

COMPARATIVE ANALYSIS OF CONVENTIONAL AND NON-CONVENTIONAL MINE WATER TREATMENT TECHNOLOGIES IN THE CONTEXT OF THE CIRCULAR ECONOMY: SMART GOALS AND LIFE CYCLE ASSESSMENT

Katerina Nikolova, Svetlana Bratkova, Anatoliy Angelov, Petia Genova, Miglena Ivanova

University of Mining and Geology “St. Ivan Rilski”, 1700 Sofia; E-mail: ivanov@abv.bg

ABSTRACT. Mine water poses a significant environmental risk due to its high acidity and metal and sulphate concentrations. It also represents a potential resource in the context of circular economy. This paper presents a comparative analysis of conventional and non-conventional/innovative technologies. The analysis is structured according to circular economy principles, focusing not only on removal efficiencies but also on opportunities for resource recovery. A Life Cycle Assessment (LCA)-based approach is applied to compare the environmental impacts of different technologies. Example SMART goals for mine water management within sustainable mining operations are proposed. The advantages and limitations of each group of technologies, as well as the prospects for combined hybrid systems consistent with circular economy principles, are discussed.

Key words: mine water treatment; circular economy; metal recovery; LCA; SMART goals.

СРАВНИТЕЛЕН АНАЛИЗ НА КОНВЕНЦИОНАЛНИ И НЕКОНВЕНЦИОНАЛНИ ТЕХНОЛОГИИ ЗА ПРЕЧИСТВАНЕ НА МИННИ ВОДИ В КОНТЕКСТА НА КРЪГОВАТА ИКОНОМИКА: SMART ЦЕЛИ И LCA

Катерина Николова, Светлана Браткова, Анатолий Ангелов, Петя Генова, Миглена Иванова
Минно-геоложки университет „Св. Иван Рилски“, 1700 София

РЕЗЮМЕ. Минните води представляват значителен екологичен риск поради високата си киселинност, концентрации на метали и сулфати, като същевременно представляват потенциален ресурс в контекста на кръговата икономика. В настоящата разработка е представен сравнителен анализ на конвенционални и неконвенционални/иновативни технологии. Анализът е структуриран съгласно принципите на кръговата икономика, като се фокусира не само върху ефективността на отстраняване, но и върху възможностите за оползотворяване на ресурсите. Прилага се подход, базиран на оценка на жизнения цикъл (LCA), за сравняване на въздействието на различните технологии върху околната среда. Предлагат се примерни SMART цели за управление на минните води в рамките на устойчиви минни операции. Обсъждат се предимствата и ограниченията на всяка група технологии, както и перспективите за комбинирани хибридни системи, съответстващи на принципите на кръговата икономика.

Ключови думи: пречистване на минни води, кръгова икономика, възстановяване на метали, LCA, SMART цели.

Introduction

Mining industry is a major consumer of water and generator of contaminated effluents. Mine water – including acid mine drainage (AMD), neutral mine drainage, tailings seepage and process water – often contains elevated concentrations of Fe, Mn, Al and a range of base and trace metals, such as Cu, Zn, Ni, Pb, Cd, and As, together with high sulphate loadings (Akcil & Koldas, 2006; Nordstrom, 2011). In the case of AMD, the oxidation of sulphide minerals, primarily pyrite and pyrrhotite, leads to low pH, high redox potential, and enhanced metal mobility, often over decadal to centennial time scales (Younger et al., 2002; Johnson & Hallberg, 2005).

Historically, mine water management has been dominated by “end-of-pipe” approaches focused on meeting discharge limits, typically through lime neutralisation and metal hydroxide precipitation. Such linear solutions convert dissolved pollutants into large volumes of sludge that require long-term storage and management, while the water itself is discharged after single use.

