Acid Pollution in Aquatic Systems- Sources, Impacts, Mitigation, And Emerging Trends

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ABSTRACT

Acid pollution in aquatic environments is a major global challenge caused by natural and anthropogenic sources. The lowering of pH destabilizes biogeochemical cycles, mobilizes toxic metals, disrupts biodiversity, and threatens human health. This review synthesizes recent literature (2015-2025) on the causes, ecological and human impacts, mitigation technologies, and emerging solutions to acid pollution in aquatic systems. The discussion highlights acid mine drainage (AMD), industrial effluents, agricultural runoff, and atmospheric deposition as major contributors. Traditional treatments such as neutralization and constructed wetlands are compared with novel approaches including bioremediation, adsorption, membrane distillation, and resource recovery. Case studies and recent advances are evaluated to understand their sustainability, scalability, and economic feasibility. Finally, emerging research trends such as artificial intelligence-driven monitoring, circular economy approaches, and hybrid remediation strategies are outlined to inform future policy and research priorities.

Keywords: acid pollution, acid mine drainage, aquatic ecosystems, remediation, resource recovery, bioremediation, sustainability

INTRODUCTION

Aquatic ecosystems are increasingly under threat from acid pollution, defined as the input of acidic compounds into surface or groundwater leading to a decline in pH below ecologically safe levels. Natural sources such as volcanic activity and sulfide mineral weathering contribute to baseline acidification, but anthropogenic drivers- including industrial discharges, agricultural practices, fossil fuel combustion, and acid mine drainage (AMD)- have intensified the problem globally (Grennfelt et al., 2019).

The consequences of aquatic acidification extend from chemical alterations to biological disruption and socio-economic loss. Acidification increases the solubility of toxic metals such as aluminum, cadmium, and lead, reduces biodiversity, weakens ecosystem services, and imposes health risks when contaminated water is consumed (EPA, 2025). Beyond local ecosystems, acid pollution interacts with global issues such as climate change and sustainable resource management.

This review provides a comprehensive synthesis of current knowledge on acid pollution in aquatic systems. It outlines the major sources, ecological and human health impacts, traditional and emerging remediation strategies, and future research directions.

SOURCES OF ACID POLLUTION

2.1 Natural and Geogenic Inputs

Weathering of sulfide-bearing rocks (e.g., pyrite, FeS_2) produces sulfuric acid when exposed to oxygen and water (Nordstrom, 2011). Volcanic eruptions release SO_2 and H_2S that oxidize in the atmosphere and deposit as acids (Delmelle & Bernard, 2015). Carbon dioxide dissolution further contributes through the carbonic acid system, particularly in poorly buffered freshwater bodies (Zeebe et al., 2020).

2.2 Acid Mine Drainage (AMD)

AMD is among the most persistent sources of aquatic acidification. Mining exposes sulfide minerals, producing acidic effluents rich in Fe^{2+}, SO_4^{2-}, and toxic metals (Akcil & Koldas, 2006). Recent studies confirm that AMD alters soil microbial communities, reduces organic matter, and contaminates groundwater (Zhang et al., 2025).

2.3 Industrial Emissions and Effluents

Metal finishing, tannery, and chemical industries release acidic effluents and heavy metals (Fosso-Kankeu et al., 2016). Combustion of fossil fuels emits SO_2 and NO_x, leading to acid rain and subsequent aquatic acidification (EPA, 2025).

2.4 Agriculture and Urban Runoff

Nitrate fertilizers and pesticides undergo nitrification, producing nitric acid that leaches into water (Guo et al., 2010). Urban runoff transports acidic particulates, hydrocarbons, and heavy metals into aquatic systems (Hwang et al., 2016).

2.5 CO_2-Driven Acidification

Increased CO_2 uptake by aquatic systems alters carbonate equilibria, reducing alkalinity and contributing to acidification in both marine and freshwater environments (Gattuso & Hansson, 2011).

IMPACTS OF ACID POLLUTION

3.1 Physicochemical Alterations

Acidification decreases alkalinity and buffering capacity, mobilizes toxic metals, and alters speciation (Driscoll et al., 2001). Mobilized aluminum at low pH is particularly harmful, causing gill damage in fish and reducing nutrient availability.

