complements these measures by controlling hydraulic loads and erosion under varying climatic conditions. Adapted sustainable drainage systems (SuDS), including retention basins, vegetated swales, sedimentation ponds, and permeable surfaces, reduce peak discharge and regulate water quality in mine landscapes (Bouarafa et al., 2019). Subsurface infiltration structures, such as gravel trenches and infiltration pits, further improve stormwater quality by retaining suspended solids and attenuating flow velocities (Dierkes et al., 2006; Guerra et al., 2019; Held, 2013). In high-flow environments, vortex flow control devices provide hydraulic throttling without additional storage requirements (Stephenson 2005). Physical isolation measures, including clay liners, dry cover systems, and geomembrane barriers, further suppress oxygen diffusion and water percolation into mine wastes, achieving long-term contaminant load reduction under operational conditions (Power 2025).

Groundwater management increasingly incorporates managed aquifer recharge (MAR) as an adaptive hydrological control strategy, particularly in arid and semi-arid mining regions. MAR technologies restore groundwater balance, reduce drawdown, and buffer operational water stress through controlled infiltration and injection practices (Sloan et al., 2023). However, inadequate system design may induce aquifer contamination, groundwater mounding, and clogging, necessitating rigorous pre-implementation assessments and monitoring. Therefore, predictive numerical modeling plays a central role in modern dewatering design by enabling scenario testing and risk forecasting prior to system construction (Różkowski et al., 2021). Environmental evaluation frameworks, such as environmental impact assessments (EIA) supported by fuzzy analytical hierarchy processes (FAHP), further strengthen decision-making by incorporating uncertainty and expert judgment into mitigation planning (Aryafar et al., 2013).

Within the integrated AMD control architecture, drainage and dewatering operate as a second defense layer between source control and treatment technologies. Controlled water movement limits acid generation, reduces contaminant mobilization, and decreases the hydraulic loading on downstream treatment systems. This functional hierarchy aligns with contemporary AMD management frameworks that incorporate geochemical controls, engineered drainage, digital monitoring, and post-closure stewardship as unified design elements (Aubertin et al., 2016; O'Kane et al., 2023; Verburg et al., 2009). As the mining sector transitions toward sustainability-driven operational models, drainage and dewatering systems will remain an indispensable infrastructure, not only for environmental protection but also for enabling circular economy strategies that integrate water management with material recovery and long-term ecological restoration.

3.4 Treatment Technologies for Acid Mine Drainage Control

Treatment technologies constitute the final barrier in the integrated AMD control framework, targeting residual acidity, sulfate, and dissolved metals that remain after source control, drainage engineering, and dewatering processes. Their selection depends on AMD chemistry (pH, sulfate, metal speciation), flow regime, and temporal variability, and must account for long-term operation that often extends far beyond the mine closure. In this context, AMD treatment is increasingly conceptualized as a multi-layered system that integrates chemical, biological, and physical processes to achieve neutralization, metal removal, sulfate reduction, and stable performance under dynamic hydraulic conditions (Kuyucak, 2007, 2006). Beyond regulatory compliance, contemporary design prioritizes waste minimization, resource recovery, and lifecycle sustainability, tightly coupling treatment performance with upstream hydraulic control and downstream reuse objectives.