In contrast, contemporary policy frameworks emphasise resource efficiency, climate mitigation and circular economy concepts, aiming to retain materials and water in circulation for as long as possible and to reduce primary resource extraction (Ellen MacArthur Foundation, 2015; European Commission, 2020). In a circular economy perspective, mine water is not only an environmental liability but also a potential source of:

- Metals and metalloids (Cu, Zn, Ni, Co, REEs, and others)

that can be recovered and fed back into value chains (Falagán et al., 2017);

- Mineral products, e.g. gypsum, iron oxyhydroxides, and other precipitates that can be used as sorbents or construction materials after appropriate stabilisation (Lottermoser, 2011);
- Industrial wastewater with a high salt content, high metal ions, and high hardness that can be reused for processing, dust suppression, or even potable use after advanced treatment (Xu et al., 2024);
- Energy carriers, in particular in biological processes where organic substrates and sulphates can be transformed into biogas or reduced sulphur species that can be further valorised (Kaksonen & Puhakka, 2007).

Realising this potential requires a shift from purely compliance-driven treatment towards integrated systems that maximise resource recovery while minimising environmental burdens over the full life cycle. This, in turn, calls for robust decision-support tools such as Life Cycle Assessment (LCA) to evaluate the environmental performance of alternative treatment trains beyond local water quality improvements (ISO 14040, 2006; Guinée et al., 2011).

In parallel with these policy developments, mining industry is under increasing pressure from investors, regulators, and civil society to demonstrate alignment with environmental, social, and governance (ESG) criteria. Water-related risks - including competition for freshwater with other users, long-term liabilities associated with tailings and mine water discharges, and the

potential for catastrophic failures - are now explicitly recognised as material financial risks. This has accelerated interest in mine water treatment and reuse options that both ensure regulatory compliance and contribute to corporate climate and resource-efficiency strategies by reducing freshwater abstraction, lowering life-cycle greenhouse gas emissions, and producing secondary products from waste streams (Matebese et al., 2024).

Despite significant progress in individual technologies and numerous case studies, there is still a lack of systematic, comparative assessments of conventional and innovative mine water treatment systems from a circular economy and life-cycle perspective. Many published studies focus on local water quality outcomes or short-term operational performance, while overlooking upstream and downstream burdens associated with reagent manufacture, energy supply, sludge management, and recovery of by-products. Moreover, decision-making in practice is often driven by capital and operating costs, with environmental performance assessed only qualitatively. Addressing this gap requires integrated analyses that combine process-level understanding of treatment technologies with LCA-based quantification of environmental impacts and explicit formulation of SMART targets that can guide the transition from linear, end-of-pipe treatment towards genuinely circular mine water management (Mancini et al., 2024).

This paper aims to:

- evaluate key conventional and innovative mine-water treatment technologies in terms of removal performance, resource and energy demand, sludge production, and resource-recovery potential;
- demonstrate how life-cycle assessment can identify environmentally preferable system configurations and expose trade-offs across impact categories;
- present exemplar SMART targets for mine-water management that are grounded in circular-economy principles and informed by existing case studies.

Mine water treatment technologies

Conventional technologies

Lime neutralisation and metal hydroxide precipitation. Lime neutralisation followed by metal hydroxide precipitation is by far the most widely applied AMD treatment technology worldwide (Johnson & Hallberg, 2005; Akcil & Koldas, 2006). Calcium hydroxide or calcium carbonate is added to raise the pH, leading to the hydrolysis and precipitation of Fe(III), Al(III), and other metals as hydroxides, while calcium sulphate (gypsum) forms at high sulphate concentrations. The process is robust, well understood, and capable of achieving regulatory compliance for many metals. However, its drawbacks are substantial. High reagent demand and embodied emissions: Lime production is energy-intensive and associated with significant CO₂ emissions (Norgate & Haque, 2010). Large volumes of low-density sludge, often containing 1–5% solids, which require thickening, dewatering, and long-term storage, with associated costs and environmental liabilities. Limited selectivity and recovery: Metals are immobilised in a mixed sludge that is usually not economically attractive for recovery, especially when derived from dilute streams. From a circular economy standpoint, pure lime neutralisation is essentially a linear risk-transfer operation: dissolved contaminants are converted into a solid waste with

limited valorisation options. Nevertheless, it remains a key component in many treatment trains, especially as a polishing or safety barrier.

