

Long-Term Performance Evaluation of Acid Mine Drainage Treatment Technologies: A Systematic Literature Review

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ABSTRACT

Acid Mine Drainage (AMD) remains a persistent environmental challenge due to its low pH and high concentrations of dissolved metals. **This study aimed to** evaluate the long-term performance of AMD treatment technologies through a systematic literature review. **Following the PRISMA framework**, 29 peer-reviewed studies published between January 2022 and March 2026 were analyzed from Scopus, ScienceDirect, Web of Science, and Google Scholar. The studies were classified into active, passive, hybrid/emerging, and biological treatment technologies. Active treatment provided rapid pH correction and high metal removal efficiency but was constrained by sludge generation, reagent consumption, and operational costs. Passive systems required less operational input but experienced performance deterioration associated with substrate depletion, clogging, and inconsistent contaminant removal. Hybrid/emerging technologies demonstrated promising potential for improving treatment efficiency and resource recovery; however, long-term field validation remains limited. Biological technologies also showed potential for sulfate reduction and metal recovery, although their long-term applicability remains constrained by substrate requirements and environmental sensitivity. From a sustainable-development perspective, AMD treatment is directly relevant to SDG 6, particularly Targets 6.3 and 6.6, and is also connected to SDG 12.2 on sustainable resource use and SDG 13.1–13.2 on climate resilience and planning. **Overall, long-term AMD treatment assessment should** integrate technical performance, operational sustainability, environmental recovery, field-scale validation, resource recovery, and measurable contributions to relevant SDG targets.

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1. INTRODUCTION

Acid Mine Drainage (AMD) constitutes a major environmental challenge associated with mining activities [1, 2]. AMD forms when sulfide-bearing minerals are exposed to oxygen and water, producing acidic water containing dissolved metals and sulfate that can degrade surface water, groundwater, soils, and aquatic ecosystems [3]. Recent reviews emphasize that AMD management should therefore be evaluated not only in terms of contaminant removal, but also in relation to long-term environmental protection, resource recovery, and the sustainability of treatment systems [4, 5].

Active chemical neutralization remains an important approach because alkaline reagents can rapidly increase pH and precipitate dissolved metals. Recent experimental work using magnesium oxide, for example,

reported substantial removal of Cu, Ni, Fe, Al, Mn, and Zn while also demonstrating the possibility of recovering chemical species from the treatment process [1, 6]. Nevertheless, neutralization can generate substantial precipitate or sludge, creating an additional management burden. A 2024 study of lime neutralization showed that gypsum and metal hydroxides can constitute a major fraction of the generated precipitate, confirming the importance of sludge minimization in long-term treatment planning [3, 7].

In response to these limitations, passive treatment systems have been developed as lower-input alternatives that rely on natural or semi-natural biogeochemical processes [8]. Permeable reactive barriers and related passive systems can reduce operational requirements, although their long-term performance depends on media selection, hydraulic conditions, contaminant loading, and the progressive depletion or clogging of reactive media [9, 10]. Recent studies of constructed wetlands and composite substrates also show that treatment performance may decline under strongly acidic conditions, highlighting the need to match passive-system design with site-specific AMD chemistry [11, 12].

Within the 2030 Agenda, AMD treatment has a direct relationship with SDG 6 (Clean Water and Sanitation), especially Target 6.3 on improving water quality by reducing pollution and Target 6.6 on protecting and restoring water-related ecosystems. It also supports SDG 12 through more sustainable management and efficient use of natural resources, including opportunities for recovery and reuse of treatment by-products, and SDG 13 where treatment strategies reduce resource and carbon burdens and incorporate climate-related considerations into environmental management [13, 14].

Hybrid and emerging technologies have increasingly been proposed to combine the rapid treatment capacity of active processes with the lower resource requirements or recovery potential of passive and biological approaches [9]. Recent reviews conclude that there is no single treatment configuration that is universally optimal and that combinations should be selected according to AMD composition, target contaminants, and intended effluent use [5, 15]. However, a persistent research gap concerns the translation of promising laboratory or pilot-scale performance into durable field-scale treatment. Accordingly, this systematic review evaluates long-term performance by comparing treatment categories, treatment scales, performance indicators, operational requirements, environmental implications, and limitations, while explicitly positioning the findings within relevant Sustainable Development Goal (SDG) targets [16, 17, 18].

