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International Case Studies of Acid Mine Drainage: Environmental Impacts, Treatment Performance, and Transferable Lessons for Global Mine-Water Management — A Critical Review (2020–2026)

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Abstract

Acid mine drainage (AMD), acid rock drainage (ARD), and related acidic or metalliferous mine waters remain among the most persistent liabilities of sulfide-bearing mining because oxidation, hydrologic transport, secondary-mineral reactions, and legacy infrastructure can sustain contaminant release for decades after extraction ceases. This critical review synthesizes international case studies published from 2020 through September 2026, emphasizing the causal links among mineralogy, climate, hydrology, mine-waste architecture, hydrochemistry, treatment design, residuals management, and long-term field performance. The evidence shows that treatment success cannot be judged solely by short-term pH correction or dissolved-metal removal. Robust performance requires controlling acidity generation and flux, recognizing seasonal and multi-decadal variability, managing sulfate and salinity, preventing secondary reacidification, and establishing defensible routes for sludge, brine, and spent reactive media. Case studies from North America, Latin America, Europe, Africa, Asia, and Oceania demonstrate that source control, active neutralization, passive systems, and hybrid treatment trains each occupy distinct operating windows. Long-duration field evidence supports passive dispersed alkaline substrates and engineered covers in selected settings, whereas high-flow or highly variable systems often still require active treatment. Emerging approaches increasingly couple AMD control with water reclamation, critical-metal recovery, remote sensing, machine learning, reactive-transport modeling, and life-cycle assessment. The central conclusion is that AMD management should move from technology-by-technology selection toward adaptive, site-specific treatment trains evaluated across water quality, residual stability, carbon intensity, operational resilience, and life-cycle cost.

Keywords: acid mine drainage; acid rock drainage; mine water treatment; mine closure; passive treatment; resource recovery

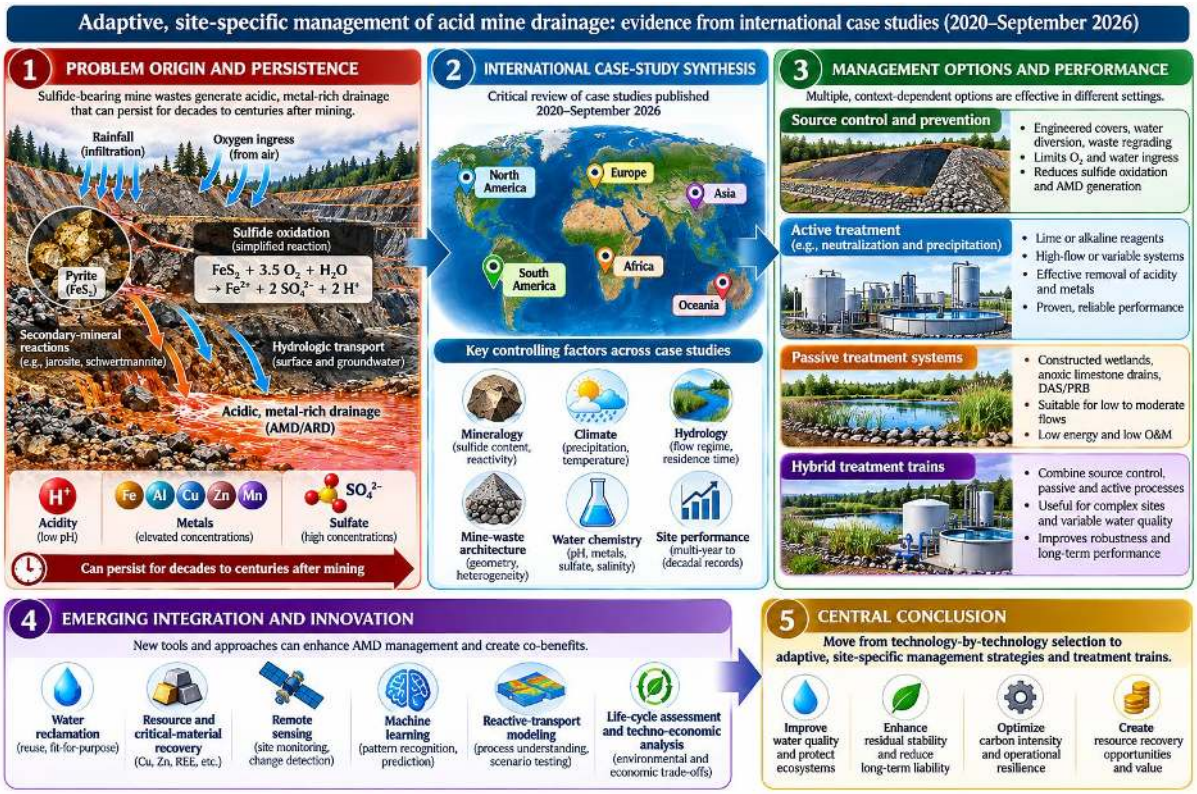
Highlights

- Field-scale AMD performance is controlled by mineralogy, hydrology, climate, and residence time, not pH alone.
- Source control generally reduces long-term treatment burden but requires representative characterization and field validation.
- Active, passive, and hybrid systems should be selected as treatment trains matched to contaminant flux and end-use targets.
- Resource recovery, residual stability, monitoring, carbon intensity, and life-cycle cost should be evaluated together.

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Graphical abstract



1. Introduction

1.1. Acid mine drainage as a long-lived process liability

Acid mine drainage (AMD), also termed acid rock drainage (ARD) when the drainage is not restricted to mine workings, develops when sulfide minerals are exposed to oxidants and water faster than neutralizing phases can consume the acidity they generate. Pyrite oxidation is the canonical reaction pathway, but field behavior depends on mineral associations, particle size, microfracturing, secondary minerals, microbial catalysis, oxygen transport, water flux, and alkalinity supply. Consequently, two wastes with similar total sulfur can display very different lag times, acidity release rates, and contaminant signatures. Recent literature has therefore shifted from simple acid–base accounting toward integrated mineralogical, kinetic, and field-based prediction frameworks (Acharya & Kharel, 2020; Bao et al., 2022; Elghali et al., 2021; Elghali et al., 2023; Fan et al., 2022; Kusi et al., 2024; Lemos et al., 2021; Lim et al., 2024; Mafra et al., 2020; Mahanta et al., 2024; Nordstrom, 2020; Opitz et al., 2025; Schaffer et al., 2024; Simon et al., 2025; Singer et al., 2026; Tabelin et al., 2020; Thisani et al., 2020; Vriens et al., 2020; Yang et al., 2024; Zhang et al., 2026; T. Zhang et al., 2023).

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This distinction has substantial practical importance. AMD is not only a low-pH water problem; it is a coupled geochemical transport problem in which Fe and Al hydrolysis can generate additional acidity, sulfate can remain conservative after metal removal, and sorption or co-precipitation can temporarily immobilize contaminants that later remobilize when pH, redox state, or mineral stability changes. Recent studies also document climate-driven changes in metal loading, seasonal first-flush effects, freeze–thaw impacts, and reacidification of previously neutralized waters, showing that treatment systems designed from a single sampling campaign can be systematically mis-specified (Desmau et al., 2024; Gomes & Valente, 2024; Gu et al., 2026; Jewiss et al., 2020; Jouini et al., 2020; Manning et al., 2024; Moreno-González et al., 2026; Qiu et al., 2026; Rue & McKnight, 2021; Singer et al., 2026).

The global case-study approach adopted here is intended to expose those process interactions rather than to produce a catalog of sites. Table 1 summarizes the principal AMD-generating settings and their controlling variables, Figure 2 locates representative case-study anchors, and Figure 3 develops the causal chain used throughout the review. Table 2 then compares representative international cases, while Table 3 and Table 4 (Panels A and B) translate field experience into cross-case lessons and treatment-selection criteria. Figure 5 closes the synthesis with an adaptive-management loop suitable for long-lived liabilities.

1.2. Why the 2020–2026 evidence window matters

The 2020–2026 period is especially informative because the literature increasingly links geochemical prediction to operational outcomes, integrates long-term field monitoring with remote sensing and machine learning, and reframes mine water as both a liability and a potential secondary resource. Recent reviews converge on three themes: prevention must be evaluated before end-of-pipe treatment, no single treatment technology is universally applicable, and circularity claims are credible only when recovered products and treatment residuals meet quality and stability requirements (Chen et al., 2021; Du et al., 2025; Masindi et al., 2022; Mosai et al., 2024; Nauyryzbay et al., 2026; Ngerem et al., 2026; Otunola & Mhangara, 2024; Yang et al., 2023).

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Selected pre-2020 publications are used only as foundational contextual literature for established concepts such as pyrite-oxidation kinetics, source prevention, active and passive remediation, and hydrogeochemical interpretation (Singer & Stumm, 1970; Johnson & Hallberg, 2005; Akcil & Koldas, 2006; Nordstrom, 2011). These references are not counted within the 161-publication analytical corpus defined for 2020–September 2026.

At the same time, long-duration observations challenge simplified assumptions. Mine-pool chemistry may evolve over decades; covers can change gas and water transport seasonally; passive systems can perform well for years but lose capacity under changed hydraulic loading; and active systems may remove dissolved metals while transferring environmental burden to sludge, brine, reagent production, and energy consumption. The most useful recent studies therefore couple performance metrics with temporal variability, secondary-solid mineralogy, carbon or life-cycle burdens, and management of end products (Hersey & Power, 2023; Larochelle et al., 2025; Mahmoudi Kouhi et al., 2024; Moreno-González et al., 2023; Roy et al., 2026; A. Zhang et al., 2023a; A. Zhang et al., 2023b; A. Zhang et al., 2024).