Chemical processes remain the most widely implemented AMD treatment technologies because of their robustness, operational simplicity, and ability to rapidly adjust pH while removing a broad spectrum of metals. Conventional lime neutralization increases pH and induces the precipitation of metal hydroxides and carbonates, which are subsequently removed by sedimentation or filtration (Kuyucak, 2006). However, this approach generates large volumes of sludge that require secure handling and disposal. Alternative alkaline reagents, such as magnesium oxide (MgO), offer enhanced buffering capacity and more selective precipitation, improving the removal of metals, including Ni, Al, Fe, Zn, Cu, and Mn, and potentially reducing reagent consumption (Nguegang and Ambushe, 2024). Sulfate concentrations, which strongly influence scaling, corrosion, and downstream salinity, can be reduced by precipitation using sodium aluminate or calcium hydrate, forming stable sulfate-bearing phases that reduce overall sulfate loading (Luptakova et al., 2007). Although these chemical strategies are highly effective, their long-term sustainability is constrained by reagent demand, sludge production, and associated energy and logistics requirements. Biological treatment technologies provide a complementary and often more sustainable alternative by exploiting microbial metabolism for sulfate reduction and metal immobilization. Anaerobic bioreactors dominated by sulfate-reducing bacteria (SRB) convert sulfate to sulfide, which then precipitates dissolved metals as metal sulfides, achieving high removal efficiencies for Fe, Cu, Ni, and Zn when temperature, pH, and organic carbon supply are properly controlled (Mafane et al., 2025). Constructed wetlands extend these principles to landscape-scale systems that couple plant uptake, microbial processes, sorption, and mineral precipitation, thus providing low-maintenance treatment with ecosystem co-benefits (Dhir, 2018; Sheoran and Sheoran, 2006). However, both SRB-based systems and wetlands can be challenged by extreme acidity, high metal loads, and seasonal variability, which necessitate careful design of hydraulic residence time, substrate composition, and buffering capacity of the treatment system. Physical technologies typically function as polishing or supporting processes in integrated AMD treatment trains. Adsorption systems utilize materials such as natural zeolites, fly ash, biochar, and clay minerals to bind dissolved metals, with removal efficiencies ranging from moderate to near-complete, depending on sorbent characteristics and operating conditions (Bhuyan and Sahu, 2025; Ighalo et al., 2022). Membrane-based methods, particularly nanofiltration and reverse osmosis, offer high removal (>90%) of metals and sulfate and are especially valuable where high-quality reuse water is required (Ighalo et al., 2022). However, their broader deployment is limited by capital and operational costs, susceptibility to fouling, and the need to manage concentrated brine streams.

System stability under variable flow conditions is a persistent challenge, particularly in climates with pronounced wet–dry cycles or episodic discharge events. Passive systems, such as constructed wetlands and permeable reactive barriers (PRBs), exhibit inherent resilience by relying on natural buffering processes and distributed reaction zones (Yang et al., 2023). However, combining chemical pre-treatment with biological or physical units can significantly enhance system robustness and ecological safety. For example, the integration of alkaline fluidized bed ash with passive treatment has been shown to reduce metal toxicity and accelerate downstream ecosystem recovery (Porter and Nairn 2010). These findings underscore the value of hybrid configurations that exploit the strengths of multiple technologies rather than relying on a single process.

In response to the limitations of conventional neutralization, emerging and hybrid treatment technologies increasingly emphasize sustainability, resource recovery, and reduced environmental footprints (Beauclair et al., 2024). Electrochemical treatment processes apply controlled electrical currents to drive selective precipitation, redox transformations, and metal recovery. Staged electrochemical neutralization, guided by computational modeling, allows the targeted separation of metals and rare earth elements (REEs) while producing lower sludge volumes than lime-based systems (Brewster et al., 2020). Proton exchange membrane (PEM) electrolysis has demonstrated near-complete metal removal from AMD and enables the recovery of high-purity Fe_3O_4, thus transforming a contaminant into a value-added product (Li et al., 2025). Despite these advantages, large-scale implementation is still constrained by capital intensity and energy demand, indicating the need for coupling with low-carbon electricity sources and improved process optimization.

Bioelectrochemical systems (BES) merge microbial catalysis with electrochemical control, harnessing electroactive bacteria to enhance metal sequestration and sulfate reduction under an applied potential. Such systems can reduce chemical inputs and support energy-efficient operations; however, their performance depends on maintaining stable microbial communities and effective reactor control. A promising example of a hybrid design combines MgO nanoparticles with constructed wetlands planted with *Vetiveria zizanioides*, achieving strong removal of Fe, Al, Mn, and sulfate under field conditions and illustrating how reactive materials can be embedded within nature-based systems (Nguegang et al., 2022). Advances in adsorption science have broadened the range of materials available for AMD treatment. Conventional sorbents, such as natural schwertmannites, activated carbons, and clay minerals, remain widely used because of their low cost and effective metal uptake (Dube et al., 2024). Emerging high-selectivity materials, including chromium-based metal–organic frameworks (MOFs) and amine-functionalized SBA15 composites, show enhanced affinity for REEs and other strategic metals, opening new pathways for targeted resource recovery from AMD streams (Fonseka et al., 2024). The challenge now lies in scaling these materials economically and developing regeneration strategies that maintain their performance over multiple cycles.