3.2 Effects on Biodiversity

Acidified lakes and rivers show declines in fish populations, shifts in plankton communities, and proliferation of acidophilic algae and fungi (Kowalik & Ormerod, 2006). Egg mortality of salmonids increases sharply below pH 5.4 (Lydersen et al., 2004).

3.3 Human Health Risks

Consumption of acidified water leads to metal exposure (arsenic, lead, mercury) associated with neurotoxicity and carcinogenicity (WHO, 2017). Acid rain also contributes indirectly to respiratory illness by increasing particulate pollution (Chen et al., 2021).

3.4 Socio-Economic Implications

Declining fisheries, agricultural losses, and increased water treatment costs represent major economic burdens. Infrastructure corrosion from acid rain further compounds the cost (EPA, 2025).

MITIGATION AND PREVENTION STRATEGIES

Table 1. Overview of Acid Pollution Mitigation Strategies

Method	Mechanism	Advantages	Limitations
Neutralization (lime, NaOH)	Raises pH, precipitates metals	Rapid, effective	High cost, sludge generation

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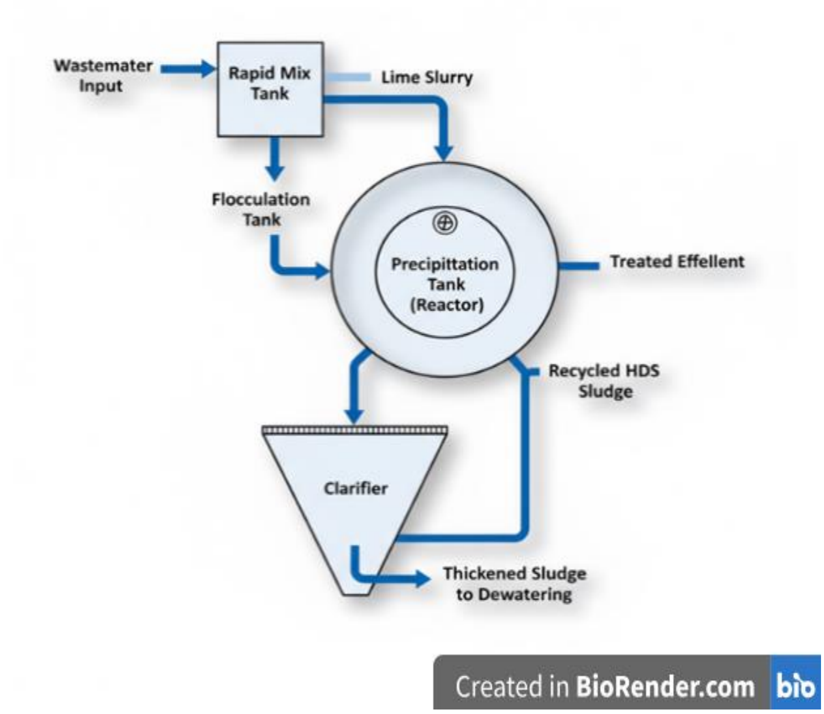
Constructed wetlands	Natural neutralization, microbial sulphate reduction	Low maintenance, ecological benefits	Land-intensive, slow
Adsorbents (biochar, zeolites)	Surface binding, ion exchange	Targeted removal, regenerable	Selectivity issues, scaling challenges
Membrane technologies	Physical separation, crystallization	High efficiency, resource recovery	Energy intensive, fouling
Bioremediation	Sulphate-reducing bacteria, algae	Sustainable, low chemical input	Sensitive to conditions, slow kinetics

4.1 Neutralization and Chemical Precipitation

Lime dosing is the cornerstone of acid mine drainage (AMD) remediation, offering rapid neutralization of acidity and concurrent precipitation of dissolved metals such as Fe, Mn, Al, and others. In large-scale applications, systems like the High-Density Sludge (HDS) process raise pH levels to ~9, at which point most toxic metals become insoluble and are removed as precipitates. This process significantly improves water quality but is accompanied by substantial costs related to the procurement, handling, and application of lime, as well as the frequent need for sludge disposal and management of residuals. Notably, recent process optimizations (e.g., two-stage neutralization or improved sludge recycling) can reduce lime dose by up to 85% and sludge yield by over 74%, yet high operational costs remain a barrier, especially for legacy mines or sites with high water flow (Skousen et al., 2019).