1.3. Objectives and critical-review questions

This review has four objectives: (i) compare internationally documented AMD cases across geology, climate, hydrochemistry, and mining context; (ii) identify the mechanisms that explain treatment success, failure, or performance drift; (iii) evaluate prevention, active, passive, hybrid, and resource-recovery routes as parts of site-specific treatment trains; and (iv) define research priorities for 2026–2035. The analysis is organized around a central question: which features of a successful AMD intervention are transferable to another site, and which are inseparable from local mineralogy, flow regime, climate, residuals management, or regulatory end points?

2. Review Methodology and Evidence Appraisal

2.1. Scope and evidence base

The review was developed from a curated analytical corpus of 161 peer-reviewed publications published from 2020 through September 2026 and covering AMD generation,

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prediction, monitoring, environmental impact, prevention, active treatment, passive treatment, hybrid systems, water reclamation, critical-metal recovery, techno-economics, life-cycle assessment, and mine-closure performance. The final literature update for this revised submission was closed on September 28, 2026. The geographic classification follows six regions—North America, Latin America, Europe, Africa, Asia, and Oceania—while the technical classification distinguishes source control, active treatment, passive treatment, hybrid treatment trains, and resource recovery. Studies were prioritized when they contained field, pilot, multi-season, multi-year, or process-mechanistic evidence rather than solely conceptual claims. The 161-publication count refers only to the primary 2020–September 2026 analytical corpus; selected older references are used separately for foundational context.

Because the evidence base was assembled as a curated critical-review bibliography rather than as a database export with a fully preserved identification, deduplication, and exclusion log, numerical PRISMA screening counts are not reported and have not been retrospectively reconstructed. The recoverable search record supports keyword-driven discovery, cross-publisher searching, and backward and forward citation chaining, but it does not support auditable database-by-database hit counts. Accordingly, this article remains a critical review rather than a systematic review. Figure 1 presents a PRISMA-inspired evidence-synthesis workflow that makes the review logic explicit while preserving methodological transparency; it should not be interpreted as formal PRISMA compliance.

Representative search concepts combined AMD/ARD terminology with site evidence, treatment, and performance. Examples of Boolean blocks used during the final update included: (“acid mine drainage” OR “acid rock drainage” OR “metalliferous mine water”) AND (“case study” OR field OR pilot OR “long-term”) AND (treatment OR remediation OR prevention OR “source control”); (“acid mine drainage” OR “acid rock drainage”) AND (mineralog* OR hydrogeochem* OR sulfate OR acidity OR “secondary mineral*”) AND (monitor* OR prediction OR “reactive transport”); and (“acid mine drainage” OR “acid rock drainage”) AND (“resource recovery” OR “rare earth element*” OR membrane* OR adsorption OR “ion exchange” OR crystallization OR electrochem*) AND (LCA OR “life cycle” OR TEA OR “techno-economic” OR residual*). Search strings were adapted to publisher syntax and topic-specific terminology rather than applied as one invariant query.

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Eligibility was restricted to peer-reviewed journal articles and reviews in English for the primary analytical corpus, with emphasis on 2020–September 2026. Conference abstracts, theses, patents, preprints, non-peer-reviewed web material, and records lacking sufficient technical detail for the question being discussed were excluded from the primary corpus. Backward citation chaining was used to identify indispensable foundational studies, and forward citation chaining was used to locate newer field or mechanistic evidence. Foundational pre-2020 publications are cited only for context and are reported separately from the analytical corpus.

For the revised submission, bibliographic metadata for newly added and specifically queried records were checked against DOI landing pages, publisher records, or authoritative bibliographic records where available. Because the original curation did not preserve a database-specific export trail, the manuscript does not claim exhaustive coverage of any single indexing database, and it does not report reconstructed Scopus, Web of Science, or PRISMA identification counts.

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Figure 1

Critical-review evidence synthesis for international acid mine drainage case studies

Note. Conceptually adapted from the review-design principles used in recent AMD prediction and treatment syntheses, including Elghali et al. (2023), Masindi et al. (2022), Mosai et al. (2024), and Otunola and Mhangara (2024). The corpus size reflects the curated bibliography assembled for this review; formal screening counts were not available.

2.2. Inclusion logic and analytical dimensions

Evidence was interpreted along six dimensions: source mineralogy and acid-generation mechanism; waste or mine geometry; hydrologic and climatic forcing; influent hydrochemistry and contaminant flux; treatment mechanism and operating intensity; and long-term destination of treated water and residual solids. This structure prevents a common review bias in which treatment technologies are compared only by removal percentage even though sites differ by orders of magnitude in acidity, flow, sulfate load, land availability, and operational continuity.

The literature base also includes advanced monitoring and model-development studies because case-study transferability depends on the quality of site characterization. Satellite and

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uncrewed aerial system (UAS) hyperspectral mapping, electrical-conductivity and optical sensing, stable isotopes, reactive-transport models, PHREEQC-based design tools, and machine-learning approaches are therefore treated as management technologies rather than as peripheral analytical methods (Camargo et al., 2026; Chalkley et al., 2023; Cravotta, 2021; Farahnakian et al., 2024; Flores et al., 2021; Hanelli et al., 2023; Hasrod et al., 2024; Leiva et al., 2021; Moreno-González et al., 2026; Reuß et al., 2023; Wang et al., 2025).

2.3. Critical appraisal criteria and limitations

Greater evidentiary weight was assigned according to evidence directness rather than an artificial numerical quality score. For service-life and transferability claims, the hierarchy used was: field/full-scale evidence → pilot-scale evidence → long-duration laboratory or mechanistic evidence → short-duration laboratory evidence → review/modeling evidence. Within each level, greater weight was given to multi-season or multi-year records, explicit influent and effluent chemistry, documented hydraulic conditions, mineralogical characterization of secondary solids, and transparent operating conditions. Laboratory studies remain important for mechanism discovery, but their transfer to field scale was treated cautiously because residence-time distribution, gas transfer, armoring, clogging, microbial community shifts, freeze–thaw cycles, and extreme flows can alter behavior. This distinction is consistent with recent prediction literature emphasizing representative sampling, kinetic testing, and field-scale validation (Elghali et al., 2023; Fan et al., 2022; Hersey & Power, 2023; Lim et al., 2024; Su et al., 2024).

Four boundary conditions should be explicit. First, the review is bounded by the curated evidence base, so the absence of a site or technology should not be interpreted as a global absence of evidence. Second, geographical representation is illustrative rather than statistically representative: mature long-duration evidence is denser for some regions than for others. Third, “successful treatment” is jurisdiction- and end-use-dependent because discharge standards, reuse criteria, and closure obligations vary internationally. Fourth, several emerging 2026 studies are recent enough that independent replication is limited. Accordingly, the discussion separates mature field lessons from promising but less validated

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directions, particularly for advanced membranes, machine learning, CO_2 mineralization, and selective critical-metal recovery.

2.4. Minimum reporting framework for cross-case comparability

Cross-case comparison should report contaminant mass flux as well as concentration. For constituent i, the instantaneous load is $L_i = Q \times C_i$, where Q is water flow and C_i is concentration; studies should therefore report flow-weighted loads such as kg acidity/day, kg Fe/day, kg sulfate/day, and kg target metal/day whenever the source data permit. A minimum hydrochemical dataset should include pH, acidity in standardized equivalents (preferably mg/L as $CaCO_3$), alkalinity, flow, sulfate, Fe, Al, Mn, conductivity or total dissolved solids (TDS), and site-specific contaminants. This distinction is essential because dilution can lower concentration while increasing total contaminant export.

For passive and biological systems, comparison should additionally report hydraulic loading, acidity loading per unit area or reactor volume, hydraulic residence time (HRT), mass removal per unit area or volume, reactive-media mass where relevant, and operating years or service life. Service life is treated as a first-order performance endpoint rather than a secondary descriptive variable. Claims of durable treatment should also document precipitate or residual mineralogy, aging behavior, pH/redox cycling where relevant, leachability, and the possibility of secondary acidity regeneration.

Whole-system performance should include residual production and final-water destination. Where available, residuals should be normalized as kg dry solids per m^3 treated or per kg acidity neutralized and described by moisture content, dewaterability, mineralogy, leachability, storage requirement, and product value. Treatment adequacy should be assessed against the intended endpoint—environmental discharge, process-water reuse, irrigation, industrial reuse, or potable-treatment precursor—because each requires a different water-quality specification.

3. Geochemical Controls and Global Typology of AMD

3.1. Mineralogy, oxidation pathways, and secondary acidity

The classical pyrite reaction can be summarized as $FeS_2 + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$, followed by Fe^{2+} oxidation, Fe(III) hydrolysis, and, under sufficiently acidic conditions, ferric-iron attack on sulfides. In real waste, however, the rate-controlling steps vary with

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mineral liberation, surface oxidation layers, gangue buffering, and secondary-mineral formation. Polysulfide and thiosulfate pathways, weathered sulfide surfaces, and Fe oxyhydroxide coatings can change both acidity production and arsenic or metal mobility (Bao et al., 2022; Elghali et al., 2021; Fan et al., 2022; Mafra et al., 2020; Tabelin et al., 2020).

Mineral texture matters because exposed reactive surface, not bulk sulfur alone, controls short-term kinetics. Particle-size effects, pyrite liberation from gangue, and physical locking determine whether desulfurization is practical and whether smaller fractions disproportionately contribute to acid generation. This is especially important for reprocessing and source-control strategies that target reactive sulfide fractions before waste placement (Botero et al., 2024; Lim et al., 2024; Mafra et al., 2020; Na et al., 2024).