2. METHODS

2.1. Search Strategy

This systematic literature review was conducted following the PRISMA framework to ensure transparency and reproducibility [10]. A comprehensive search of electronic databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, was undertaken to identify peer-reviewed articles published between January 2022 and March 2026. The search was restricted to peer-reviewed English-language publications published between January 2022 and March 2026. This relatively recent publication window was selected to capture the latest developments in AMD treatment technologies and to ensure that the review reflects contemporary treatment approaches, performance indicators, and sustainability considerations [19, 20]. Because the primary objective of this review was to evaluate recent technological developments and their reported long-term performance implications, studies published before 2022 were not included in the systematic evidence synthesis. However, this temporal restriction may exclude earlier field-monitoring studies that provide valuable evidence on treatment performance over periods of several decades [21, 22]. Such historical evidence was therefore recognized as an important limitation of the present review and as an area for future research. Additionally, the reference lists of retrieved articles were manually screened to identify additional studies of relevance.

2.2. Inclusion and Exclusion Criteria

Studies were included if they met all of the following criteria: (1) the study directly addressed AMD treatment using active, passive, hybrid/emerging, or biological technologies; (2) the study reported quantitative or qualitative evidence of treatment performance, including pH improvement, metal removal efficiency, sulfate reduction, or ecological recovery; (3) the study provided evidence relevant to long-term performance, defined as sustained treatment performance over an extended observation period or evidence concerning performance stability, degradation, media or substrate exhaustion, clogging, armoring, maintenance requirements, or long-term applicability; and (4) the study was a peer-reviewed journal article published in English between January 2022 and March 2026.

Studies were excluded if they: (1) did not specifically evaluate AMD treatment; (2) focused exclusively on AMD prediction, formation, or prevention without evaluating treatment performance; and (3) did not provide evidence relevant to sustained treatment performance or long-term applicability. The study identification, screening, eligibility assessment, and final selection process are presented in the PRISMA 2020 flow diagram in Fig. 1.

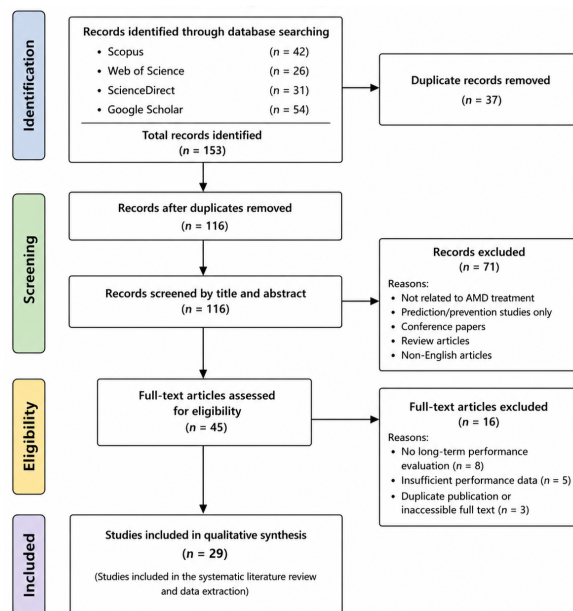


Figure 1. PRISMA 2020 flow diagram

2.3. Data Extraction and Analysis

Data were extracted from each included study using a standardized form covering author(s), publication year, study location, treatment technology, treatment scale, AMD characteristics, operating conditions, treatment duration, performance indicators, long-term performance outcomes, and reported limitations. To improve comparability across studies, the extracted evidence was standardized according to technology category, treatment scale, initial AMD characteristics, contaminant type, performance indicator, and observation period [11, 23]. Where reported, pH improvement, metal removal efficiency, sulfate reduction, treatment duration, and operational requirements were recorded together with the corresponding experimental or field conditions [24].

Quantitative synthesis was conducted using a stratified comparison rather than direct pooling of all reported values [5, 15, 25]. Performance results were first grouped according to treatment category and then interpreted in relation to treatment scale, AMD characteristics, and evaluation parameters [4]. Laboratory/pilot-scale and field-scale evidence were considered separately to avoid inappropriate comparisons between controlled experimental conditions and heterogeneous field conditions. Reported performance values were summarized as ranges when sufficient comparable data were available. Statistical meta-analysis was not performed because of substantial heterogeneity in AMD composition, treatment configurations, operating conditions, performance indicators, and monitoring durations. Accordingly, the quantitative synthesis was used to identify performance patterns and comparative tendencies rather than to estimate a single pooled treatment effect.