Coagulation–flocculation and filtration. To improve solids separation and colloidal-metal removal, coagulants (FeCl₃, Al₂(SO₄)₃) and polymeric flocculants are commonly dosed after neutralisation, followed by sedimentation and filtration (sand/multimedia filters, filter presses) to enhance effluent clarity and reduce suspended solids; however, these steps increase chemical consumption and sludge production, with life-cycle impacts largely driven by reagent manufacture, transport and sludge handling (Aguilar-Garrido et al., 2023). Circular opportunities include substituting conventional coagulants with iron-rich industrial residues, optimising dosing, and using high-efficiency flocculants to cut chemical demand, and improving dewatering to lower sludge volumes and enable potential reuse or valorisation (Matebese et al., 2024).

Ion exchange. Ion-exchange resins can selectively remove target cations or anions (e.g., U(VI), As(V), Cr(VI), base metals) and are therefore frequently deployed as polishing steps or for recovery of high-value metals in relatively low-salinity mine water, since high ionic strength, competing ions and solids reduce efficiency in many feed streams (Lebron et al., 2023). From a circular-economy perspective, ion exchange is attractive because regeneration solutions concentrate metals and can feed hydrometallurgical recovery routes; however, resin manufacture, regeneration reagents, and spent-regenerant management contribute substantially to life-cycle impacts, so integration into broader valorisation schemes is critical to maximise benefits (Roa et al., 2024).

Membrane technologies. Membrane processes (UF, NF, RO, membrane distillation/crystallisation) are increasingly applied for mine-water polishing and reuse where high-quality permeate is required: UF removes suspended solids/colloids, while NF/RO provide high rejection of dissolved salts and metals and produce a concentrated brine suitable for downstream recovery or crystallisation. Advanced approaches, such as membrane distillation and membrane crystallisation, enable simultaneous water recovery and salt/mineral recovery from concentrate streams, improving circularity when integrated with ion-exchange or selective precipitation steps (Lebron et al., 2023; Nthunya et al., 2025). Key trade-offs include energy/carbon intensity of desalination, brine management, and potential for resource recovery from the concentrate, which must be assessed in a life-cycle framework to determine overall circularity (Gómez et al., 2024). Aligning membrane technologies with circular economy principles requires access to low-carbon electricity, integration with metal and salt recovery (e.g. crystallisation of gypsum or sodium sulphate), and design for high recovery ratios to minimise brine volumes.

Conventional biological processes. Conventional biological treatment systems (e.g. activated sludge, biofilters) are less commonly used for highly acidic and metal-rich mine water, but they play a role where organic contaminants, nitrates or cyanide are present (Johnson & Hallberg, 2005). In neutral or weakly contaminated streams, biological processes can offer low-energy polishing and partial nutrient removal. In AMD contexts, the more relevant biological processes are

sulphate-reducing and metal-precipitating systems, which are discussed below under non-conventional technologies.

Non-conventional and innovative technologies

Passive treatment systems. Passive treatment systems, such as constructed wetlands, anoxic limestone drains, and successive alkalinity-producing systems, rely on natural geochemical and biological processes to neutralise acidity, reduce sulphate, and precipitate metals, and are therefore widely used for low-cost, low-energy remediation of mine-impacted water (Daraz et al., 2023). They generally require minimal energy and routine operational input once established, although performance is sensitive to influent acidity, hydraulic loading, and media selection. Recent comparative life-cycle studies indicate that passive systems can have substantially lower global-warming potential and cumulative energy demand per cubic metre treated than fully active chemical systems, while trading off larger land requirements, lower controllability, and site-specific treatment timescales (Alam et al., 2023). From a circular-economy perspective, passive systems contribute through low operational resource demand, opportunities for co-benefits (habitat creation, landscape rehabilitation), use of local/secondary materials (e.g., organic substrates, industrial by-products) as reactive media, and by enabling downstream recovery routes when coupled with hybrid trains — but long-term media stability, metal fate in sediments, and risks from media clogging remain critical design considerations.