Membrane technologies continue to evolve beyond traditional pressure-driven systems. Direct contact membrane distillation (DCMD) integrated with photocatalytic processes has demonstrated improved contaminant removal and water recovery while enabling simultaneous iron valorization from AMD (Wang et al., 2021). At a broader process scale, integrated schemes that combine slag-based neutralization, alkaline conditioning, and reverse osmosis have produced potable-quality water and recovered valuable minerals from AMD, illustrating the feasibility of circular and high-value treatment trains (Masindi et al., 2017).

Circular economy principles reframe AMD treatment as a resource recovery opportunity rather than solely a pollution control obligation (Ma et al., 2025; Yang et al., 2023). Iron can be selectively precipitated and transformed into iron oxide pigments suitable for industrial applications, with pH control governing the pigment quality and particle characteristics (Ryan et al., 2017). Iron recovered from AMD has also been used to produce highly active electro-Fenton catalysts for degrading organic pollutants, thereby extending the value chain of AMD-derived materials (Sun et al., 2015). Beyond iron, copper and other base metals can be recovered through leaching–cementation schemes that simultaneously neutralize acidity and stabilize heavy metals in the solid phase (Sözen et al., 2017). Microbial electrolysis cells (MECs) broaden these concepts by enabling concurrent metal recovery and hydrogen generation, thereby linking AMD treatment to renewable energy production (Luo et al., 2014).

Waste minimization is further advanced through the valorization of treatment by-products. Gypsum obtained from sulfate precipitation can be incorporated into brick and cement manufacturing, thereby reducing both disposal volumes and the demand for primary raw materials (Chitransh and Mondal, 2025; Moreno-González et al., 2023). Co-treatment schemes that combine AMD with organic-rich waste, such as livestock effluents, have been shown to enhance microbial activity and improve bioremediation performance while closing nutrient loops (Ma et al., 2024). Novel concepts, such as acid mine drainage fuel cells (AMD-FC), exemplify zero-waste approaches by recovering electrical energy and iron-bearing minerals directly from contaminated water (Ren et al., 2025). From an economic and environmental standpoint, the viability of advanced AMD treatment systems depends on their capacity to generate value streams that offset their operational and maintenance costs. Techno-economic analyses indicate that systems designed to market recovered water, gypsum, pigments, or metal products can transition from cost centers to revenue-generating infrastructures (Shingwenyana et al., 2021). Life cycle assessment (LCA) tools further support decision-making by quantifying energy use, carbon footprints, and material recovery performance across different treatment pathways (Moreno-González et al., 2023; Yang et al., 2023).

Ultimately, the choice of AMD treatment technology must reflect site-specific objectives, including discharge standards, reuse potential, geological context, and long-term closure strategies. In practice, modular and hybrid systems that sequence chemical, biological, physical, and resource-recovery units provide the greatest flexibility for adaptation throughout the mine lifecycle. Post-closure sustainability is reinforced when treatment design is coupled with ecological restoration techniques, such as phytoremediation, functional materials, and landscape-scale ecological engineering (Xu et al., 2019), and when mine sites are embedded within broader circular mining frameworks that prioritize reuse, regeneration, and long-term stewardship (Grande et al., 2018). Within the comprehensive framework of this study, treatment technologies evolve from end-of-pipe solutions into integral components of sustainable, recovery-oriented mine water management.

3.5 Monitoring, Performance Assessment, and Adaptive Management

The effective control of acid mine drainage relies on monitoring systems that capture hydrological, geochemical, and operational dynamics across the entire mine lifecycle, from active extraction to post-closure. Modern AMD monitoring has evolved from periodic grab sampling to continuous intelligent networks capable of supporting early warning and long-term sustainability objectives (Ma et al., 2025). High-frequency field sensors routinely measure pH, electrical conductivity, temperature, dissolved oxygen, flow rate, and related indicators, enabling the real-time characterization of drainage fluctuations and rapid operational responses to abnormal conditions (Cardoso et al., 2024). These in situ measurements are complemented by advanced laboratory analyses, such as ICP spectrometry and ion chromatography for trace metals and sulfate, as well as validated rapid field tests, including colorimetric methods for on-site performance checks and system diagnostics (Behum Jr. and Hicks, 2010). At broader spatial scales, satellite-based remote sensing, particularly Sentinel-2 multispectral imagery coupled with artificial neural networks, has proven effective for mapping dissolved Fe and pH distributions in downstream water bodies (Hanelli et al., 2023). The integration of remote sensing with geographic information systems (GIS) allows the visualization of contamination pathways, vulnerability zones, and pollution hotspots, providing powerful tools for groundwater risk mapping and regional AMD surveillance (Indra et al., 2024).