2.4. Data Extraction and Quantitative Synthesis

Data were extracted using a standardized form covering study characteristics, treatment technology, treatment scale, observation period, AMD characteristics, and reported treatment-performance indicators. Quantitative indicators included pH improvement, metal removal efficiency, sulfate reduction, treatment duration, and other technology-specific performance measures when available [13, 26, 14]. A structured quantitative synthesis was performed to complement the descriptive analysis. For each treatment category, reported performance values were summarized as ranges and, where sufficient comparable data were available, compared

across technologies. The synthesis also distinguished laboratory/pilot-scale evidence from field-scale evidence to avoid direct interpretation of results obtained under substantially different operating conditions. The proportion of studies reporting specific performance indicators and the distribution of studies across treatment categories and treatment scales were also summarized.

A statistical meta-analysis was not conducted because the included studies differed substantially in AMD composition, treatment configurations, operating conditions, monitoring durations, performance indicators, and experimental or field designs. Consequently, pooling effect sizes across studies would not provide a sufficiently valid or meaningful estimate of comparative treatment performance. The quantitative synthesis therefore focused on transparent comparison of reported performance ranges and study distributions rather than statistical aggregation of heterogeneous effect sizes.

3. RESULTS

3.1. Overview of Included Studies

The systematic search and screening process identified 29 peer-reviewed studies that met the inclusion criteria. As shown in Fig. 2, the studies covered active chemical neutralization ($n = 9$), passive treatment ($n = 5$), hybrid/emerging technologies ($n = 8$), and biological treatment ($n = 7$). Table 1 summarizes the selected studies according to treatment technology, treatment scale, key performance outcomes, and long-term limitations. Most studies ($n = 18$) were conducted at laboratory or pilot scale, while 11 studies reported field-scale performance, indicating a notable gap between controlled experimental conditions and real-world implementation. This difference should be considered when interpreting long-term sustainability and SDG-related outcomes, as laboratory performance does not necessarily demonstrate durable improvements in water quality or ecosystem protection at operational mine sites.

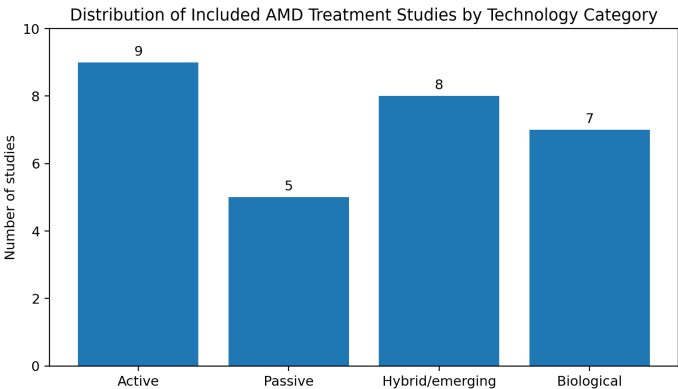


Figure 2. Distribution of included AMD treatment studies by technology category.

Table 1. Summary of Included Studies on AMD Treatment Technologies and Their Long-Term Performance

Study	Technology Type	Treatment Scale	Key Performance Outcomes	Long-Term Limitations
Azizi et al. (2024) [2]	Active (MgO selective precipitation)	Laboratory	Removed Cu and Ni by 100%; Fe 99.9%; Al 99%; Mn 98.6%; Zn 97.2%; sulfate 76%.	Chemical precipitation can generate sludge; long-term field validation remains limited.
Pocaaan et al. (2025) [10]	Passive (Mixed media)	Laboratory	Optimized mixed media achieved pH < 9 and 70–99% removal for Cu, Fe, Mn, Ni, and Al.	Long-term stability and performance under variable field conditions remain uncertain.
Li et al. (2025) [24]	Hybrid (Electrochemically Activated Lime-stone)	Laboratory + actual AMD	Extracted 82.3–100.0% of Cu, Cd, and Zn with high-purity metal recovery.	Commercial-scale validation and broader long-term evidence remain limited.
Munyai et al. (2024) [27]	Active (Quicklime + Fly Ash)	Field	Improved water quality and ecological indicators in AMD-affected agricultural systems.	Residual sulfate and metals require continued long-term monitoring.
Cun et al. (2024) [11]	Passive (Constructed wetland + composite substrate)	Laboratory	Composite organic substrates supported AMD treatment through abiotic and biotic pathways.	High acidity reduced treatment performance and inhibited functional microbial activity.