Permeable reactive barriers (PRBs). PRBs are in-situ systems installed in the path of contaminated groundwater flows filled with reactive media, such as elemental iron, limestone, organic matter, or industrial residues (Sakr et al., 2023). They promote processes such as sulphate reduction, redox transformation, and sorption. An emerging trend is the use of industrial by-products (e.g. steel slags, red mud) as PRB media, effectively turning waste streams into remediation resources. This directly supports circular economy objectives by coupling remediation with waste valorisation. Long-term performance, permeability maintenance, and stability of immobilised contaminants remain critical design considerations (Salih et al., 2024).

Electrochemical processes. Electrochemical (EC) processes, such as electrocoagulation and electrooxidation, generate coagulants or oxidants in situ and can efficiently remove metals and other contaminants; recent bench- and pilot-scale studies report high removal efficiencies for Ni, Cr, Fe and other ions and show potential reductions in sludge volume compared with chemical coagulation in specific cases. Their compatibility with circular-economy principles depends on the carbon intensity of the electricity supply, the ability to combine electrochemical steps with downstream recovery (e.g., metal-rich flocs suitable for recovery), and the durability/recyclability of electrodes; as power decarbonisation progresses, the relative life-cycle performance of EC technologies is expected to improve (Mao et al., 2023).

Adsorption using secondary raw materials and bio-based sorbents. Adsorption is widely used for polishing and targeted contaminant removal in mine effluents; there is growing interest in low-cost sorbents derived from industrial and agricultural residues (e.g. biochar, fly ash, steel slags, red mud, and other

biosorbents) because they can combine lower material cost and environmental burden with waste-valorisation opportunities (Gallego-Ramírez et al., 2023). These residue-derived adsorbents can reduce dependence on virgin activated carbons, enable co-valorisation of another industry's waste stream, and, where suitably stabilised, permit beneficial reuse of spent sorbents (for example as components in construction materials), but each pathway requires demonstration of long-term stability and acceptable leachability of immobilised metals (Xu et al., 2022). Crucially, LCA-supported assessments (and where possible integrated LCA–LCC studies) are needed to quantify lifecycle impacts and avoid burden-shifting from water to soil or landfill compartments when sorbents are produced, applied, and disposed or reused (Chen et al., 2021).

Biotechnologies for metal recovery and valorisation.

Bioprocesses based on sulphate-reducing bacteria and other functional guilds can convert sulphate to sulphide, precipitating dissolved metals as metal sulphides that are more concentrated and suitable for hydrometallurgical recovery (Kaksonen & Puhakka, 2007). Other microbial processes, such as biosorption and bioaccumulation, can further contribute to metal uptake. Falagán et al. (2017) review several pilot-scale systems demonstrating high removal efficiencies for Cu, Zn, and other metals from mine water, with metal-rich sludge subsequently processed to recover saleable products. These biotechnologies are particularly aligned with circular economy goals as they convert a dispersed pollution problem into a concentrated secondary resource, operate at relatively low temperatures and often moderate energy inputs, and can be integrated with passive or semi-passive systems using locally available organic substrates.

Integrated valorisation and near-zero liquid discharge (ZLD) scheme.

The most advanced circular configurations combine several of the above technologies into integrated flowsheets that aim to maximise internal water recycling, recover metals and mineral products, minimise or eliminate liquid discharges (near-ZLD or ZLD), or reduce life-cycle impacts per unit of treated water. Typical elements include pre-neutralisation (passive or active), selective metal recovery (biological or chemical), membrane concentration, and crystallisation/evaporation for salt recovery. LCA studies of ZLD systems show that, while energy requirements are high, integrating resource recovery and using low-carbon energy sources can lead to net environmental benefits compared with linear discharge-oriented treatment (Xu et al., 2024).

LCA of Mine Water Treatment Technologies

Methodological framework

LCA is standardised by ISO 14040/14044 and comprises four main stages: Goal and scope definition; Life cycle inventory (LCI); Life cycle impact assessment (LCIA); Interpretation of results (ISO 14040, 2006; Guinée et al., 2011). For mine water treatment systems, the functional unit is often defined as “treatment of 1 m³ of mine water to meet regulatory discharge limits” or “recovery of 1 kg of metal at a given effluent quality”. The system boundary (“cradle-to-grave” or “cradle-to-gate”) typically includes:

- 1) Production and transport of reagents (lime, coagulants, adsorbents, ion exchange resins);
- 2) Consumption of electricity and fuels;
- 3) Construction, operation and maintenance of infrastructure (reactors, ponds, membranes, pipelines);
- 4) Treatment and/or disposal of sludge, brine, and other waste streams;

- 5) Potential credits for recovered products (metals, salts, treated water, energy).