4.2 Passive Treatment

Passive treatment systems, such as constructed wetlands and anoxic limestone drains (ALD), harness natural biogeochemical processes to increase water alkalinity, facilitate microbial sulphate reduction, and precipitate metals. Constructed wetlands, both aerobic and anaerobic, use layers of organic matter and/or limestone to promote reactions that neutralize acidity and reduce trace metals. ALDs and successive alkalinity producing systems (SAPS) bury limestone beds to maintain anaerobic conditions, allowing for slower but sustainable acid neutralization. The cost effectiveness and ecological benefits (e.g., habitat provision) of passive systems are well-documented, though they are limited by land area requirements, slower response to peak acidity, and variable long-term resilience under changing hydrology and temperature. (Johnson & Hallberg, 2005).

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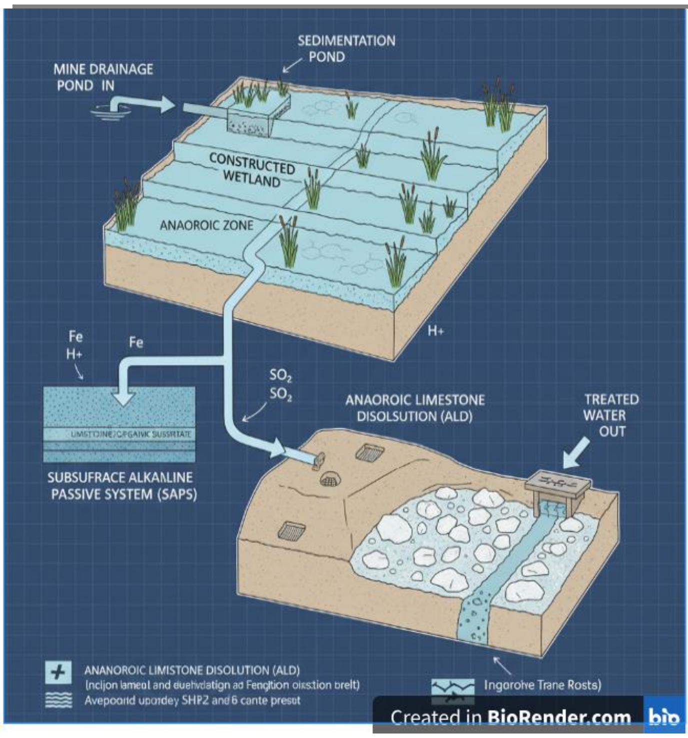
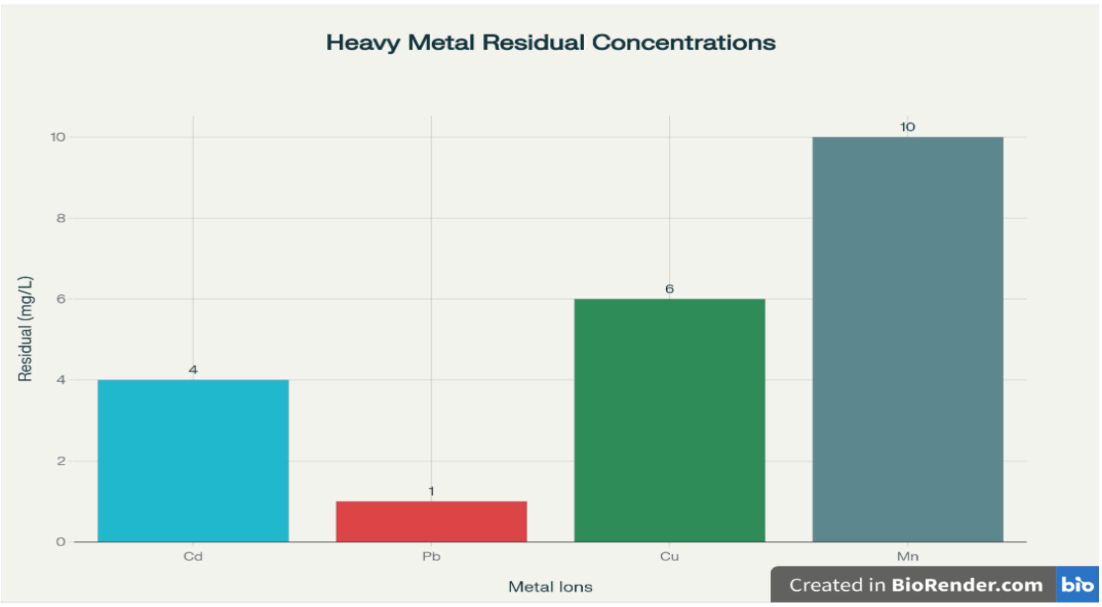