3.2. Hydrology, climate, and temporal evolution

Hydrology converts acid generation into environmental loading. Net infiltration through waste rock or covers controls oxygen and water supply, while mine-pool depth, residence time, fracture connectivity, and seasonal discharge determine dilution and contaminant flux. Long-term records from coal and hard-rock districts show that drainage chemistry can evolve toward new quasi-steady states rather than simply decline monotonically after closure (Hersey & Power, 2023; Jewiss et al., 2020; Murray et al., 2021; Newman et al., 2023; Petach et al., 2021; Schaffer et al., 2024; Singer et al., 2026).

Climate modifies those trajectories. Freeze–thaw affects reactive media and treatment residues; intense rainfall can generate first flushes; arid and semi-arid systems can accumulate salts between flow events; and warming can increase stream metal concentrations in mineralized catchments. Physics-informed and machine-learning approaches are beginning to quantify climate sensitivity, but calibration against field hydrology remains essential (Desmau et al., 2024; Jouini et al., 2020; Kumar et al., 2024; Manning et al., 2024; Qiu et al., 2026; Singh & Chakraborty, 2022b; Zhang et al., 2026).

3.3. Global AMD settings and management implications

Table 1 groups recurrent AMD settings by the processes that most strongly control risk and treatment design. The table is not a ranking; it is a diagnostic framework. For example, coal-mine drainage often combines acidity, Fe, Al, and sulfate with large, seasonally variable flows, whereas polymetallic sulfide wastes may have lower flow but more complex Cu–Zn–

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Pb–As signatures. Uranium settings add radionuclide and groundwater-protection constraints, and pit lakes introduce vertical mixing and long water residence times.

Table 1

AMD-Generating Settings, Dominant Controls, and Management Implications

Setting	Dominant source/process	Key controls	Typical management challenge	Implication	Evidence anchors
Coal waste and flooded coal mines	Pyrite-rich coal/overburden; Fe–Al acidity	Mine-pool depth, flooding history, seasonal flow	Large flow, Fe/Al, sulfate, long post-closure release	Flow-resilient active or passive trains; long-term load monitoring	(Acharya & Kharel, 2020; Chen et al., 2020; Kumar et al., 2024; Schaffer et al., 2024; Yang et al., 2024)
Polymetallic/VMS tailings	Pyrite/pyrrhotite with Cu–Zn–Pb sulfides	Fine particle size, secondary minerals, oxidation fronts	High acidity and multi-metal/metalloid mixtures	Source segregation, covers, selective precipitation, residual stability	(Elghali et al., 2021; Ferreira et al., 2021; León et al., 2021; Papaslioti et al., 2024; Simon et al., 2025)
Porphyry Cu waste rock	Disseminated pyrite with variable carbonate buffering	Particle-size distribution and sulfide liberation	Spatially heterogeneous acid-generating fractions	In-process desulfurization and selective waste handling	(Botero et al., 2024; Kusi et al., 2024; Lim et al., 2024; Vriens et al., 2020)
Gold/arsenopyrite wastes	Pyrite/arsenopyrite and Fe secondary phases	As-bearing soluble phases and Fe sorbents	Acidity plus arsenic mobility	Oxidation control and mineralogically stable As sinks	(Lemos et al., 2021; Opitz et al., 2025; Tabelin et al., 2020)
Uranium waste and mine water	Sulfides plus radionuclide-bearing minerals	Groundwater pathways, redox, sulfate generation	Acidity with radionuclide-management constraints	Source tracing, staged treatment, long-term groundwater protection	(Camargo et al., 2026; Lawrence, 2022; Nogueira et al., 2025; Pereira et al., 2022; Y. Zhang et al., 2023)
Acidic pit lakes	Wall-rock oxidation and flooded mine workings	Stratification, mixing, sludge/mineral reactions	Large stored acidity; evolving Fe/Al controls	Mass-balance treatment plus geochemical lake evolution	(Gammons & Icopini, 2020; Gu et al., 2026; Hanelli et al., 2023; Nordstrom, 2020)
Cold-region sulfide wastes	Sulfides under seasonal freezing	Freeze–thaw, low temperature, infiltration and insulation	Slower kinetics but persistent seasonal release	Insulating covers and low-temperature passive/biological systems	(Desmau et al., 2024; El Kilani et al., 2021; Larochelle et al., 2025; Virpiranta et al., 2022)
Karst and fractured aquifers	Sulfide oxidation linked to high-connectivity flow paths	Rapid recharge, conduit flow, water–rock interaction	Fast transport and spatially variable plume chemistry	Hydrogeochemical zonation and source-pathway interception	(Bu et al., 2024; Ren et al., 2021; Tang et al., 2024; Yang et al., 2024)

Note. AMD = acid mine drainage; VMS = volcanogenic massive sulfide. The categories synthesize recurrent patterns in the reviewed literature and should be refined with site-specific mineralogical and hydraulic data.

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Figure 2 places representative case-study anchors on a common global frame. The distribution shows that similar AMD symptoms arise in very different climatic and regulatory contexts, which is why directly transferring a treatment flowsheet from one site to another can be misleading.

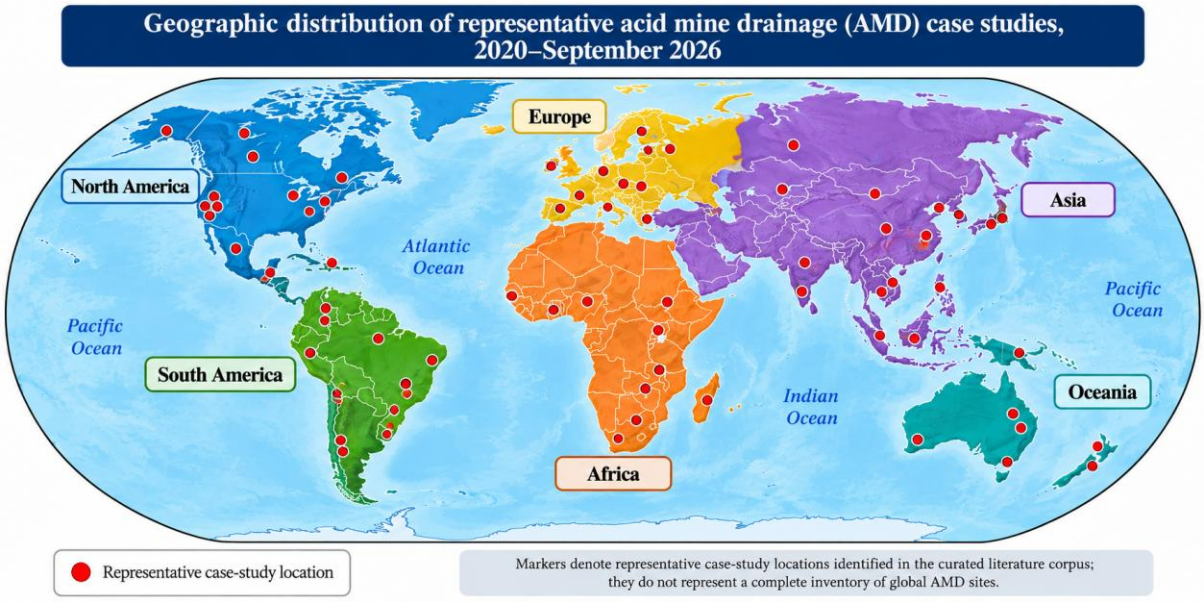


Figure 2

Geographic distribution of representative AMD case studies in the 2020–2026 evidence base

Note. Original synthesis based on the geographic case studies cited in Table 2, including North American hard-rock and coal districts, South American mining regions, the Iberian Pyrite Belt, Witwatersrand, Asian coal and metal districts, and Oceania. Marker locations are approximate and are intended for review visualization rather than site surveying.

Figure 3 summarizes the causal logic used to compare those sites. The key implication is that treatment performance is downstream of source and transport controls: if the source flux changes, or if a treatment changes secondary-mineral stability, the apparent treatment optimum can shift.

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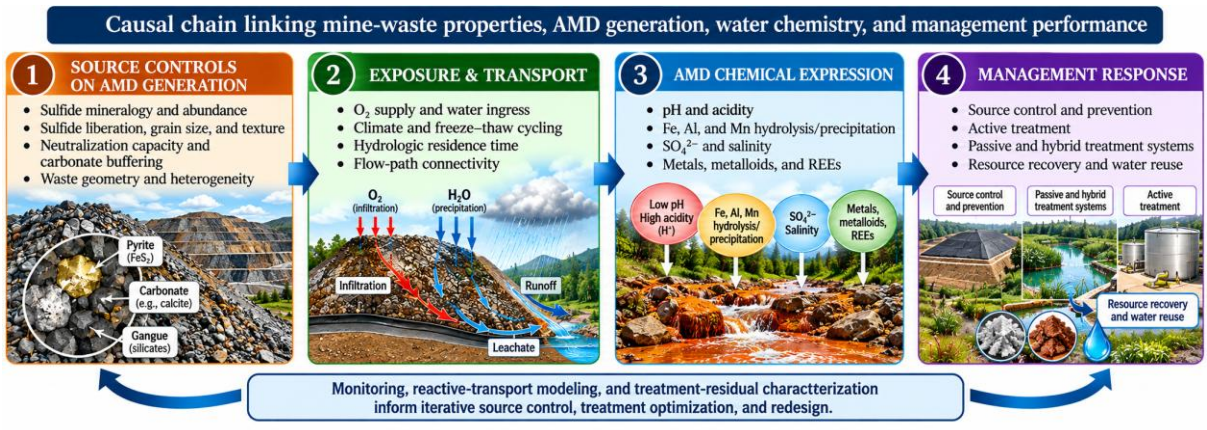


Figure 3

Causal chain linking mine-waste properties to AMD chemistry and management performance

Note. Conceptually adapted from the process relationships synthesized by Vriens et al. (2020), Elghali et al. (2023), T. Zhang et al. (2023), and Masindi et al. (2022). The diagram is an original synthesis and does not reproduce a source figure.