Basically considered impact categories include global warming potential (GWP), eutrophication, acidification, resource use (fossil fuels, metals and minerals), and human and ecotoxicity (Hauschild et al., 2013). The choice of impact categories and assessment methods should reflect the decision context and key environmental concerns.

Table 1. Management goals of mine wastewater
(S – Specific, M – Measurable, A – Achievable, R – Relevant, TB – Time-Bound)

Goal 1. Reduction of sulphates and electrical conductivity	
S	Reduce sulphate concentration in mine water discharge by 40% and electrical conductivity (EC) by 30%, hybrid treatment
M	Monthly measurements for the prior 12 months, Interim checks with corrective actions if needed
A	Low-cost secondary materials can neutralise acidity, immobilise contaminants, and reduce EC and metal concentrations, sulphidogenic bioreactors can achieve sulphate reductions (43–87% and higher sulphate-reduction rates, realistic conditions) (Virpiranta et al., 2022; Aguilar-Garrido et al., 2023).
R	Aligns with ESG stewardship, reduces tailings-related liabilities, opportunities for metal recovery and sludge valorisation.
TB	Within 3 years
Goal 2. Process water recycling	
S	Increase the share of recycled process water in the PP
M	At least 60% of total water demand to be covered by internally recycled streams
A	Industrial-scale plants in copper and iron ore mining have achieved >70% internal water recycling by combining tailings thickening/filtration with UF + NF/RO, thereby reducing freshwater abstraction and discharge (Xu et al., 2024)
R	Reduces freshwater intake and operating costs, improves water security
TB	Within 5 years
Goal 3. Metal recovery	
S	Implement a sulphate reducing bioreactor for Cu and Zn recovery as metal sulphides from the main AMD stream
M	Recover at least 30% of dissolved Cu and Zn (kg/year)
A	Pilot and semi-industrial sulphate reducing systems have achieved >90% removal of dissolved metals (Fe, Cu, Zn, Ni) with generation of concentrated metal sulphide sludges suitable for downstream metal extraction (Falagán et al., 2017)
R	Decreases the load on polishing steps and creates secondary metal concentrates
TB	Industrial implementation within 3 years after successful pilot operation
Goal 4. Reduction of life cycle carbon footprint of treatment	
S	Reduce the GWP per 1 m ³ of treated mine water compared with a baseline lime only neutralisation scheme
M	≥ 25% reduction in kg CO ₂ eq/m ³ (LCA based)
A	LCA studies show that partially substituting lime with alkaline industrial residues (fly ash, slags, red mud), and combining passive units with energy optimised active steps, can significantly lower life cycle GHG emissions while maintaining treatment performance (Lottermoser, 2017; Xu et al., 2024)
R	Supports corporate decarbonisation and regulatory compliance
TB	Within 7 years
Goal 5. Sustainable sludge management and valorisation	
S	Reduce the amount of sludge sent to landfill and increase the share of sludge valorised as construction or backfilling material
M	At least 50% (dry mass) of sludge to be reused
A	Mine/metal bearing sludge, when stabilised/solidified with cementitious and pozzolanic binders, can be safely used as backfill or low-grade construction products with controlled metal leaching and reduced overall environmental impacts (Lottermoser, 2017)
R	Lowers disposal needs and long-term environmental risks
TB	Within 5 years
Goal 6. Transparency and stakeholder engagement	
S	Implement a system for regular LCA based and circularity-oriented reporting on mine water management
M	Annual public report with KPIs: % recycled water, kg recovered metals, t CO ₂ eq avoided vs. baseline, % sludge valorised
A	An increasing number of mining companies publish GRI based sustainability reports complemented with LCA/LCC indicators; collaborations with universities, data collection and analysis, improve trust among regulators and communities (Norgate & Haque, 2010; EC, 2020)
R	Strengthens the social licence to operate and meets investor/ESG expectations
TB	First public report within 2 years, then annually