4.3 Adsorption and Advanced Materials

Recent advancements leverage biochar, activated carbon, and engineered composites to achieve high (>90%) removal efficiencies of dissolved metals under laboratory and pilot conditions. Biochar's high surface area, alkaline buffering, and affinity for heavy metals have proven especially promising in contaminated mine tailings and effluent scenarios. Studies now identify optimal feedstocks and pyrolysis conditions and recommend specific biochar blends for maximum retention and minimal metal desorption-a critical step for scaling up and preventing rebound contamination. (Dube et al., 2024).



4.4 Membrane-Based Processes

The use of advanced membrane technologies, such as membrane distillation crystallization (MDCr) and reverse osmosis (RO), represents a new frontier in AMD treatment. These technologies physically separate contaminants and enable simultaneous water purification and mineral resource recovery. MDCr, for instance, achieves >97% salt rejection and allows for gypsum ($CaSO4·2H2O$) crystal harvesting, offering a dual benefit of clean water and economic mineral recovery-though scaling, membrane fouling, and energy demand remain engineering challenges (Nthunya et al., 2025).

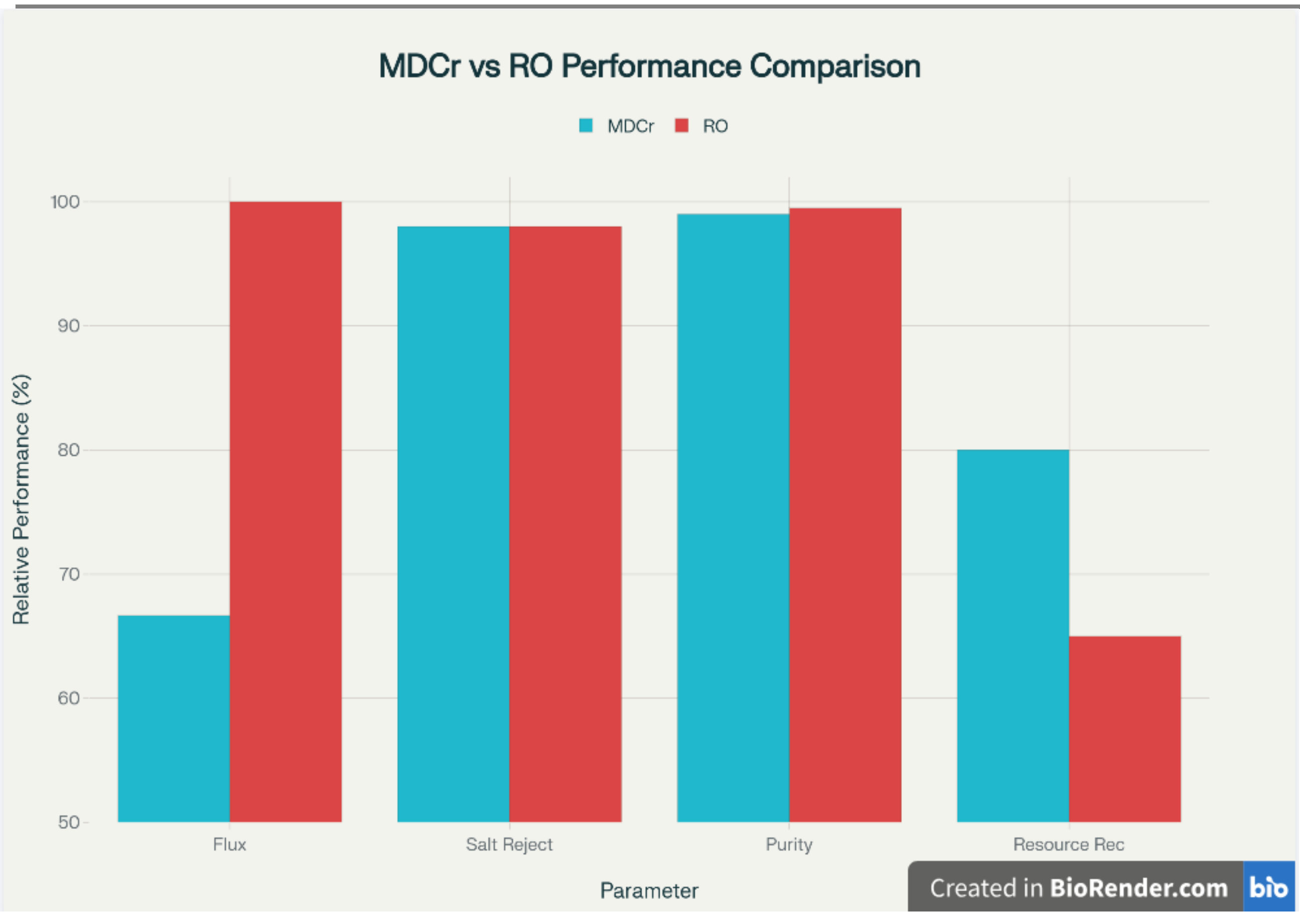


Table 2. Performance and Cost Comparison of Acid Mine Drainage Remediation Technologies

Technology	Metal Removal Efficiency (%)	Sludge Generation	Energy Cost	Treatment Cost Reduction
Lime Dosing	98% (Fe, Mn, Al)	High	Moderate	-
Constructed Wetlands	80–95%	Low	Low	Up to 40%
Biochar Adsorption	80–100% (lab)	Minimal	Low	20–35%
Membrane Distillation	99% (salts)	Minimal	High	10–25%
Bioremediation (SRB)	98–100% (As, Cu, Fe, Ni, Zn)	Minimal	Moderate	-
Hybrid DAF System	>99%	Minimal	Low	10–20%

4.5 Bioremediation

Eco-friendly bioremediation leverages sulphate-reducing bacteria (SRB), algae, and microbial consortia to treat AMD by precipitating metals as sulphides (e.g., FeS, ZnS) and assimilating toxic elements. Industrial-scale processes such as BioSulphide® and Thiopaq® have demonstrated 98–100% metal and sulphate removal efficiency under optimized conditions, supporting marketable metal sulphide production and clean water release. The major challenge lies in maintaining robust microbial populations, optimizing electron donor supply (e.g., ethanol, acetic acid), and scaling up from laboratory to continuous, field-scale reactors (Adetunji et al., 2025).