4. International Case Studies by Region

4.1. North America

North American cases illustrate the importance of long time scales and hydrologic context. At Berkeley Pit, Montana, copper recovery and in-pit lime-treatment sludge disposal altered lake circulation and geochemistry; Gammons and Icopini (2020) reported a pH increase from about 2.5 to approximately 4.1, a roughly 35% decline in total acidity, and precipitation of more than 99% of dissolved Fe. This case matters because it shows that a treatment intervention can reorganize an entire pit-lake geochemical system, with beneficial removal of Fe-associated elements but simultaneous increases in some solutes released from sludge-related reactions (Gammons & Icopini, 2020; Gu et al., 2026; Nordstrom, 2020).

Appalachian coal-mine drainage provides a contrasting high-flow legacy. Multi-decadal data show that flooded underground mine chemistry evolves with mine-pool depth, mineral equilibria, and cation exchange, while watershed-scale treatment outcomes remain sensitive to loading and the persistence of untreated sources (Acharya & Kharel, 2020; Schaffer et al., 2024; Spirnak et al., 2025). In the Silverton/upper Animas system of Colorado, long records separate hydrologic variability from remedial effects: surface reclamation reduced some snowmelt-related Zn loading, whereas cessation of treatment and structural changes produced more complex base-flow responses (Petach et al., 2021; Walton-Day et al., 2021). These

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cases show why concentration-only metrics should be complemented by seasonal load calculations.

Canadian evidence emphasizes long-term reclamation and cold-region performance. Field studies of covers and organic reclamation systems demonstrate that water balance, insulation, oxygen transport, and seasonal freezing must be treated as design variables, not boundary conditions. The East Sullivan long-term field record and subarctic passive-reactor studies are particularly relevant to service-life expectations (El Kilani et al., 2021; Hersey & Power, 2023; Larochelle et al., 2025; Roy et al., 2026).

4.2. Latin America

Latin American cases span coal, gold, uranium, and polymetallic mining under tropical, subtropical, arid, and high-altitude climates. In southern Brazil, coal-mining legacies continue to affect river systems, while recent work at a coal-waste deposit examines whether attenuation can justify shifting from continuous active treatment to passive management (Cardoso & Fan, 2024; Keller et al., 2025; Viola et al., 2026). In Minas Gerais, gold-tailings characterization and uranium-mine studies show that AMD risk analysis must integrate mineralogy, radionuclides, and groundwater pathways (Camargo et al., 2026; Lemos et al., 2021; Pereira et al., 2022).

Peruvian work highlights both watershed-scale and treatment-scale challenges. Studies in Arequipa distinguish geological and anthropogenic contributions to metal(loid)s and identify mineralogical controls on tailings drainage, while constructed wetlands and native-macrophyte systems demonstrate the appeal—and the site dependence—of low-intensity treatment for smaller flows (Nuñez-Bustamante et al., 2025; Simon et al., 2024; Simon et al., 2025; Vergaray Andagua et al., 2022). In the semi-arid Puna of Argentina, seasonal hydrogeochemistry and modeling at the Pan de Azúcar Pb–Ag–Zn mine show how evaporation, episodic recharge, and mineral reactions create time-dependent drainage chemistry (Murray et al., 2021).

The regional lesson is that “tropical AMD” or “Andean AMD” is too coarse a design category. Rainfall intensity, elevation, karst or fractured flow paths, waste mineralogy, and mine-water storage can dominate over latitude. Treatment transfer therefore requires a flux-based description of acidity, sulfate, and contaminants rather than a climate label alone.

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4.3. Europe

The Iberian Pyrite Belt remains one of the most information-rich AMD regions. Mine waters have been evaluated both as contaminant sources and as secondary REE resources; full-scale passive treatment and long-term dispersed alkaline substrate (DAS) experience provide a rare bridge from field demonstration to multi-decade technology assessment (Guerrero et al., 2024; León et al., 2021; León et al., 2026; Orden et al., 2021). São Domingos, Portugal, additionally demonstrates that legacy-mining landscapes contain spatially distinct exposure zones: strongly acidic depositional surfaces and relatively regenerated areas can coexist, so revegetation and source-control measures should be spatially differentiated (Ferreira et al., 2021; Gomes & Valente, 2024; Gomes et al., 2025).

European monitoring studies also illustrate the value of combining field chemistry with remote sensing. Sentinel time series have been used to model pit-lake AMD in Lusatia, while UAV photogrammetry and hyperspectral observations improve mapping of contaminated waters and waste dispersion (Barroso et al., 2025; Flores et al., 2021; Hanelli et al., 2023). These tools are valuable when they reduce sampling bias, but they do not replace the mineralogical and flow measurements required to establish causality.

4.4. Africa

South Africa combines one of the world's best-known mine-water legacies with a strong body of treatment research. In the Witwatersrand Goldfields, three large HDS plants were reported to treat about 185 ML/day as a short-term response, yet salt loading to the receiving system remains a long-term constraint. Modelling has therefore explored alternative water-use pathways such as irrigation, illustrating a shift from simple neutralization toward fitness-for-use assessment (Annandale et al., 2023; Lourenco & Curtis, 2021).

African research has also contributed substantially to passive barriers, hybrid MgO–wetland systems, resource recovery, and techno-economic evaluation. These studies show that low operational intensity does not automatically mean low life-cycle burden: reactive media replacement, sludge or precipitate management, and land requirements remain important (Mahmoudi Kouhi et al., 2024; Nguegang et al., 2022; Shabalala & Masindi, 2022; Shingwenyana et al., 2021; Thisani et al., 2022). Policy-oriented work in Ghana further

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shows that small-scale mining impacts can be difficult to separate from broader water-management and governance constraints (Kazapoe et al., 2023).

4.5. Asia

Asian case studies cover coal fields, metal mines, karst systems, and advanced treatment research. In China, AMD-impacted karst rivers and abandoned coal-mine basins show strong spatial and seasonal variation, and researchers have used hydrogeochemical zonation to design remediation around source and flow-path differences (Bu et al., 2024; Tang et al., 2024; Wang et al., 2025; Yang et al., 2024). In India, long-term constructed-wetland research demonstrates how vegetation, loading rate, electron donor, microbial pathways, and seasonality alter treatment response (Kumar et al., 2024; Singh & Chakraborty, 2020; Singh & Chakraborty, 2021; Singh & Chakraborty, 2022a; Singh & Chakraborty, 2022b).

Japan provides examples of ferrite-forming active treatment and pilot-scale passive treatment for Mn and Zn. These studies are important because they address contaminants that can remain problematic after simple Fe/Al neutralization and because they link mineral-product formation to treatment chemistry (Igarashi et al., 2020; Tum et al., 2024).

4.6. Oceania

Mount Lyell, Tasmania, demonstrates the durability of legacy impacts from historical waste disposal. Long-term monitoring found pH below 3.5 downstream of a major impacted tributary and below 5 across the river system toward Macquarie Harbour, together with dissolved metals above guideline levels; the authors argue that remediation and potential Cu/Co recovery deserve consideration (Nascimento et al., 2023). In Papua New Guinea, desulfurization of sulfide tailings has been evaluated from an environmental-compliance perspective, emphasizing the need to connect mineral-processing performance to closure objectives (Kiwingim et al., 2024). New Zealand studies further show how rainfall-enhanced discharges can dilute concentrations while increasing total contaminant export, reinforcing the distinction between concentration and load (Jewiss et al., 2020).

Table 2 consolidates the principal regional lessons. It focuses on process transferability rather than declaring a universal “best” technology.

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Table 2

Representative International AMD Case Studies and Transferable Lessons

Region	Case	Context	Management approach	Transferable lesson	Evidence
North America	Berkeley Pit, USA	Acidic pit lake; Cu mining legacy	Cu recovery, sludge reactions, long-term pumping/treatment	Whole-lake geochemistry can shift after intervention; secondary solids control the next buffering regime	Gammons & Icopini, 2020
North America	Appalachian Basin, USA	Flooded coal mines	Active/passive treatment and long-term monitoring	Mine-pool depth and geochemical aging influence decades-long drainage chemistry	Schaffer et al., 2024
North America	Silverton/Animas, USA	Hard-rock polymetallic district	Surface reclamation, treatment, bulkheads	Hydrologic variability can mask or reverse apparent remediation trends	Petach et al., 2021; Walton-Day et al., 2021
North America	East Sullivan, Canada	Acid-generating tailings	Long-term organic cover reclamation	Service-life evidence is essential for cover design	Roy et al., 2026
Latin America	Santa Catarina, Brazil	Coal waste and AMD-impacted rivers	Active treatment with passive-transition studies; REE recovery research	Legacy load and resource recovery can be assessed together	Cardoso & Fan, 2024; Keller et al., 2025; Viola et al., 2026
Latin America	Caldas, Brazil	Decommissioned uranium mine	Source tracing and biological neutralization	Groundwater pathways, radionuclides, and metal/REE precipitation require integrated control	Camargo et al., 2026; Nogueira et al., 2025; Pereira et al., 2022
Latin America	Arequipa/Hualgayoc, Peru	Tailings and polymetallic mine waters	Characterization, wetlands, organic amendments	Mineralogical source attribution should precede passive treatment design	Nuñez-Bustamante et al., 2025; Simon et al., 2024, 2025
Europe	Iberian Pyrite Belt	Massive sulfides and historic mines	DAS, passive treatment, REE recovery	Long-term passive treatment can be robust when acidity loading and media are matched	León et al., 2021, 2026; Orden et al., 2021
Europe	São Domingos, Portugal	Historic sulfide mine	Natural attenuation and revegetation assessment	Proximal and distal zones may need different remediation strategies	Ferreira et al., 2021
Europe	Lusatia, Germany	Open-pit lakes	Sentinel-based monitoring and modelling	Remote sensing improves spatial-temporal surveillance but requires field calibration	Hanelli et al., 2023
Africa	Witwatersrand, South Africa	Goldfield mine-water legacy	HDS and water-reuse scenarios	Treatment must address salinity and beneficial-use constraints, not acidity alone	Annandale et al., 2023; Lourenco & Curtis, 2021
Asia	NE India coalfields	Coal-mine drainage	Constructed wetlands and biochemical treatment	Season, loading, and electron donor control passive-system response	Singh & Chakraborty, 2020, 2021, 2022a, 2022b
Asia	Guizhou and SW	Karst/coal and	Hydrogeochemical	Fast karst transport	Bu et al., 2024;