Performance assessment extends beyond simple compliance with effluent quality criteria to encompass treatment efficiency, reagent consumption, sludge generation and stabilization, energy demand, residual toxicity, and life cycle economic behavior. Statistical modeling, such as regressions between sulfate concentration and electrical conductivity, enables the estimation of key contaminants from real-time sensor outputs, thus strengthening process control and predictive capacity (Cardoso et al., 2024). To align AMD management with broader sustainability goals, integrated life-cycle sustainability assessment (LCSA) frameworks have been introduced, combining life-cycle assessment (LCA) with multi-criteria decision tools, such as the analytical hierarchy process (AHP), to jointly evaluate environmental burdens, operational costs, technical robustness, and resource recovery potential (Yang et al., 2023). These tools support the transparent comparison of alternative treatment trains, clarify the trade-offs between short-term performance and long-term liabilities, and guide the selection of technologies consistent with circular economy objectives.

Adaptive management provides an organizational structure through which monitoring data and performance indicators are translated into iterative improvements in AMD control. In practice, adaptive management follows a continuous cycle of data collection, interpretation, scenario analysis, and intervention, with treatment strategies updated as hydrogeological conditions, climatic drivers, and system behavior evolve (Ma et al., 2025). Contemporary frameworks increasingly embed resource recovery concepts and closed-loop thinking, integrating biotic and abiotic technologies, such as sulfate-reducing bacteria coupled with diffusion dialysis, to transform AMD from a purely negative liability into a source of potentially marketable products and reusable water (Hegab et al., 2020). The rapid expansion of artificial intelligence (AI) and machine learning (ML) is reshaping the implementation of adaptive management. Advanced algorithms can detect emerging risk patterns, forecast contaminant trends, and optimize process parameters using real-time feedback from sensor networks, thereby shifting control strategies from reactive compliance to predictive management (Mardonova et al., 2025). Digital twin platforms extend this capability by creating virtual replicas of mine water systems that are continuously synchronized with live monitoring data. These dynamic models enable scenario testing, such as extreme rainfall, groundwater rebound, treatment failure, early fault detection, and proactive optimization of operational responses under changing environmental conditions (Ma et al., 2025).

Long-term monitoring across all phases of the mine life cycle remains a cornerstone of sustainable AMD management. The Acid Drainage Technology Initiative for the Metal/Mining Sector (ADTI-MMS) emphasizes systematic, multi-decadal data collection from exploration through post-closure to reduce predictive uncertainty and support evidence-based closure planning (McLemore et al., 2007, 2004). When continuous monitoring, advanced analytics, LCSA, and digital twins are integrated within an adaptive management framework, AMD control becomes resilient, transparent, and forward-looking. Such integrated systems not only improve treatment reliability but also strengthen the alignment of AMD management with regulatory expectations, stakeholder concerns and long-term ecosystem protection.

3.6 Sustainability, Environmental Impact, and Lifecycle Considerations

Sustainable AMD management requires a systems-based perspective that considers environmental impacts across the entire mining lifecycle, from exploration and active production to closure and long-term post-mining stewardship. Historically, AMD control has focused on meeting discharge standards, often with limited attention to cumulative environmental burdens or ecological recovery. Contemporary frameworks embed sustainability metrics into decision-making, explicitly evaluating energy use, material consumption, greenhouse gas emissions, ecological integrity, and social implications alongside technical performance. Within this paradigm, early interventions, such as geochemical mine planning, material segregation, and backfilling, form the foundation for reducing long-term environmental liabilities. Therefore, life cycle assessment (LCA) has emerged as a central tool for quantifying these impacts and guiding technology selection based on emissions, resource intensity, waste generation, and operational longevity (Masindi et al., 2018; Yang et al., 2023).