Comparison of conventional and non-conventional technologies using LCA

Literature indicates several consistent patterns. Lime neutralisation with calcium hydroxide often dominates GWP and resource use due to the energy-intensive production of lime and the management of large volumes of sludge (Norgate & Haque, 2010). Membrane systems (NF/RO) have relatively high energy demand, but their lower chemical consumption and ability to enable high water recovery and metal concentration can result in comparable or even lower life-cycle impacts in scenarios that include resource recovery and internal water reuse (Xu et al., 2024).

Passive treatment systems generally show the lowest energy use and GWP per m³ of treated AMD, but are constrained by hydraulic capacity, seasonal variability and land requirements. Biotechnologies for metal recovery can deliver net environmental benefits through “avoided burden” effects, where secondary metals produced from mine water displace primary production and its associated impacts (Kaksonen & Puhakka, 2007; Norgate & Haque, 2010; Falagán et al., 2017).

The selection of the “best” technology is highly context-dependent and influenced by different factors (environmental, technological, economical, etc.) - mine water composition and flow rate; local energy mix (coal-based vs. low-carbon systems); market demand and logistics for recovered products; regulatory requirements, risk tolerance and social acceptance. LCA thus serves not to prescribe a single universal solution, but to reveal trade-offs and identify context-specific optima.

LCA has a crucial role in designing circular mine water treatment systems. LCA provides a quantitative basis for:

- Selecting reagents and materials with lower embodied impacts (e.g. partial substitution of lime with alkaline industrial residues);
- Assessing the benefits of using secondary raw materials (slag, fly ash, red mud, bio-based sorbents) as reactive media or adsorbents;
- Comparing “treatment-only” scenarios with “treatment + resource recovery” scenarios, including metal and salt recovery and high-level water reuse;
- Identifying “hotspots” (e.g. lime production, electricity use in membrane stages, sludge disposal) that should be prioritised for optimisation or substitution.

SMART goals for mine water management within the scope of circular economy

Integrating LCA into the early design phases of mine-water treatment schemes enables selection of technologies that both meet water-quality standards and minimise life-cycle impacts while maximising recovered value (Alam et al., 2023; Mancini et al., 2024). In a circular-economy context, LCA-guided design supports the shift from linear, end-of-pipe solutions to integrated mine-water management where treatment, resource recovery, and long-term environmental performance are optimised jointly rather than in isolation. The implementation of circular-economy concepts and LCA in mining operations requires formalising strategic and operational objectives; the SMART (Specific, Measurable, Achievable, Relevant, Time-bound) framework is useful for translating broad visions into actionable plans. Table 1 presents example SMART goals for a typical mining operation.

Circular economy perspective

From a circular economy standpoint, the performance of mine water treatment technologies should be assessed not only in terms of contaminant removal and compliance, but also regarding resource recovery potential, life-cycle impacts, and long-term liabilities (Aguilar-Garrido et al., 2023). Conventional technologies, such as lime neutralisation, coagulation-flocculation, filtration, and membrane processes, remain an essential foundation for reliable compliance with water quality standards in mining. However, in their traditional linear form, they contribute only modestly to circular economy objectives, as they entail high consumption of primary reagents and energy and generate large volumes of low-value sludge that require long-term management. In contrast, non-conventional and innovative approaches - including passive treatment systems, permeable reactive barriers, the use of secondary raw materials as reactive media, biotechnologies for metal recovery, and integrated valorisation or near-ZLD schemes - show potential to transform mine water from a waste stream into a secondary resource for metals, mineral products, and reusable water, particularly when combined into appropriately designed hybrid treatment chains (Mancini et al., 2024).