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Region	Case	Context	Management approach	Transferable lesson	Evidence
	China	metal-mine drainage	mapping and zoned remediation	demands source-pathway-specific control	Tang et al., 2024; Yang et al., 2024
Asia	Japan legacy mines	Metal-mine drainage	Ferrite formation and passive Mn/Zn treatment	Product mineralogy and low-residual-metal targets shape process choice	Igarashi et al., 2020; Tum et al., 2024
Oceania	Mount Lyell, Australia	Historic Cu mine and tailings	Long-term water-quality monitoring; recovery options	Without source remediation, severe river impacts can persist for decades	Nascimento et al., 2023
Oceania	Ok Tedi, Papua New Guinea	Sulfide tailings	Desulfurization compliance assessment	Mineral processing can be a closure-control tool when residual sulfide risk is demonstrated	Kiwingim et al., 2024

Note. The table synthesizes representative cases from the curated corpus. It is not a complete inventory of AMD sites, and treatment descriptions are intentionally condensed to the evidence most relevant to transferability.

5. Cross-Case Comparative Assessment

5.1. Climate and hydrology are treatment variables

Across regions, the strongest commonality is that water flux governs contaminant load and hydraulic stress on treatment systems. Seasonal concentration decreases can coincide with higher total metal export when discharge rises, whereas dry-season concentration increases may occur at low load. This explains why long-term datasets and flow-weighted loads are more informative than isolated concentration measurements (Jewiss et al., 2020; Manning et al., 2024; Moreno-González et al., 2026; Petach et al., 2021; Singer et al., 2026).

Cold climates introduce a different failure mode: reduced reaction kinetics can coexist with freeze–thaw damage, altered permeability, or seasonal release pulses. Field and pilot studies therefore emphasize thermal insulation, media resilience, and low-temperature microbial activity rather than simply lowering design reaction rates (Desmau et al., 2024; El Kilani et al., 2021; Jouini et al., 2020; Larochelle et al., 2025; Virpiranta et al., 2022).

5.2. Hydrochemistry determines which “removal” is meaningful

Neutralization commonly removes Fe and Al efficiently, but sulfate, Mn, Mg, and some trace metals can remain. Further, Fe precipitation can beneficially scavenge As, P, V, or Cr, yet changes in Fe or Al mineral stability may later release acidity or sorbed contaminants. Berkeley Pit and neutralized pit-lake studies make this point particularly clear (Gammons & Icopini, 2020; Gu et al., 2026; Nordstrom, 2020). The critical metric is therefore not only

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dissolved removal at the plant outlet but also mineralogical stability of the produced solids under realistic disposal conditions.

Selective precipitation can improve residual quality and resource recovery, but selectivity is strongly influenced by coexisting ions and pH trajectory. Ferrite formation, schwertmannite routes, magnetite precipitation, and precipitation–flotation–dewatering strategies illustrate the growing focus on engineering the solid product rather than treating sludge as an unavoidable waste (Igarashi et al., 2020; Jiang et al., 2024; Liu et al., 2025; Rapeta et al., 2024; Song et al., 2022).

5.3. Success and failure mechanisms

Table 3 distills recurrent mechanisms that explain why apparently similar technologies perform differently across sites. The central pattern is that failure often originates outside the treatment unit: under-characterized source flux, hydraulic overload, poorly managed residuals, or changing influent chemistry can overwhelm a technically sound reactor.

Table 3

Recurring AMD Treatment Success and Failure Mechanisms

Mechanism	Cause	Observed risk	Design response	Evidence anchors
Representative characterization	Static tests or few samples fail to capture reactive heterogeneity	Design acidity/load is biased; source zones missed	Mineralogy + kinetic tests + field validation	(Elghali et al., 2023; Kusi et al., 2024; Opitz et al., 2025)
Hydraulic variability	Peak flow shortens residence time or bypasses reactive media	Seasonal treatment deterioration	Load-based design, equalization, modular trains	(Jewiss et al., 2020; Petach et al., 2021; Singer et al., 2026; Spirnak et al., 2025)
Armoring/clogging	Fe/Al precipitates coat limestone or fill pores	Declining alkalinity release and permeability	Pre-oxidation, distributed alkalinity, media grading	(León et al., 2026; Orden et al., 2021; Shabalala & Masindi, 2022)
Secondary reacidification	Al/Fe transformations or unstable solids release acidity/metals	Delayed water-quality deterioration	Mineralogical residual characterization and geochemical modeling	(Gu et al., 2026; Jouini et al., 2020; Nordstrom, 2020)
Cold-climate stress	Freeze–thaw and low temperature alter kinetics and hydraulics	Reduced biological or passive performance	Insulation, low-temperature consortia, seasonal design margins	(Desmau et al., 2024; El Kilani et al., 2021; Larochelle et al., 2025; Virpiranta et al., 2022)
Residual burden	Treatment transfers contaminants to sludge/brine	Secondary disposal impact and lifecycle cost	Dewatering, stabilization, beneficial use, recovery feasibility	(Du et al., 2025; Moreno-González et al., 2023; Mosai et al., 2024; Nthunya et al., 2025)
Scale mismatch	Lab residence time and mixing do not represent	Poor transfer from bench to site	Pilot/field validation and	(Elghali et al., 2023; Vasquez et al., 2022)

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Mechanism	Cause	Observed risk	Design response	Evidence anchors
	field systems		residence-time assessment	
Uncontrolled sulfide source	End-of-pipe treatment continues indefinitely	High OPEX and long liability	Covers, passivation, desulfurization, selective waste handling	(Botero et al., 2024; Butar Butar et al., 2025; Na et al., 2024; Si et al., 2023; Y. Zhang et al., 2024)

Note. The mechanisms are cross-case interpretations. Quantify their relative importance based on site-specific acidity and contaminant loads, hydraulic variability, mineralogy, and service-life requirements.

6. Prevention and Source Control

6.1. Prediction before placement and closure

Prevention is most credible when prediction resolves reactive heterogeneity before placing waste or fixing closure geometry. Recent work consistently argues that static tests are useful screening tools but cannot establish field reaction rates on their own. Representative sampling, mineralogical characterization, kinetic tests, and explicit scale-up are required (Elghali et al., 2023; Fan et al., 2022; Kusi et al., 2024; Opitz et al., 2025). Electrical, optical, and isotopic methods can augment this framework by identifying active oxidation or migration pathways (Camargo et al., 2026; Leiva et al., 2021; Reuß et al., 2023; Su et al., 2024).

6.2. Desulfurization, reprocessing, passivation, and covers

Source control can be chemical, physical, or hydrological. Chemical passivation approaches include organosilane and silica coatings that aim to suppress pyrite oxidation; microbially induced carbonate precipitation and biochar covers represent related attempts to restrict oxidant access or modify surface reactivity (Butar Butar et al., 2025; Dong et al., 2020; Xu et al., 2026; Y. Zhang et al., 2023). Their challenge is not initial inhibition but persistence under abrasion, wetting–drying, and long exposure.

Physical removal of reactive sulfides can offer a more durable pathway when liberation permits it. Porphyry-copper waste-rock research has demonstrated in-process identification and flotation of reactive fine fractions, while broader reviews show how reprocessing sulfide tailings can couple AMD prevention with metal recovery (Botero et al., 2024; Kiwingim et al., 2024; Na et al., 2024). Such strategies are strongest when the residual waste is re-tested to demonstrate that acid-generation potential has actually been reduced rather than redistributed.

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Cover systems reduce water infiltration and oxygen supply, but performance depends on seasonal water balance, gas transport, vegetation, material aging, and climate. Multi-year field studies and reactive-transport modeling show that cover assessment should be based on fluxes through the system rather than nominal layer thickness (Hersey & Power, 2023; Larochelle et al., 2025; Roy et al., 2026; Si et al., 2023; A. Zhang et al., 2023a; A. Zhang et al., 2023b; A. Zhang et al., 2024).

6.3. Source control as a life-cycle decision

The decision between perpetual treatment and source intervention is both economic and geochemical. Upfront earthworks or reprocessing may be costly, but they can reduce treatment capacity, reagent consumption, sludge generation, and long-term operational risk. Conversely, disturbing old wastes can temporarily increase oxidation or create new fine fractions. Source-control alternatives should therefore be compared with perpetual or long-duration treatment over a common project horizon using explicit discount rates, replacement cycles, post-closure monitoring, residual disposal, and closure obligations. The material balance should include recovered products, residual sulfide inventory, altered water and oxygen fluxes, and post-intervention monitoring (Ait-Khouia et al., 2025; Botero et al., 2024; Na et al., 2024; Vriens et al., 2020; Y. Zhang et al., 2024).