Study	Technology Type	Treatment Scale	Key Performance Outcomes	Long-Term Limitations
Piñon-Flores et al. (2024) [28]	Active/adsorptive (Mn-oxide waste)	Laboratory	Demonstrated removal of multiple metals from real AMD using mining-derived Mn-oxide waste.	Performance and regeneration requirements require further long-term assessment.
Pocan et al. (2025) [26]	Passive (Mixed Media)	Laboratory	Mixed media approach using limestone, low-grade ores, fly ash, and concrete wastes effectively treated AMD.	Individual materials can only partially remove sulfate and heavy metals; long-term stability uncertain.
Frederico et al. (2022) [29]	Biological (Sulfate-Reducing Bacteria)	Laboratory (Continuous-Flow Bioreactor)	SRB bioreactors achieved high sulfate reduction and metal recovery rates under optimized conditions. Bio I reduced sulfate to 4.7–19 mM in the effluent, while Bio II achieved 5.6–18 mM.	Two acidophilic sulfidogenic consortia were operated for 302 days. Bio I reduced sulfate to 4.7–19 mM, while Bio II achieved 5.6–18 mM. Both bioreactors showed similar performance in treating acidic mine water.
Stylianou et al. (2022) [23]	Hybrid (Electrocoagulation)	Laboratory	Highly effective in removing heavy metals and anions from AMD.	Metal removal efficiency varied over time; dependency on final pH and electrode material.

3.2. Active Treatment Technologies

Active chemical neutralization remains an important AMD treatment approach because it can rapidly increase pH and remove dissolved metals. Recent evidence indicates that selective precipitation can achieve high removal efficiencies while creating opportunities for chemical-species recovery. However, precipitate formation remains a central long-term consideration. Lime-neutralization studies show that gypsum and metal hydroxides can account for a substantial proportion of treatment residues, reinforcing the need to evaluate sludge generation and residue management together with water-quality performance.

Recent work also indicates that active treatment can be improved through resource-efficient materials and process integration. Research on biochar–CaO composites derived from solid waste demonstrates the potential to combine neutralization and adsorption while reducing dependence on conventional treatment inputs. These developments support the use of active systems where rapid correction is necessary, but they do not eliminate the need for long-term monitoring of residual contaminants, sludge, reagent demand, and ecological recovery.

3.3. Passive Treatment Technologies

Passive treatment systems offer a lower-input alternative to active neutralization by relying on natural or semi-natural treatment processes. Recent reviews of permeable reactive barriers identify their relatively modest operational requirements and potential long-term stability, while also emphasizing the importance of material selection, hydraulic conditions, and barrier design. Experimental work with mixed media has likewise demonstrated substantial removal of several metals, but the long-term stability of the media under variable AMD conditions remains an important uncertainty.

Constructed wetlands and other passive biological systems can provide additional treatment functions, including sulfate reduction and contaminant immobilization. However, recent evidence shows that strong acidity can reduce both abiotic and biotic treatment pathways and inhibit functional microorganisms. Adsorption studies also indicate that treatment media can display contaminant selectivity, meaning that high removal of one metal does not necessarily imply comprehensive removal of all target contaminants. These findings support the conclusion that passive systems should be evaluated over their anticipated service life rather than on initial removal efficiency alone.

3.4. Hybrid and Emerging Technologies

Hybrid and emerging technologies represent a promising frontier because they seek to combine the efficiency of active methods with resource efficiency, recovery potential, or biological processes. The electrochemically activated limestone (EAL) system reported by Li et al. extracted 82.3–100.0% of Cu, Cd, and Zn from AMD and demonstrated the potential for valuable-metal recovery. Recent reviews similarly conclude that combinations of treatment technologies can be selected according to AMD composition and the intended quality or end use of the treated water.

Electrochemical and adsorption-based approaches also demonstrate the potential of hybrid treatment. Recent mine-water research combining electrocoagulation with ceramic membrane filtration achieved high heavy-metal removal while reducing suspended solids and supporting reuse or discharge objectives. These results are promising, but the broader literature still indicates that scale-up, energy demand, material regeneration,

and long-term field monitoring must be addressed before laboratory or pilot results are treated as established long-term performance.