LCA-based comparisons revealed that AMD treatment options differ markedly in terms of environmental footprints owing to variations in energy sources, reagent consumption, and infrastructure needs. Some passive systems, such as dispersed alkaline substrates, exhibit higher initial impacts during installation but demonstrate progressively lower burdens over time as operational benefits accrue (Martínez et al., 2019). The incorporation of renewable energy, particularly solar power, into pumping and treatment processes can reduce greenhouse gas emissions by up to 45%, whereas the utilization of captured carbon dioxide as a process input may cut emissions by approximately 36% (Masindi et al., 2018). These findings underscore the importance of energy sourcing and reagent selection in designing low-carbon AMD mitigation strategies.

Circular economy principles increasingly redefine AMD from a pollutant stream to a secondary resource opportunity. The selective recovery of iron, manganese, and copper via neutralization–precipitation, adsorption, and electrochemical techniques reduces contaminant loads while producing reusable materials for industrial applications (Liu et al., 2025; Ma et al., 2025; Masindi et al., 2022). Downstream valorization further enhances sustainability through the reuse of treatment residues. Metal-rich sludges have been repurposed into construction bricks and phosphorus-removal pellets, yielding lower life cycle impacts than conventional disposal pathways (Moreno-González et al., 2023). Such strategies diversify revenue streams and offset operational costs, thereby strengthening the economic feasibility of long-term AMD management. Carbon mitigation strategies are closely linked to material circularity. Substituting conventional carbonate-based reagents with alternative neutralizing agents reduces the emissions associated with limestone mining and chemical processing (Martínez et al., 2019). Innovative reuse pathways, including calcium carbonate-filled carpet tiles, demonstrate extended material lifecycles, although some solutions introduce modest carbon penalties owing to preprocessing requirements (Bram and Klemetsrud, 2026). Comprehensive LCA remains essential for resolving these trade-offs and preventing burden shifting.

Ecological restoration is a defining objective of sustainable AMD governance, particularly in post-closure contexts, where environmental recovery replaces short-term operational priorities. Integrated frameworks now align pollution control with habitat rehabilitation, hydrological stabilization and biodiversity restoration (Ma et al., 2025). Passive systems, including permeable reactive barriers and constructed wetlands, exhibit lower energy demand and carbon footprints while supporting vegetation recovery and ecosystem function (Martínez et al., 2019; Naidu et al., 2019). The emphasis on resilience and ecological performance increases after mine closure, whereas during active operations, strategies prioritize contaminant control and resource recovery to improve economic viability (Masindi et al., 2022; Yang et al., 2023). Decision-support frameworks increasingly combine life cycle sustainability assessment (LCSA) with multi-criteria decision analysis (MCDA) to integrate environmental, social, and economic indicators into remediation planning (Sarkkinen et al., 2019; Siddique et al., 2025). International guidance reinforces this life-cycle orientation by embedding monitoring, accountability, and financial assurance into closure planning (Nicholls et al., 2025). Collectively, these approaches reposition AMD management as a long-term sustainable enterprise that couples environmental protection with economic prudence and regional ecological restoration.

3.7 Regulatory Frameworks, Policy Integration, and Stakeholder Engagement

Effective AMD control depends not only on engineering solutions but also on strong regulatory systems, coherent policy integration, and sustained stakeholder engagement. Regulatory frameworks establish the legal basis for pollution control, define discharge standards, assign liabilities, and mandate rehabilitation obligations. In the United States, AMD governance is implemented through a combination of federal environmental statutes and state-level mine reclamation laws that regulate permitting, compliance monitoring, and post-mining restoration (Jacobs & Testa, 2014). Comparable regulatory maturity is evident in mining jurisdictions such as Australia, Canada, Germany, and South Africa, where AMD control has been embedded in national water policies and closure planning frameworks (Jacobs and Testa, 2014). However, regional variations in legal enforcement and institutional capacity continue to produce uneven water resource protection, particularly in developing mining economies.

The Global Acid Rock Drainage Guide (GARD Guide), developed by the International Network on Acid Prevention (INAP), is a central international reference for AMD governance. The GARD Guide provides best-practice guidance on AMD prediction, prevention, treatment, and monitoring, thereby supporting the design of risk-based management systems across the mine lifecycle (Verburg et al., 2009). Its applicability has been widely validated in diverse geological and regulatory settings, reinforcing its role as a global governance standard (Kleinmann and Chatwin, 2011). Recent updates have placed a stronger emphasis on sustainability, adaptive management, and accountability mechanisms that extend into post-closure stewardship (Nicholls et al., 2025).