7. Treatment Systems: Active, Passive, Hybrid, and Advanced Routes

7.1. Active neutralization and engineered precipitation

Active treatment remains indispensable for high and variable loads, strict discharge targets, and sites with limited land. Lime or alkaline neutralization is mature, but the critical design questions concern reagent efficiency, sludge density, sulfate behavior, and the stability or value of precipitated solids. High-density sludge (HDS) systems improve solids recycle and dewatering, while staged neutralization can separate contaminant groups (Du et al., 2025; Lourenco & Curtis, 2021; Otunola & Mhangara, 2024; Yang et al., 2023). Performance should be reported as both water-quality change and load removal, together with dry-residual generation, moisture/dewaterability, mineralogy, and long-term leachability. Reactive MgO

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provides an alternative alkalinity source where controlled dissolution and Mg-based chemistry are advantageous (Nguegang et al., 2022; Pereira, 2025).

Engineered mineral formation is a more selective extension of neutralization. Ferrite-forming systems can immobilize Cu, Zn, and As while producing magnetic solids, although dissolved silica can inhibit ferritization. Schwertmannite-based pretreatment, magnetite precipitation, and precipitation–flotation–dewatering likewise attempt to create separable, lower-volume products (Igarashi et al., 2020; Jiang et al., 2024; Liu et al., 2025; Rapeta et al., 2024; Song et al., 2022). These approaches are attractive when product mineralogy is deliberately managed rather than accepted as an uncontrolled by-product.

7.2. Passive systems and reactive barriers

Passive systems trade process intensity for land area, residence time, and sensitivity to influent variability. Constructed wetlands, organic-substrate systems, limestone/zeolite units, permeable reactive barriers (PRBs), and dispersed alkaline substrates (DAS) have all demonstrated meaningful field or pilot performance (Chen et al., 2020; León et al., 2026; Li et al., 2021; Lin et al., 2021; Orden et al., 2021; Schwarz & Pérez, 2021; Shabalala & Masindi, 2022; Silva et al., 2021; Singh & Chakraborty, 2020; Singh & Chakraborty, 2021; Singh & Chakraborty, 2022a; Singh & Chakraborty, 2022b; Vasquez et al., 2022; Vergaray Andagua et al., 2022). Their main advantages are low continuous reagent and energy demand, but their service life is constrained by alkalinity depletion, clogging, media replacement, temperature, and hydraulic short-circuiting. Transferable reporting should therefore include hydraulic and acidity loading, HRT, media inventory, mass-removal intensity, and years of operation rather than removal percentage alone.

DAS technology is particularly important because the 2026 synthesis of two decades of application reports high acidity and metal removal across multiple field settings and emphasizes media formulations that maintain porosity. The broader lesson is that passive design should engineer solids location and pore structure, not merely provide alkalinity (Guerrero et al., 2024; León et al., 2026).

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7.3. Sulfidogenic and biological treatment

Biological sulfate or sulfur reduction can generate alkalinity while precipitating metals as sulfides. Recent work extends this concept to highly acidic conditions, arsenate removal, decommissioned uranium mine water, and low-temperature operation (Gou et al., 2024; Nogueira et al., 2021; Nogueira et al., 2025; Sun et al., 2020; Virpiranta et al., 2022; Xia et al., 2026; Zou et al., 2023). Performance depends on electron donor, sulfur source, microbial community, pH, and sulfide management. These systems can support selective recovery, but uncontrolled sulfide toxicity, odor, gas handling, and residual organic demand must be included in scale-up.

7.4. Membranes, adsorption, ion exchange, and electrochemical routes

Advanced separation technologies target the fraction of AMD chemistry that conventional neutralization does not resolve. Nanofiltration and reverse osmosis (RO) can separate dissolved ions and support water reclamation, but fouling and scaling become major constraints in gypsum-saturated waters, and high-recovery operation transfers salts to brine or concentrate that must be managed. Sequential adsorption and ion exchange can selectively recover REEs or other metals after bulk acidity and Fe are controlled (Felipe et al., 2021; Fonseka et al., 2022; Jiao et al., 2024; Jiao et al., 2025; José et al., 2024; Roa, López, Battaglia, et al., 2024; Roa, López, & Cortina, 2024a, 2024b; Roa et al., 2025; Siew et al., 2020). Electrochemical approaches can complement these routes, but electrode passivation, electricity demand, and residual handling remain design constraints.

7.5. Hybrid treatment trains rather than single technologies

The strongest recent consensus is that AMD should be treated as a sequence of site-specific functions rather than by a single named technology. One practical train may remove Fe and acidity before sulfate control, selective recovery, and final polishing, but this sequence is illustrative rather than universal. The optimum order changes with influent Fe, target metals, sulfate, scaling tendency, residual-mineral stability, product objectives, and the intended final water use because each upstream operation changes ionic strength, competition, fouling

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potential, and residual generation (Chen et al., 2021; Mosai et al., 2024; Nguegang et al., 2022; Rodríguez-Alegre et al., 2024; Thisani et al., 2022; Yang et al., 2023).

Figure 4 presents a qualitative applicability matrix to make those trade-offs explicit. It is not a scorecard and should not be read as declaring a universally superior technology. Instead, it shows why selection changes when the design objective shifts from metal removal to sulfate control, low-energy operation, small footprint, or resource recovery.

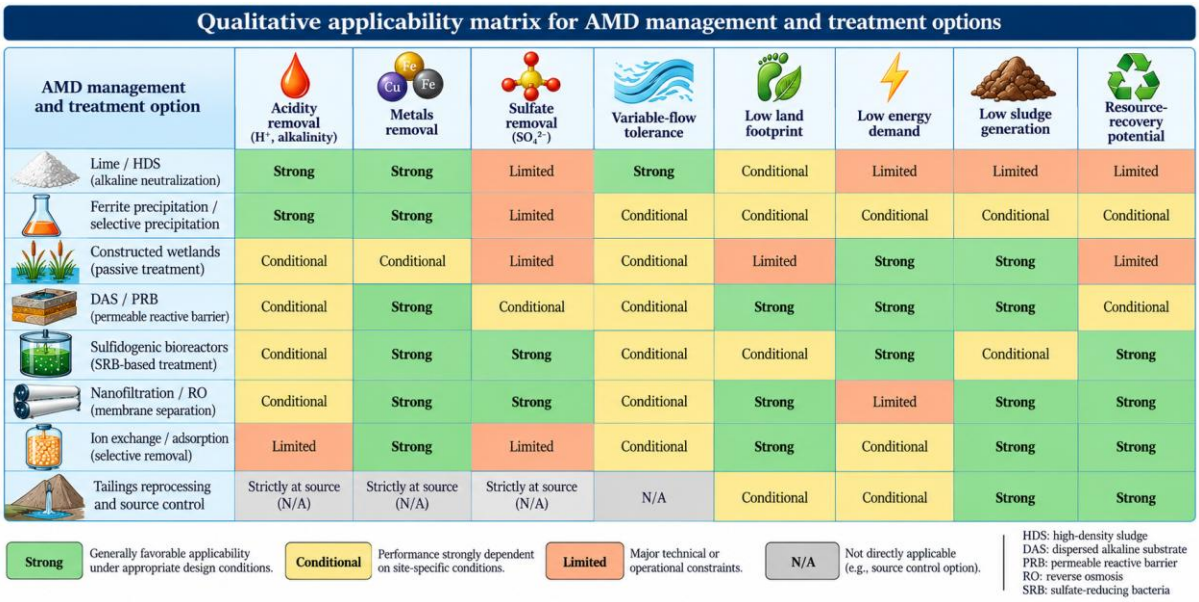


Figure 4

Qualitative applicability matrix for AMD management options

Note. Original decision-support synthesis informed by Chen et al. (2021), Masindi et al. (2022), Yang et al. (2023), Mosai et al. (2024), Du et al. (2025), and León et al. (2026). "Strong," "conditional," and "limited" indicate typical applicability in the reviewed evidence, not a universal ranking.

Table 4 is presented as two complementary panels to improve readability. Panel A summarizes mechanism, best-fit context, and typical treatment-train role; Panel B summarizes strengths, principal constraints, and evidence anchors. The panels emphasize functional complementarity rather than technology ranking.

Table 4

Comparison of AMD Management Technologies in a Treatment-Train Context (Panels A and B)

Panel A. Mechanism, operating context, and treatment-train role.

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Technology	Primary mechanism	Best-fit context	Typical role
Lime/HDS	Rapid neutralization and hydroxide precipitation	High-flow/high-acidity systems	Bulk treatment stage
Selective/ferrite precipitation	Controlled pH/redox and mineral formation	Metal/metalloid separation	After or within neutralization
Constructed wetlands	Biogeochemical reduction, sorption, precipitation	Low-to-moderate loads with land available	Polishing or small-flow treatment
DAS/PRB	Distributed alkalinity and reactive media	Persistent acidic flows	Passive primary or secondary stage
Sulfidogenic reactors	Biological sulfur/sulfate reduction and metal sulfide precipitation	Metal-rich waters where selective sulfide recovery is useful	Intermediate selective-recovery stage
Nanofiltration/RO	Pressure-driven ionic separation	Water-reclamation targets after solids control	Downstream polishing/recovery
Ion exchange/adsorption	Selective sorption/complexation	Dilute valuable metals/REEs after bulk impurity removal	Downstream recovery
Electrochemical systems	Electrocoagulation/electrode reactions	Targeted metal/anionic removal	Hybrid treatment/polishing
Source reprocessing	Physical separation of reactive sulfides	Waste streams with liberation opportunity	Upstream prevention

Panel B. Strengths, constraints, and evidence anchors.