LCA is a key tool for objectively comparing such options, identifying environmental hotspots and revealing trade-offs between local water quality improvements and upstream or downstream burdens associated with reagent production, energy use, and sludge management. LCA-based design enables the selection of mine water treatment configurations that both ensure regulatory compliance and minimise life-cycle impacts, while supporting resource recovery. Within this framework, the formulation of SMART goals is crucial for practical implementation of circular strategies in mining, translating sustainability aspirations into specific, measurable, and time-bound targets for water recycling, metal recovery, carbon footprint reduction, sludge valorisation, and transparent reporting. Future work should focus on scaling up and de-risking biotechnologies for metal recovery from mine water, improving the long-term stability and safety of reused sludge and reactive media, integrating LCA with life cycle costing and risk assessment to support investment decisions, and aligning regulatory and market frameworks, so that they actively incentivise circular mine water management and the use of secondary raw materials in the mining sector (Araya et al., 2021; Aguilar-Garrido et al., 2023;).

In practice, the most promising solutions from a circular economy perspective are hybrid treatment trains, which: combine passive and biotechnological stages for pre-treatment and metal recovery; integrate membrane or ion-exchange steps for polishing and high-level water recycling; employ industrial by-products as reagents or sorbents where environmentally and technically appropriate; and are designed and optimised using LCA to minimise overall life-cycle impacts (GWP, resource use, toxicity) while maximising recovered value (metals, salts, reusable water) (Mancini et al., 2024; Matebese et al., 2024). Thus, the circularity of mine water management depends less on the choice of a single “best” technology and more on the intelligent integration of complementary processes into site-specific, LCA-optimised systems.

Conclusions

Conventional treatments are essential for meeting mine water quality standards but, in their traditional linear form, they use large amounts of primary reagents and energy and produce bulky low-value sludge that burdens long-term management. By contrast, innovative treatment can shift mine water from waste to resource (metals, minerals, reusable water) when combined into well-designed treatment trains. Life Cycle Assessment provides an objective basis to compare these pathways, pinpoint environmental hotspots, and expose trade-offs between on-site water benefits and upstream/downstream impacts (reagent manufacture, energy, sludge handling). LCA-driven design allows the selection of configurations that meet regulations while minimising lifecycle impacts and enabling resource recovery. SMART goals are then needed to translate circular-economy aims into concrete goals for water reuse, metal recovery, carbon reduction, sludge valorisation, and transparent reporting. Future research should concentrate on scaling and de-risking biotechnological routes for metal recovery from mine water, enhancing the long-term stability and safety of reused sludge and reactive media, and coupling LCA with life-cycle costing and risk assessment to inform investment decisions. Concurrently, regulatory and market instruments must be reformed to create explicit incentives for circular mine-water management and secondary-material utilisation, integrating environmental protection, resource efficiency, and economic value creation.