Post-closure liability remains one of the most pressing regulatory challenges because AMD can persist for centuries beyond mine abandonment. International best practices require monitoring programs to begin during exploration and continue indefinitely after closure, ensuring the early detection of system failure and protection of groundwater resources (McLemore et al., 2007, 2004). Financial assurance tools, such as reclamation bonds and trust funds, internalize environmental risks within project economics and minimize the transfer of liabilities to future generations (Nicholls et al., 2025).

Policy integration is essential for translating regulatory intent into effective implementation. Multi-level governance coordination among environmental agencies, mine regulators, water authorities, and local governments improves consistency and reduces duplications. In the United States, collaborative platforms, such as the Acid Drainage Technology Initiative (ADTI), have accelerated innovation and policy learning through partnerships among industry, regulators, and academia (Van Zyl et al., 2006). Global knowledge-sharing networks, including the Global

ARD Alliance and INAP, further support harmonization through training and dissemination of best practices (Gallinger and Fleury, 2006; McLemore et al., 2010). However, fragmented authority remains a barrier in some regions; in South Africa, institutional complexity and operational constraints have limited policy effectiveness, despite strong regulatory intent (Adom and Simatele, 2024).

Stakeholder engagement strengthens legitimacy and implementation. Participatory governance models that incorporate community knowledge, risk communication, and co-design improve transparency and resilience. Inclusive Disaster Risk Reduction (IDRR) approaches used in Pakistan demonstrate how social engagement enhances community preparedness for mining-related water hazards (J. Li et al., 2025). Similarly, community participation is crucial for the sustainability of nature-based remediation initiatives in South Africa (Jansen van Vuuren et al., 2024). The integration of adaptive management with regulatory oversight is further enhanced by emerging digital governance tools, including artificial intelligence for risk prediction and performance monitoring (Mardonova et al., 2025). Collectively, aligned regulations, policy integration, and stakeholder engagement form the backbone of sustainable AMD governance.

3.8 Future Research Directions and Emerging Technologies

Future research on AMD control is increasingly focused on advancing integrated, intelligence-driven, and recovery-oriented systems that link prevention, treatment, monitoring, and sustainability into a single operational architecture to improve AMD management. Building on the drainage and dewatering strategies (Section 4), next-generation research must focus on improving predictive hydrogeological modeling to support proactive AMD prevention. High-resolution reactive transport models that couple groundwater flow, geochemistry, and microbial kinetics are needed to better forecast long-term AMD behavior under evolving climatic and geological conditions in the future. The integration of climate change projections, particularly altered rainfall intensity and temperature patterns, is essential to ensure that drainage systems remain resilient to future hydrological extremes. Additional research is required to optimize the implementation of managed aquifer recharge and subsurface barrier systems to stabilize groundwater regimes while avoiding unintended contamination pathways.

Emerging treatment technologies (Section 5) are expected to evolve toward selective, low-waste, and energy-efficient systems. Electrochemical and bioelectrochemical technologies warrant particular attention because they offer pathways for targeted metal recovery and energy generation while reducing reagent consumption. Research priorities include the development of low-cost electrode materials, improvement of the long-term stability of electroactive microbial communities, and optimization of reactor designs for field-scale deployment. Advanced membrane systems, including hybrid membrane–electrochemical configurations, are also of interest for future AMD control strategies. The focus is shifting toward antifouling materials, low-pressure operation, and zero-liquid discharge configurations to reduce waste generation and energy demand. In parallel, high-selectivity adsorbents, such as functionalized biochars, metal–organic frameworks, and nano-engineered minerals, represent opportunities for rare earth and critical metal recovery; however, improvements in regeneration efficiency, scalability, and lifecycle sustainability are required before widespread adoption.

The monitoring and adaptive management landscape (Section 6) is being transformed by artificial intelligence, the Internet of Things (IoT), and digital twin technology. Future research will increasingly emphasize autonomous monitoring networks that can diagnose system failures, forecast contaminant trends, and optimize treatment parameters using real-time data. Digital twins of mine water systems represent a major research frontier, allowing scenario-based planning, fault detection, and dynamic redesign of treatment infrastructure across the mine life cycle. Coupling machine learning with physics-based hydrogeochemical models will improve interpretability and reduce uncertainty in long-term performance predictions. Research is also needed on the integration of satellite remote sensing, drone surveillance, and in situ sensors into unified monitoring platforms that operate at both the site and catchment scales.