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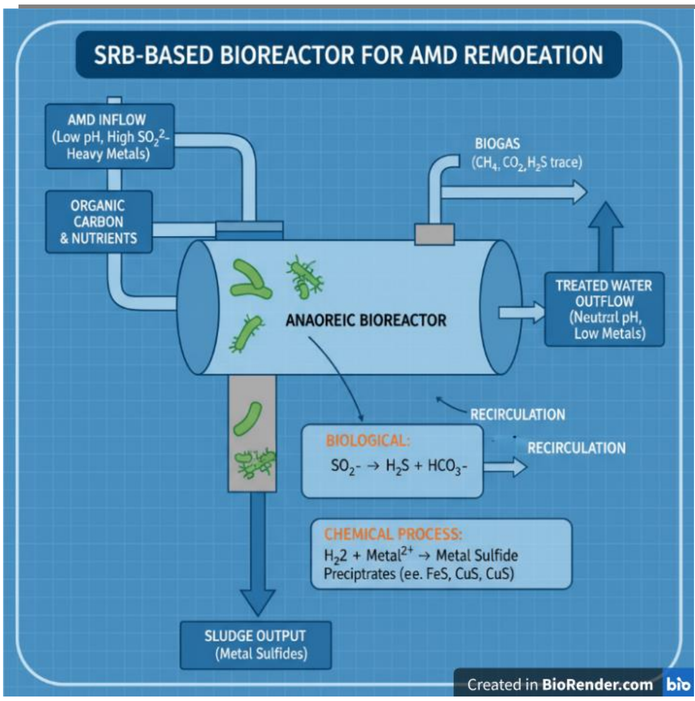
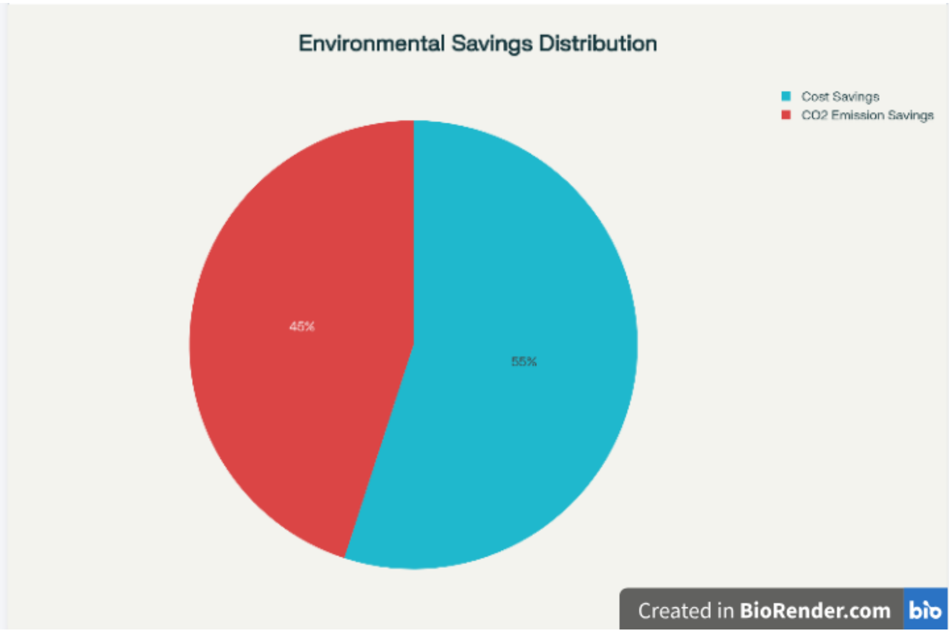


EMERGING TRENDS

5.1 Resource Recovery

Resource recovery transforms AMD from a waste stream into a potential source for valuable metals, including Fe, Al, and rare earth elements (REEs). Supported liquid membranes, modified adsorbents, and selective precipitation are now used to extract REEs with high purity, influenced by feedstock pH, competitive cation concentrations, and membrane interface dynamics. Life cycle assessments show significant cost and emissions reductions (e.g., 17.9% lower cost, 60.1% less CO_2) versus conventional neutralization (Li et al., 2025).



5.2 Artificial Intelligence

Integration of AI and machine learning into AMD management systems enables predictive modelling of AMD generation, assessment of contamination risk via hyperspectral mapping, automated monitoring, and adaptive optimization of remediation plants. Unmanned aerial systems, satellite imagery, and real-time sensors are increasingly used for high-resolution mapping, anomaly detection, and rapid field intervention (Mogashane et al., 2025).