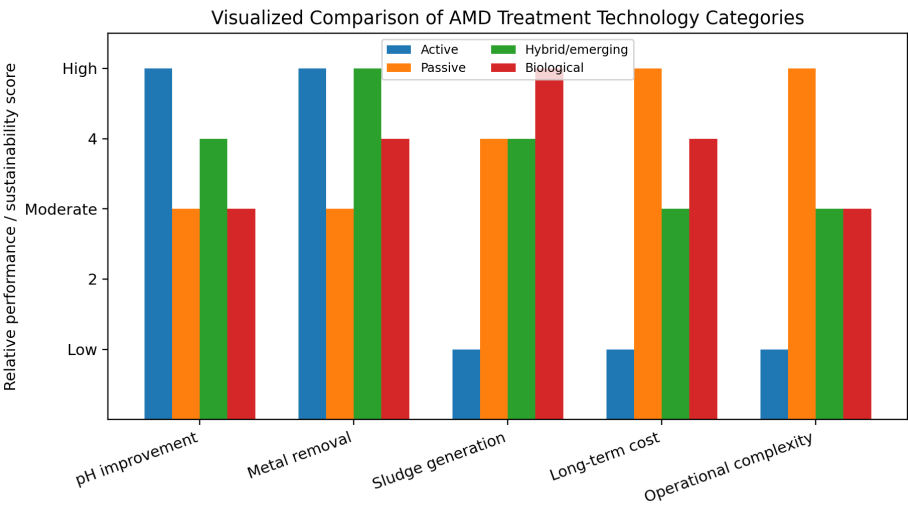


Figure 3. Visual comparison of performance and sustainability characteristics across AMD treatment technology categories

Table 2. Comparative Performance and Sustainability of AMD Treatment Technology Categories

Performance Metric	Active Neutralization	Passive Treatment	Hybrid/Emerging	Biological Treatment
pH Improvement	Rapid (pH 6 to 9)	Gradual (pH 6 to 8)	Rapid to moderate	Moderate (pH 6 to 7)
Metal Removal Efficiency	80% to 100% (Fe, Al); variable (Mn)	60% to 90% (Fe, Cu); limited (Mn)	82.3% to 100% (Cu, Cd, Zn)	70% to 95% (sulfate reduction)
Sludge Generation	High	Low to moderate	Low to moderate	Low
Long-Term Cost	High (reagent, sludge disposal)	Low (maintenance only)	Moderate (energy, materials)	Low to moderate (substrate)
Operational Complexity	High (continuous monitoring)	Low (minimal intervention)	Moderate to high	Moderate (process control)

3.5. Biological Treatment Technologies

Table 3. Key Long-Term Challenges and Limitations of AMD Treatment Technologies

Technology Category	Long-Term Challenge	Supporting Evidence
Active Neutralization	Armoring of neutralizing agents by iron hydroxide and gypsum coatings; excessive sludge production; escalating reagent costs	[2, 3, 27]
Passive Treatment	Clogging by accumulated precipitates; declining substrate reactivity; inconsistent removal of all target contaminants	[9, 10, 11, 23]
Hybrid/Emerging	Lack of commercial-scale validation; sensitivity to water chemistry fluctuations; uncertain long-term stability of novel materials	[24, 5]
Biological Treatment	Substrate availability and cost; microbial sensitivity to environmental conditions; process instability during startup	[? 25]
All Categories	Disparity between laboratory and field performance; insufficient long-term monitoring data; limited integration of chemical and biological recovery indicators	[4, 5, 11]

Biological treatment technologies, particularly those employing sulfate-reducing bacteria (SRB), have gained increasing attention as lower-chemical-input approaches. Recent research demonstrates that sulfate-reducing systems can remove metals and sulfate through biologically mediated sulfide formation, while newer work explores bioaugmentation and substrate optimization to improve performance under acidic conditions.

These approaches are consistent with sustainability objectives because they can reduce dependence on conventional chemical neutralization and create opportunities for sulfur or metal recovery.

Despite this potential, biological systems remain sensitive to substrate availability, microbial adaptation, pH, temperature, and contaminant loading. Recent reviews and experimental studies emphasize that biological treatment is promising but still requires careful control of operating conditions and further validation under realistic mine-water conditions. Therefore, claims of long-term sustainability should distinguish between sustained laboratory performance and demonstrated field-scale durability.

3.6. Quantitative Synthesis of Treatment Performance

The quantitative synthesis demonstrated substantial differences in reported AMD treatment performance, although direct statistical comparison was not feasible because of methodological heterogeneity. Active systems generally provide rapid pH correction and high metal-removal performance, while passive systems offer lower operational inputs but greater sensitivity to media condition and water chemistry.