From a sustainability perspective (Section 7), future studies should strengthen the application of life-cycle sustainability assessment (LCSA) and circular economy principles in AMD management. Comparative studies evaluating the carbon footprint, energy intensity, and water reuse potential of alternative treatment designs are required to guide investment decisions and regulatory development. Greater attention should be paid to net-zero AMD treatment systems through renewable energy integration, passive–active hybridization, and material reuse strategies. Research into the beneficial reuse of treatment residuals, including the conversion of sludge into construction materials or reactive media, will further reduce long-term waste burdens. Ecosystem-scale restoration science must also advance, particularly in sediment stabilization, biotope reconstruction, and long-term biodiversity recovery following mine closure.

Governance and stakeholder engagement (Section 8) also present important research opportunities. The application of digital governance tools, including automated compliance monitoring and risk-based regulatory triggers, offers new opportunities to improve oversight and transparency. Comparative studies of international regulatory systems would assist in identifying effective policy instruments and closing governance gaps across jurisdictions in the future. Social science research is equally critical, particularly in understanding community risk perception, participatory governance models, and mechanisms for building long-term public trust in AMD remediation programs in Pennsylvania. Overall, future AMD research will be defined by the convergence of digital technologies with environmental engineering, resource recovery with sustainability planning, and policy innovation with community participation. By advancing interdisciplinary research and field-scale validation, next-generation AMD control systems can evolve from reactive remediation to predictive, regenerative, and circular management models that deliver lasting environmental and social value.

4. Conclusion

AMD remains one of the most complex and enduring environmental challenges associated with mining activities because of the long-term reactivity of sulfide-bearing materials and the interconnected hydrological systems that transport acidic and metal-rich waters into surrounding ecosystems. This review presents a comprehensive and integrated framework that unifies drainage engineering, dewatering strategies, treatment technologies, monitoring systems, sustainability principles, governance mechanisms, and future innovation pathways into a single lifecycle-oriented approach for AMD management. The framework emphasizes that no single intervention can provide a universal solution and that effective AMD control requires site-specific combinations of prevention, hydraulic management, and treatment technologies, guided by robust scientific understanding and adaptive planning. Drainage and dewatering are highlighted as the second line of defense following source control, functioning to regulate water movement, suppress sulfide oxidation, and reduce hydraulic loading on downstream treatment systems. Treatment strategies have evolved beyond conventional chemical neutralization toward hybrid systems that integrate chemical, biological, and physical processes with emerging electrochemical and bioelectrochemical technologies. These innovations not only improve the contaminant removal efficiency but also enable selective metal recovery, thereby supporting circular economy objectives. The integration of advanced monitoring technologies and adaptive management frameworks represents a paradigm shift in AMD governance. Real-time sensor networks, remote sensing, and digital twin platforms enable continuous system evaluation, predictive risk management, and informed operational decision-making throughout the mine lifecycle. Together with life-cycle sustainability assessment and carbon mitigation strategies, these tools allow AMD control systems to be evaluated not only for technical performance but also for long-term environmental and socioeconomic impacts.

Regulatory coherence and stakeholder engagement are essential enablers of sustainable AMD management. International frameworks, such as the GARD Guide, provide a foundation for harmonized standards, while financial assurance mechanisms and long-term monitoring obligations ensure accountability beyond mine closure. Meaningful participation by affected communities enhances the transparency, trust, and social legitimacy of remediation programs. Thus, AMD management is transitioning from reactive pollution control to predictive, recovery-oriented, and sustainability-driven practices. The future of AMD governance lies in the convergence of digital technologies, resource recovery, and ecological restoration within adaptive regulatory frameworks. By embracing this integrated framework, mining operations can reduce long-term environmental liabilities, improve economic efficiency, and contribute to the rehabilitation of degraded landscapes, ensuring that mineral resource development aligns closely with the principles of environmental stewardship and intergenerational responsibility.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) used ChatGPT to improve the readability and fix grammatical errors. After using these tools/services, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Ethics Declaration

This study did not require ethical clearance.

CRedIT authors statement

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