Technology	Strengths	Main constraints	Evidence
Lime/HDS	Mature, controllable, robust	Reagent demand; sludge; sulfate may remain	(Du et al., 2025; Lourenco & Curtis, 2021; Otunola & Mhangara, 2024)
Selective/ferrite precipitation	Can improve solid stability and recoverability	Co-ion sensitivity; process control	(Igarashi et al., 2020; Jiang et al., 2024; Rapeta et al., 2024)
Constructed wetlands	Low energy, ecological integration	Seasonality, clogging, land footprint	(Li et al., 2021; Singh & Chakraborty, 2020; Singh & Chakraborty, 2021; Singh & Chakraborty, 2022a; Singh & Chakraborty, 2022b)
DAS/PRB	Low continuous energy; modular	Media depletion, hydraulic capacity	(León et al., 2026; Schwarz & Pérez, 2021; Shabalala & Masindi, 2022)
Sulfidogenic reactors	Metal recovery potential; sulfate reduction	Biological control; sulfide management	(Gou et al., 2024; Sun et al., 2020; Virpiranta et al., 2022; Xia et al., 2026; Zou et al., 2023)
Nanofiltration/RO	High-quality permeate; concentration of values	Scaling, fouling, energy, brine	(Jiao et al., 2024; Jiao et al., 2025; Roa, López, Battaglia, et al., 2024; Roa et al., 2025; Siew et al., 2020)
Ion exchange/adsorption	High selectivity and product concentration	Competition, resin regeneration	(Depp et al., 2024; Felipe et al., 2021; Goodman et al., 2023; José et al., 2024; Roa,

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Technology	Strengths	Main constraints	Evidence
			López, & Cortina, 2024a, 2024b)
Electrochemical systems	Compact and controllable	Electricity, electrode/passivation burden	(Stylianou et al., 2022; Villa Gomez et al., 2023)
Source reprocessing	Reduces future source term and recovers value	Requires mineral-processing feasibility	(Botero et al., 2024; Na et al., 2024)

Note. HDS = high-density sludge; DAS = dispersed alkaline substrate; PRB = permeable reactive barrier; RO = reverse osmosis; REEs = rare earth elements. Site-specific treatability testing is required before design. Performance should be normalized to contaminant load, operating intensity, service life, residual generation, and the intended final-water endpoint where the underlying study reports these data.

8. Monitoring, Circular Economy, and Decision Support

8.1. Monitoring and modeling as control technologies

Monitoring increasingly combines conventional hydrochemistry with remote sensing, sensors, isotopes, and models. UAS and satellite methods can map AMD-affected waters and waste dispersion; optical and electrical measurements can track treatment response; stable isotopes can distinguish sulfur sources and oxidation pathways; and PHREEQC or reactive-transport models can test mineral controls and treatment scenarios (Barroso et al., 2025; Camargo et al., 2026; Chalkley et al., 2023; Cravotta, 2021; Farahnakian et al., 2024; Flores et al., 2021; Hanelli et al., 2023; Hasrod et al., 2024; Leiva et al., 2021; Moreno-González et al., 2026; Ren et al., 2021; Reuß et al., 2023; Su et al., 2024; Wang et al., 2025).

Machine learning is most useful when it augments, rather than replaces, process understanding. Classifying AMD signatures or predicting sulfate and pH can improve surveillance, but extrapolating beyond the hydrochemical and climatic domain represented in the training data is risky. Models should report uncertainty under extrapolation, preserve physics- or geochemistry-informed variables where possible, and be recalibrated against field observations. Remote-sensing products likewise require field calibration before they are used for compliance or treatment-control decisions (Farahnakian et al., 2024; Hasrod et al., 2024; Zhang et al., 2026).

8.2. Resource recovery and water reclamation

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AMD contains contaminants, but it also contains dissolved metals, REEs, sulfate, and water that may have recoverable value. Ion exchange, selective precipitation, manganese-oxide adsorption, nanofiltration, crystallization, and electrochemical systems have all been evaluated for REE or metal concentration and water reuse (Baloyi et al., 2026; Depp et al., 2024; Felipe et al., 2021; Fonseka et al., 2022; Goodman et al., 2023; Hermassi et al., 2022; José et al., 2024; León et al., 2021; Li et al., 2022; Mahlohla et al., 2026; Muedi et al., 2025; Mwewa et al., 2022; Nthunya et al., 2025; Roa, López, Battaglia, et al., 2024; Roa, López, & Cortina, 2024a, 2024b; Roa et al., 2025; Rodríguez-Alegre et al., 2024; Villa Gomez et al., 2023; Viola et al., 2026; Wang et al., 2021). Water reclamation should be assessed against an explicit fitness-for-purpose endpoint—environmental discharge, process-water reuse, irrigation, industrial reuse, or potable-treatment precursor—using the corresponding salinity, sulfate, hardness, trace-element, and microbiological specifications rather than the generic label “treated water.”

The critical distinction is among metal captured, metal recovered, and qualified marketable product. A process that concentrates REEs into a sludge does not automatically create a saleable product if Fe, Al, radionuclides, or other contaminants remain. Techno-economic work on AMD precipitates and water reclamation therefore needs product specifications, recovery yield from influent to final qualified product, downstream refining requirements, chemical consumption, realistic market scale, and management of off-specification solids (Fritz et al., 2021; Mahlohla et al., 2026; Shingwenyana et al., 2021).

Carbon mineralization and conversion of treatment residues into useful products can further improve circularity, but these routes must be compared against baseline treatment and disposal using consistent system boundaries (Ju et al., 2022; Mahmoudi Kouhi et al., 2024; Moreno-González et al., 2023; Radfarnia et al., 2024).

8.3. Life-cycle and carbon considerations

Active treatment usually imposes larger continuous reagent and energy demands than passive treatment, but life-cycle conclusions depend on plant scale, reagent source, pumping, land use, construction, media replacement, and residual disposal. LCA should therefore state system boundaries and functional units explicitly; where data permit, impacts should be

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reported both per m³ of water treated and per unit acidity or contaminant load managed. Recent carbon-focused review work separates direct reaction effects from energy, reagent-production, and biological contributions, while LCA studies show that metal recovery can be environmentally unfavorable when reagent intensity dominates the benefit (Du et al., 2025; Mahmoudi Kouhi et al., 2024; Moreno-González et al., 2023; Praveen et al., 2022). TEA comparisons between source control and long-duration treatment should use a common economic horizon and disclose discount rate, replacement cycles, monitoring costs, residual disposal, and closure obligations.

Figure 5 integrates these considerations into an adaptive cycle. The sequence deliberately returns verification results to characterization and prediction because AMD systems evolve; a closure design that cannot be updated as field evidence accumulates is vulnerable to both under-treatment and unnecessary long-term cost.

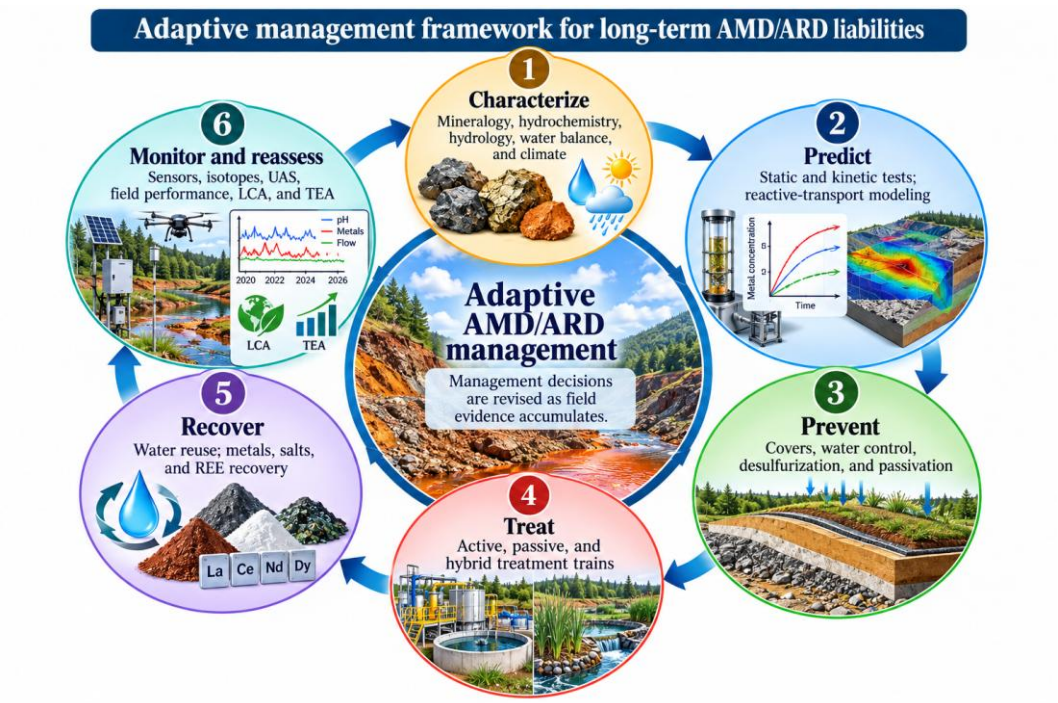


Figure 5
Adaptive management framework for long-lived AMD liabilities

Note. Author-developed conceptual decision framework synthesizing characterization, prediction, prevention, treatment, resource recovery, and verification, conceptually informed by Elghali et al. (2023), Cravotta (2021), Masindi et al. (2022), and Nauyryzbay et al. (2026). This framework has not been validated as a universal AMD-management standard and should be adapted to site-specific mineralogy, hydrology, regulatory end points, residuals, and closure objectives.

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9. Critical Research Gaps and a 2026–2035 Agenda

9.1. Long-duration field validation under changing climate

The most important evidence gap is service-life validation under non-stationary climate and hydrology. Many technologies are demonstrated over months or a few years, whereas AMD liabilities persist for decades. Research should therefore prioritize field observatories that connect precipitation, snow and freeze–thaw conditions, evapotranspiration, mine-pool level, flow, chemistry, and treatment performance. Long records from covers, pit lakes, coal mines, and passive systems show the value of this approach (Hersey & Power, 2023; Larochelle et al., 2025; Manning et al., 2024; Roy et al., 2026; Schaffer et al., 2024; Singer et al., 2026; A. Zhang et al., 2023a; A. Zhang et al., 2023b; A. Zhang et al., 2024).