Hybrid and emerging technologies showed promising quantitative performance, including high removal of selected metals in recent laboratory and pilot studies. Li et al. reported 82.3–100.0% extraction of Cu, Cd, and Zn using electrochemically activated limestone, while recent hybrid mine-water treatment achieved high removal of several heavy metals in a combined electrocoagulation–membrane process. These results indicate technological potential, but they should not be interpreted as proof of superior long-term field performance without extended monitoring.

Biological treatment evidence also indicates promising sulfate and metal removal, including recent SRB-based systems and integrated microbial approaches. Overall, the quantitative evidence suggests that active systems remain well established for rapid treatment, whereas passive, hybrid/emerging, and biological technologies provide complementary advantages that require technology-specific evaluation of durability, environmental effects, and field-scale applicability.

4. DISCUSSION

4.1. Synthesis of Long-Term Performance Findings

The findings of this systematic review reveal a consistent pattern across AMD treatment categories: short-term treatment performance can be strong, but long-term sustainability depends on whether the system can maintain removal efficiency while controlling operational inputs, residues, and environmental impacts. As illustrated in Fig. 4, long-term evaluation should consider treatment performance together with technology-specific limitations and sustainability considerations. Active systems offer rapid treatment but can generate substantial residues; passive systems reduce operational inputs but can experience media exhaustion or clogging; hybrid and emerging systems offer efficiency and recovery potential but require stronger field validation; and biological systems depend on stable ecological and substrate conditions.

Passive treatment systems, while offering economic and operational advantages, require careful consideration of media performance over time. Recent evidence on reactive barriers, mixed media, and adsorption confirms that clogging, declining reactivity, and contaminant selectivity can influence long-term performance. Consequently, system design should include a service-life assessment, monitoring plan, and provision for media rehabilitation or replacement.

Hybrid and emerging technologies show potential to improve treatment performance while reducing resource burdens and enabling resource recovery. Li et al. reported high metal extraction using electrochemically activated limestone, while other recent hybrid approaches have demonstrated high removal of mine-water contaminants and opportunities for water reuse. However, these advantages should be interpreted as promising technological potential until supported by sufficiently long field monitoring and robust life-cycle or techno-economic assessment.

Biological treatment may reduce dependence on chemical neutralization and support sulfate reduction and contaminant transformation. However, substrate requirements, microbial sensitivity, and process stability introduce additional operational constraints. Across recent studies, standardized quantitative information on treatment costs, energy consumption, complete life-cycle impacts, and resource-recovery yields remains insufficient for direct cross-technology comparison. Overall, no single AMD treatment category can currently be considered universally superior across technical, economic, environmental, and resource-recovery dimensions.

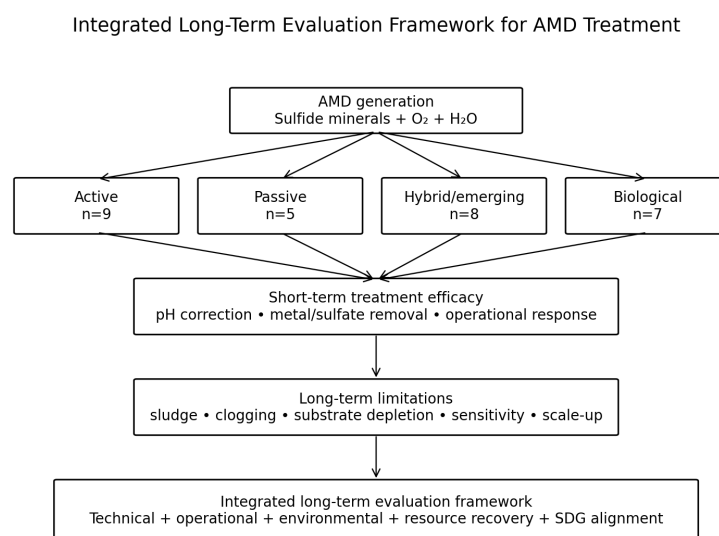


Figure 4. Integrated long-term evaluation framework linking AMD treatment categories, performance, limitations, and SDG-oriented sustainability assessment.