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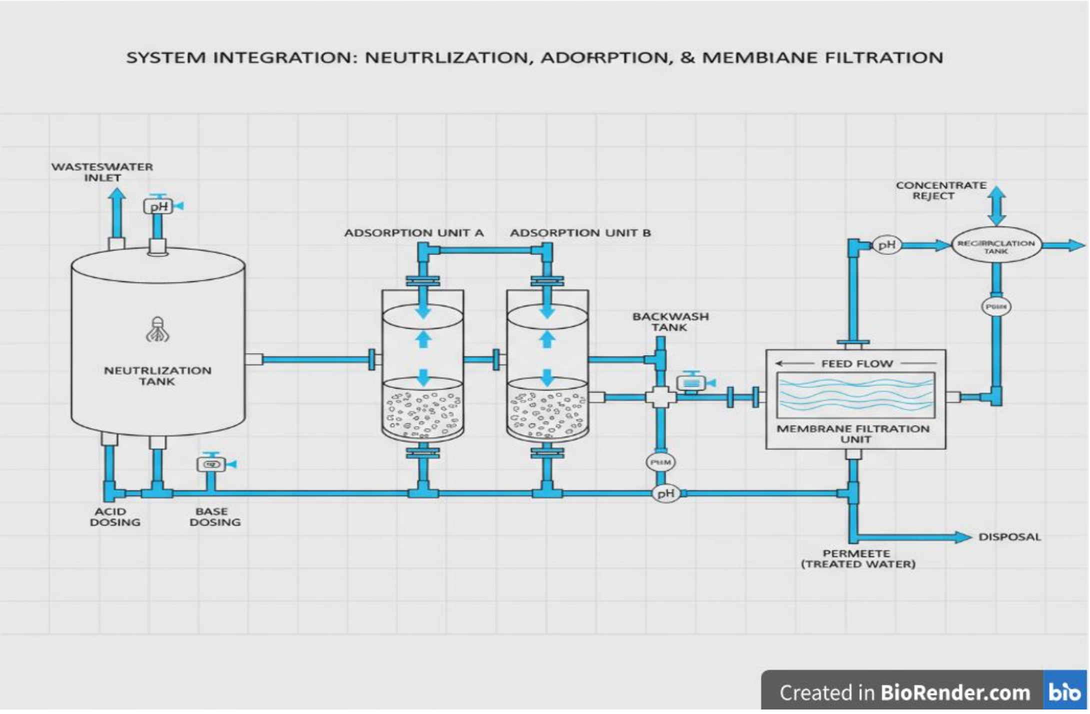
5.3 Hybrid Approaches

Hybrid remediation strategies comprise sequential or integrated combinations of neutralization, adsorption, bioreactors, and membrane separation technologies for enhanced treatment efficiency and cost-effectiveness. Case studies document that hybrid systems, such as combining GEM's hybrid DAF with walnut filters and HDS, provide drier sludge, improved removal rates, and reduced energy and footprint demands. These systems balance responsiveness, sustainability, and operational complexity- enabling tailored solutions for sites with fluctuating AMD chemistry and flow rates (Skousen et al., 2019).



5.4 Life Cycle Assessments

Recent LCA studies show that, although passive systems may require more time and land, they generally outperform active systems in sustainability metrics such as energy use, greenhouse gas footprint, and residual waste generation. This evidence is driving a shift toward nature-based solutions and circular models for AMD remediation, supporting long-term resilience and ecosystem restoration. (Du et al., 2024).