9.2. Prediction models that preserve geochemical causality

Artificial intelligence (AI) and machine learning can reduce monitoring cost and identify spatial patterns, but black-box prediction without mass-balance or mineralogical constraints risks false confidence. Future models should preserve causal variables such as sulfide inventory, reactive surface area, alkalinity, oxygen transport, water balance, and residence time, and they should report uncertainty under extrapolation (Elghali et al., 2023; Farahnakian et al., 2024; Hasrod et al., 2024; Zhang et al., 2026).

9.3. Residuals as engineered products rather than afterthoughts

Treatment residuals remain a central weakness in both active and passive systems. Future research should specify mineralogy, leachability, aging behavior, pH/redox cycling where relevant, dewatering behavior, moisture content, storage conditions, and potential recovery routes at the same stage as water-treatment design. Residual generation should be normalized, where possible, as kg dry residual per m^3 treated or per kg acidity neutralized, so that excellent aqueous removal is not achieved at the expense of an unquantified solids burden. Precipitation–flotation–dewatering, ferrite formation, sludge valorization, and crystallization point toward a product-oriented design philosophy (Igarashi et al., 2020; Liu et al., 2025; Moreno-González et al., 2023; Nthunya et al., 2025; Rapeta et al., 2024).

9.4. Integrated prevention, treatment, and recovery

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Source control and resource recovery should be assessed together where reprocessing can remove reactive sulfides or recover metals. This requires a mine-to-product balance that includes the residual waste, not only concentrate recovery. Likewise, AMD recovery flowsheets should quantify how pretreatment changes reagent use, resin loading, membrane fouling, and product purity (Botero et al., 2024; Fonseka et al., 2022; Fritz et al., 2021; León et al., 2021; Na et al., 2024; Roa, López, Battaglia, et al., 2024; Roa, López, & Cortina, 2024a, 2024b; Rodríguez-Alegre et al., 2024).

9.5. Governance, closure, and social durability

Technical performance does not remove the need for governance over decades. Long-lived mine-water liabilities cross ownership changes, mine closure, public financing, and changing standards. Work on uranium-mine rehabilitation, small-scale mining, environmental and social impacts, and watershed recovery shows that monitoring commitments and institutional responsibility are part of engineering reliability (Kazapoe et al., 2023; Lawrence, 2022; Meyer et al., 2023; Nauyryzbay et al., 2026; Shakya et al., 2021).

Table 5 translates these gaps into testable research priorities. It emphasizes field-verifiable outputs rather than broad calls for "more research."

Table 5

Priority Research Questions for AMD Management, 2026–2035

Priority	Critical question	Required evidence	Decision output	Evidence anchors
Field service life	How do treatment and source-control systems perform over decades?	Long-term paired flow–chemistry–mineralogy datasets	Design factors tied to degradation rate, not short trials	(Larochelle et al., 2025; León et al., 2026; Roy et al., 2026; Schaffer et al., 2024)
Climate resilience	How do extreme rainfall, drought, warming, and freeze–thaw alter loads?	Event-scale and seasonal mass balances	Climate-adjusted capacity and residence-time criteria	(Desmau et al., 2024; Manning et al., 2024; Singer et al., 2026; Zhang et al., 2026)
Predictive mineralogy	Which mineral/texture variables best predict field acidity flux?	Sampling + automated mineralogy + kinetic/field tests	Uncertainty-bounded source-term models	(Elghali et al., 2023; Fan et al., 2022; Lim et al., 2024; Opitz et al., 2025)
Residual stability	Which solids remain stable under realistic disposal exposure?	Mineralogy, leaching, redox cycling, dewatering	Residual specifications integrated into treatment design	(Gu et al., 2026; Igarashi et al., 2020; Moreno-González et al., 2023; Rapeta et al., 2024)
Hybrid trains	What sequence minimizes total reagent, energy, and residual burden?	Pilot trains with full mass/energy balances	Site-specific train-selection rules	(Mosai et al., 2024; Nguegang et al., 2022; Rodríguez-Alegre et al., 2024; Thisani et al., 2022)
Critical-	When do REE/metal	Product purity, recovery,	Bankable recovery	(Baloyi et al., 2026;

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Priority	Critical question	Required evidence	Decision output	Evidence anchors
metal recovery	products meet downstream specifications?	refining, TEA/LCA	routes rather than enriched sludge	Fritz et al., 2021; Hermassi et al., 2022; Mahlohla et al., 2026; Mwewa et al., 2022)
Digital monitoring	How can remote sensing/ML reduce blind spots without losing causality?	Sensor fusion with field calibration and uncertainty	Early-warning and adaptive-operation systems	(Chalkley et al., 2023; Farahnakian et al., 2024; Flores et al., 2021; Hasrod et al., 2024; Reuß et al., 2023)
Source reprocessing	When is desulfurization superior to perpetual treatment?	Liberation, sulfide recovery, residual kinetic tests, closure economics	Mine-to-closure decision framework	(Botero et al., 2024; Kiwingim et al., 2024; Na et al., 2024)

Note. TEA = techno-economic assessment; LCA = life-cycle assessment. The priorities are derived from recurrent limitations in the reviewed field and process literature.

Taken together, the broader evidence landscape reinforces the same process logic across environmental impact, treatment, and recovery studies: site characterization and source control define the influent problem; treatment redistributes acidity and elements among water and solids; and the sustainability of a route depends on what happens to those solids and to the treated water after the primary removal step (Ait-Khouia et al., 2025; Alvarenga et al., 2021; Baloyi et al., 2026; Butar Butar et al., 2025; Cardoso & Fan, 2024; Deng et al., 2026; Depp et al., 2024; Dong et al., 2020; Felipe et al., 2021; Fonseka et al., 2022; Fritz et al., 2021; Gomes et al., 2025; Goodman et al., 2023; Guerrero et al., 2024; Hermassi et al., 2022; Jiao et al., 2024; Jiao et al., 2025; José et al., 2024; Ju et al., 2022; Keller et al., 2025).

The resource-recovery literature similarly shows that value recovery is most credible after bulk acidity and major impurity loads are controlled, and when selective separation, membrane performance, product purity, and downstream refining are assessed together (Li et al., 2022; Luís et al., 2024; Mahlohla et al., 2026; Muedi et al., 2025; Mwewa et al., 2022; Ngerem et al., 2026; Nogueira et al., 2021; Nuñez-Bustamante et al., 2025; Papaslioti et al., 2024; Pereira, 2025; Pérez-López et al., 2025; Piñon-Flores et al., 2024; Radfarnia et al., 2024; Roa, López, Battaglia, et al., 2024; Roa, López, & Cortina, 2024a, 2024b; Roa et al., 2025; Rue & McKnight, 2021; Shingwenyana et al., 2021; Siew et al., 2020).

Finally, the emerging technology portfolio—from selective precipitation and electrochemical treatment to advanced monitoring, carbon-mineralization, source passivation, and integrated sustainability assessment—should be evaluated against long-duration field baselines rather than against idealized laboratory removal efficiencies (Silva et al., 2021; Song et al., 2022;

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Stylianou et al., 2022; Tang et al., 2024; Thisani et al., 2021; Tum et al., 2024; Villa Gomez et al., 2023; Viola et al., 2026; Wang et al., 2021; Xia et al., 2026; Xu et al., 2026; Yang et al., 2023; Y. Zhang et al., 2024).

10. Conclusions

International AMD case studies demonstrate that the central management problem is not simply acidity removal. It is the control of a changing contaminant flux generated by sulfide mineralogy, waste architecture, oxygen and water transport, secondary-mineral reactions, and long-lived hydrologic pathways. A treatment system can meet a short-term outlet target and still be unsustainable if it creates unstable sludge, leaves sulfate or salinity unresolved, or depends on perpetual reagent and energy inputs without a credible closure pathway.

The strongest transferable lesson is to characterize and reduce the source term before sizing downstream treatment. Where source control is feasible, selective waste handling, reprocessing, desulfurization, covers, and passivation can reduce long-term treatment burden. Where high or variable loads remain, active neutralization retains an essential role. Passive and hybrid systems are particularly valuable when hydraulic loading, land availability, temperature, and media service life fall within defensible operating windows.

A second lesson is that treatment should be designed as a train of functions rather than as a named technology. Bulk acidity and Fe removal, sulfate control, selective metal recovery, water polishing, and residual stabilization may require different unit operations, and the optimal sequence depends on influent chemistry and the intended end use of the water. Resource recovery can offset treatment burden, but only when enriched streams are converted into products with realistic purity, scale, and downstream markets.

For the next decade, the highest-value research is long-duration and field-verifiable: climate-resilient source-term models, service-life data for covers and passive media, causal integration of remote sensing and machine learning, engineered treatment residuals, and combined TEA/LCA of prevention–treatment–recovery systems. Adaptive management should be treated as a design requirement because AMD chemistry and flow evolve throughout closure and post-closure.

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The overall implication is that robust AMD management is site-specific but not site-isolated. International case studies are most useful when they are translated into process rules—mineralogical, hydraulic, chemical, operational, and life-cycle—rather than copied as complete flowsheets. That approach provides a stronger basis for reducing perpetual liabilities while improving water recovery, residual stability, and opportunities for selective resource recovery. Geographic coverage should therefore be interpreted as illustrative rather than statistically representative, regulatory end points remain jurisdiction-specific, and emerging 2026 approaches require independent replication before they are treated as mature practice.

Declarations

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Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

Author Contributions

Conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation by the author.

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