4.2. Environmental Implications and Sustainability Considerations

The environmental implications of long-term AMD treatment extend beyond immediate improvements in water quality to include economic feasibility, energy consumption, life-cycle environmental impacts, maintenance requirements, and opportunities for resource recovery. Recent studies demonstrate that treatment residues can themselves become a management challenge, while selective precipitation and recovery processes may create opportunities to valorize metals and other treatment products. Therefore, treatment efficiency should be evaluated together with reagent or substrate demand, residue generation, energy requirements, maintenance, and recovery potential.

Passive treatment generally requires lower operational and energy inputs because it relies on natural or semi-natural processes. Nevertheless, recent evidence indicates that media depletion, clogging, acidity, and contaminant-selective removal can reduce long-term reliability. Lower operational requirements should therefore not be interpreted as unlimited sustainability.

Hybrid and emerging technologies show potential to improve treatment performance while reducing resource burdens and enabling resource recovery. Li et al. reported high metal extraction using electrochemically activated limestone, while other recent hybrid approaches have demonstrated high removal of mine-water contaminants and opportunities for water reuse. However, these advantages should be interpreted as promising technological potential until supported by sufficiently long field monitoring and robust life-cycle or techno-economic assessment.

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4.3. Alignment with Sustainable Development Goals (SDGs)

AMD treatment directly contributes to the water-quality and ecosystem objectives of SDG 6. Target 6.3 calls for improved water quality through reduced pollution and safer treatment of wastewater, while Target 6.6 emphasizes the protection and restoration of water-related ecosystems. In this review, these targets provide a clear sustainability lens for evaluating whether treatment technologies merely reduce contaminants at the treatment point or also contribute to durable protection of receiving waters.

The review also supports SDG 12, particularly Target 12.2 on sustainable management and efficient

use of natural resources. This linkage is evident in the growing emphasis on metal recovery, residue valorization, lower reagent demand, and the reuse of treated mine water. Where treatment technologies reduce material inputs or enable recovery of valuable metals, their contribution extends beyond pollution control toward more circular resource management.

SDG 13 is relevant because treatment choices can influence energy demand and greenhouse gas emissions, while climate-related changes in water availability and hydrological variability can affect AMD treatment performance. Accordingly, long-term AMD management should incorporate climate resilience and resource efficiency into technology selection, consistent with SDG Targets 13.1 and 13.2. Taken together, SDG 6 provides the primary alignment for this review, while SDGs 12 and 13 provide complementary dimensions for evaluating resource efficiency, circularity, and climate resilience.

4.4. Practical Implications for Technology Selection

The findings of this review indicate that technology selection for AMD treatment cannot be based solely on reported removal efficiencies, but must instead account for site-specific mining conditions and field-scale operation. Active neutralization is most appropriate where AMD severity is high and rapid, predictable pH correction is required, provided that sludge management infrastructure and reagent supply are available. Passive systems are better suited to sites where land is available, operational inputs are limited, and long-term maintenance access is feasible. Hybrid and emerging technologies may offer advantages where metal recovery, lower residue generation, or resource efficiency is a priority, but field deployment should proceed through phased validation and monitoring. Biological treatment is most viable where substrate and environmental conditions can be maintained within suitable ranges.

Beyond treatment chemistry, practical selection should also weigh mine life-cycle stage (active operation versus post-closure passive management), site remoteness and access to skilled labor for system monitoring, local availability of low-cost neutralizing materials such as fly ash or limestone, climatic factors affecting microbial and hydrological performance, and applicable regulatory discharge standards. These operational realities are rarely addressed in laboratory or pilot-scale studies, underscoring the need for site-specific feasibility assessment rather than technology performance alone as the basis for selecting AMD treatment strategies in real-world mining contexts.

Table 4. Practical Technology Selection Framework for AMD Treatment

Field Condition	Most Suitable Technology	Rationale
Severe AMD, fluctuating discharge, strict regulatory deadlines	Active	Rapid pH correction; suitable where reagent and sludge management are available [2, 3]
Large land area available, limited budget, long-term maintenance access feasible	Passive	Low operational input but requires media management and adequate land [9, 10]
Metal recovery incentive present, electrical/monitoring infrastructure available	Hybrid/Emerging	High efficiency/resource-recovery potential, but phased validation is advisable [24, 5]
Stable organic carbon substrate available, relatively consistent temperature	Biological	Sulfate reduction and recovery potential, but sensitive to substrate and environmental conditions [? 25]

4.5. Limitations and Future Research Directions

This review is subject to several limitations that should be acknowledged. First, the restriction to English-language publications may have excluded relevant studies published in other languages, potentially introducing language bias. Second, the heterogeneity of the included studies in treatment scale, AMD characteristics, and performance metrics limited the feasibility of quantitative meta-analysis, necessitating a descriptive-analytical approach. Third, the majority of the reviewed studies were conducted at laboratory or pilot scale, so extrapolation to field conditions should be undertaken cautiously. Fourth, the January 2022–March 2026 search

window may have excluded earlier long-term field-monitoring studies that could provide additional evidence on treatment performance over extended operational periods.