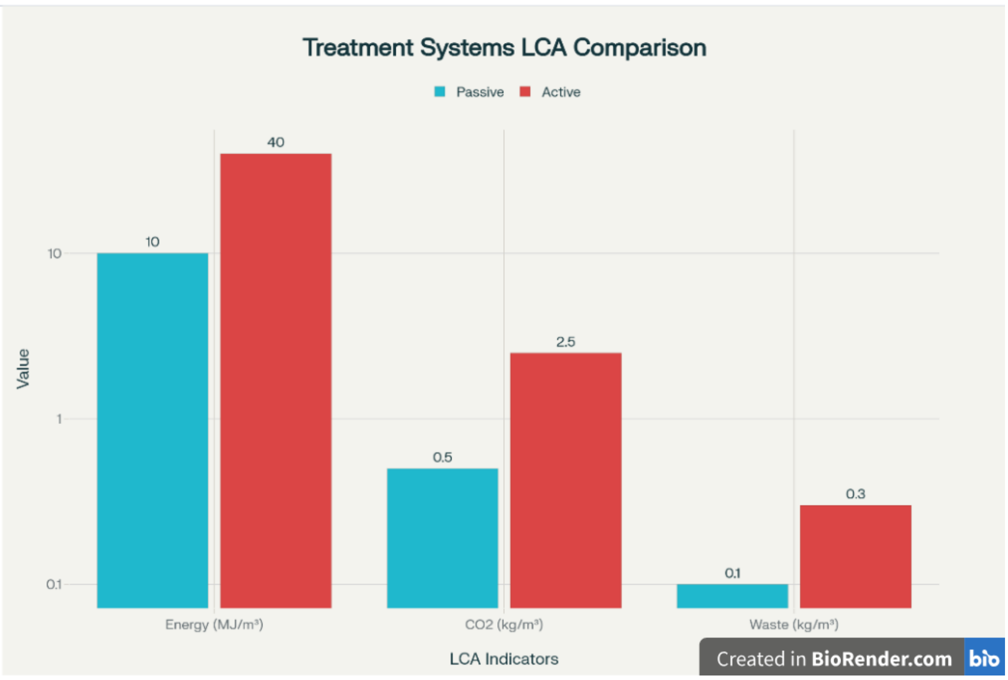


Table 3. Comparison of Emerging Acid Mine Drainage (AMD) Remediation Strategies

Strategy/Technology	Sustainability Score	Scalability (Lab and Field)	Resource Recovery Potential	Strengths	Challenges
AI-Driven Process Optimization	High	High	Indirect (enables efficiency)	Predictive control, enhances monitoring	Requires technological infrastructure
Biochar/Biosorbent-Based Systems	High	Moderately High	Moderately High	Renewable, low residual waste, metal recovery	Selectivity, regeneration, supply
Membrane Distillation Crystallization	Moderate	Moderate	High	Simultaneous clean water and mineral recovery	Energy cost, membrane fouling
Integrated/Hybrid Systems	High	High	High	Synergy between processes; greater adaptability	System design complexity, maintenance
Life Cycle Assessment-Aided Planning	High	High	Indirect	Supports sustainable selection and policy	Data requirement, evolving methodologies
Rare Earth/Metal Extraction via Selective Precipitation	Moderately High	Moderate	Very High	Direct recovery of valuable elements	Competing ions, separation efficiency
Advanced Bioreactors (e.g., SRB, Algae)	High	Moderate	High	Low energy, co-generates elemental sulphur	Biofouling, robust scale-up required

CONCLUSION

Acid pollution in aquatic systems continues to represent a critical, multidimensional global challenge, implicating environmental integrity, public health, and economic stability across diverse regions. Its impacts are manifest in altered biogeochemistry, decline of biodiversity, depletion of fisheries resources, contaminated water supplies, and complex public health burdens. The persistence and expansion of acid pollution are propelled by legacy mining, fossil fuel combustion, agricultural intensification, and emerging contaminants, all of which demand adaptive, system-level solutions.

Conventional remediation approaches, including chemical neutralization, engineered active treatments, and passive attenuation-deliver immediate results but often fall short of addressing long-term system resilience, waste minimization, and sustainability. Recognizing these limitations, contemporary practice emphasizes integrated solutions that leverage bioremediation, resource recovery, and hybrid (multi-step) systems for holistic, cost-effective management. Bioremediation utilizes microbial communities and biosorbents to sequester contaminants naturally, while resource recovery transforms pollutants into valuable materials, promoting circularity and reducing secondary waste. Hybrid systems combine physical, chemical, and biological methods, enhancing efficacy-especially for complex, mixed-contaminant scenarios.

The advent of new tools and frameworks-particularly artificial intelligence (AI), life cycle assessment (LCA), real-time digital monitoring, and advanced modelling-heralds a paradigm shift in environmental management. AI-based analytics enable predictive monitoring, rapid response, and optimization of remediation strategies, while LCA fosters the selection of sustainable, low-impact technologies suited to specific ecosystem contexts. These digital tools bridge the gap between field observation, policy guidance, and implementation, supporting multi-stakeholder collaboration and transparent decision-making.

Future research and practical implementation must focus on several critical areas:

- Scaling up pilot studies: Transitioning promising laboratory and pilot-scale biotechnologies-biochar, microbial consortia, advanced membranes-to real-world, large-scale systems.
- Reducing remediation costs: Developing low-cost, locally sourced adsorbents, energy-efficient processes, and policy mechanisms that incentivize sustainable adoption.
- Embedding within circular economy frameworks: Designing interventions that valorise waste, prioritize resource recovery, and align with circular bioeconomy principles, thereby promoting ecosystem restoration with economic co-benefits.
- Enhancing stakeholder integration: Facilitating knowledge transfer across scientific, regulatory, and community contexts; empowering local actors in adaptive management.
- Addressing knowledge gaps: Improving long-term monitoring, benchmarking performance, and integrating health impact assessments into remediation design.

In summary, the sustainable management of acid pollution in aquatic environments will depend on interdisciplinary approaches, innovative technologies, scalable practices, and policy frameworks that reinforce circular, resilient, and equitable outcomes. The confluence of scientific discovery, technological advancement, and collaborative governance offers a pathway to mitigate acid pollution and secure water resources for future generations

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