Future research should therefore prioritize longitudinal field studies that evaluate AMD treatment technologies over extended periods, ideally spanning multiple years. Such studies are needed to establish empirical evidence on performance degradation, maintenance requirements, treatment-media exhaustion, changes in water chemistry, and ecological recovery over the full operational life of treatment systems. Future systematic reviews could integrate earlier long-term field-monitoring studies with recent technological developments while maintaining transparent evidence-selection criteria. The development of standardized performance metrics and monitoring protocols would facilitate comparisons across treatment technologies. Future work should also strengthen integrated treatment strategies, resource recovery, life-cycle assessment, techno-economic analysis, and explicit SDG indicators, particularly SDG 6.3 and 6.6, complemented by SDG 12.2 and SDG 13.1–13.2.

5. MANAGERIAL IMPLICATIONS

For mine operators and environmental managers, the findings indicate that AMD treatment selection should be based on site-specific conditions rather than removal efficiency alone. Active systems are suitable when rapid pH correction and reliable contaminant removal are required, while passive systems may be preferable where operational inputs and maintenance costs need to be minimized. Hybrid and emerging technologies can be considered when resource recovery and treatment efficiency are priorities, whereas biological systems require stable substrate and environmental conditions. Managers should therefore incorporate long-term monitoring, sludge or media management, maintenance requirements, field validation, and resource availability into treatment planning. This approach can support more durable treatment performance while aligning AMD management with water-quality protection, resource efficiency, and relevant SDG targets.

6. CONCLUSION

This systematic review shows that long-term performance of Acid Mine Drainage (AMD) treatment technologies depends on more than initial contaminant removal efficiency. Active treatment provides rapid pH correction and high metal removal, but sludge generation, reagent consumption, and operational requirements remain important constraints. Passive systems offer lower operational inputs, yet their performance can decline because of clogging, substrate depletion, acidity, and contaminant selectivity. Hybrid and emerging technologies demonstrate promising removal efficiency and resource-recovery potential, although their long-term field performance remains insufficiently validated. Biological systems provide opportunities for sulfate reduction and metal recovery but remain sensitive to substrate availability and environmental conditions.

No single treatment category can therefore be considered universally superior across technical, economic, environmental, and resource-recovery dimensions. Technology selection should consider AMD characteristics, treatment scale, site conditions, operational requirements, maintenance needs, and intended water use. Long-term assessment should also extend beyond removal efficiency by considering treatment stability, residue generation, media or substrate exhaustion, energy and material requirements, and ecological recovery. Field-scale validation is particularly important because a substantial proportion of recent evidence remains based on laboratory or pilot-scale studies.

From a sustainability perspective, AMD treatment is primarily aligned with SDG 6, particularly Targets 6.3 and 6.6, while SDG 12.2 and SDG 13.1–13.2 provide complementary perspectives on resource efficiency, recovery, and climate considerations. Future research should prioritize multi-year field monitoring, standardized performance indicators, integrated treatment configurations, resource recovery, life-cycle assessment, and techno-economic evaluation. These efforts can strengthen the evidence base for selecting AMD treatment technologies that maintain treatment performance while supporting long-term environmental protection and sustainable resource management.

7. DECLARATIONS

7.1. About Authors

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7.2. Author Contributions

Conceptualization: MR, TA and NR; Methodology: MR; Software: TA; Validation: NR; Formal Analysis: TA; Investigation: MR and NR; Resources: MR; Data Curation: MR and TA; Writing Original Draft Preparation: MR and NR; Writing Review and Editing: NR; Visualization: NR; All authors, MR, TA, and NR, have read and agreed to the published version of the manuscript.

7.3. Data Availability Statement

The dataset used in this research can be obtained from the corresponding author upon request.

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The authors did not receive any funding for the research, writing, or publication of this article.

7.5. Declaration of Conflicting Interest

The authors confirm that there are no conflicts of interest, financial or personal, that could have affected the results reported in this paper.

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