References

- Aguilar-Garrido, A., Paniagua-López, M., Sierra-Aragón, M. et al. (2023). Remediation potential of mining, agro-industrial, and urban wastes against acid mine drainage, *Sci Rep* 13, 12120.
- Akcil, A., Koldas, S. (2025). Acid Mine Drainage (AMD): causes, treatment and case studies, *Journal of Cleaner Production*, 14 (12–13), 1139–1145.
- Alam, M. K., Islam, M. A. S., Saeed, T., Rahman, S. M., & Majed, N. (2023). Life Cycle Analysis of Lab-Scale Constructed Wetlands for the Treatment of Industrial Wastewater and Landfill Leachate from Municipal Solid Waste: A Comparative Assessment. *Water*, 15(5), 909.
- Araya, N., Ramírez, Y., Cisternas, L. A., Kraslawski, A. (2021). Use of real options to enhance water-energy nexus in mine tailings management, *Appl. Energy*, 303, 117626.
- Chen, J., Deng, S., Jia, W., Li, X., & Chang, J. (2021). Removal of multiple heavy metals from mining-impacted water by biochar-filled constructed wetlands: Adsorption and biotic removal routes. *Bioresour. Technol.*, 331, 125061.
- Daraz, U., Li, Y., Ahmad, I., Iqbal, R., Ditta, A. (2023). Remediation technologies for acid mine drainage: Recent trends and future perspectives. *Chemosphere*, 311(2), 137089.
- Ellen MacArthur Foundation. (2015). Towards a circular economy: Business rationale for an accelerated transition.
- European Commission. (2020). Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability (COM(2020) 474).
- Falagán, C., Grail, B. M., Johnson, D. B. (2017). New approaches for extracting and recovering metals from mine tailings, *Min Eng*, 106, 71–78.
- Gallego-Ramírez, C., Chica, E., & Rubio-Clemente, A. (2023). Life cycle assessment of raw and Fe-modified biochars: contributing to circular economy. *Materials*, 16(17), 6059.
- Gómez, J., Giraldo, H., Piaggio, G., et al. (2024). Recovery of copper sulphate from acidic mine waters by membrane crystallisation. *Journal of Membrane Science*, 700, 122707.
- Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., & Rydberg, T. (2011). Life cycle assessment: Past, present, and future. *Environmental Science & Technology*, 45(1), 90–96.
- Hauschild, M. Z., Goedkoop, M., Guinée, J. et al. (2013). Identifying best existing practice for characterisation modelling in life cycle impact assessment. *Int J Life Cycle Assess*, 18, 683–697.
- ISO 14040. (2006). Environmental management – Life cycle assessment – Principles and framework. International Organisation for Standardisation.
- Johnson, D. B., Hallberg, K. B. (2005). Acid mine drainage remediation options: a review, *Science of The Total Environment*, 338 (1–2), 3–14.
- Kaksonen, A. H., Puhakka, J. (2007). Sulphate reduction based bioprocesses for the treatment of acid mine drainage and the recovery of metals, *Eng. Life Sci.*, 7 (2007), 541–564.
- Lebron, Y. A. R., Moreira, V. R., de Souza Santos, L. V., Santos Amaral, M. C. (2023). Membrane distillation and ion exchange combined process for mining wastewater treatment, water reuse, and byproducts recovery, *Chemical Engineering Journal*, 466.
- Lottermoser, B. G. (2011). Recycling, Reuse, and Rehabilitation of Mine Wastes, *Elements*, 7(6), 405–410.
- Mancini, S., Casale, M., Tazzini, A., & Dino, G. A. (2024). Use and Recovery of Extractive Waste and Tailings for Sustainable Raw Materials Supply. *Mining*, 4(1), 149–167.
- Mao, Y., Zhao, Y., & Cotterill, S. (2023). Examining Current and Future Applications of Electrocoagulation in Wastewater Treatment. *Water*, 15(8), 1455.
- Matebese, F., Mosai, A. K., Tutu, H., Tshentu, Z. R. (2024). Mining wastewater treatment technologies and resource recovery techniques: A review, *Heliyon*, 10 (3).
- Nordstrom, D. (2011). Mine Water: Acidic to Circmneutral. *Elements*.
- Norgate, T., Haque, N. (2010) Energy and greenhouse gas impacts of mining and mineral processing operations, *Journal of Cleaner Production*, 18 (3).
- Nthunya, L.N., Ali, A., Richards, H. et al. (2025). Innovative dual-purpose remediation of acid mine drainage and resource recovery through membrane distillation crystallisation. *npj Clean Water* 8, 61.
- Roa, A., López, J., Cortina, J. L. (2024). Recovery of Rare Earth Elements from Acidic Mine Waters: A circular treatment scheme utilising selective precipitation and ion exchange, *Sep Purif Technol*, 338.
- Sakr, M., El Agamawi, H., Klammler, H., Mohamed M. Mohamed, M. M. (2023). A review on the use of permeable reactive barriers as an effective technique for groundwater remediation, *Groundwater Sustain. Dev.*, 21, 100914.
- Salih, W. T., Xiao, Z., & Dong, X. (2024). Research Enhancing Acidic Mine Wastewater Purification: Innovations in Red Mud–Loess. *Materials*, 17(9), 2050.
- Virpiranta, H., Sotaniemi, V.-H., Leiviskä, T., Taskila, S., Rämö, J., Johnson, D. B., Juha Tanskanen, J. (2022). Continuous removal of sulphate and metals from acidic mining-impacted

- waters at low temperature using a sulphate-reducing bacterial consortium, *Chem Eng Journal*, 427, 132050.
- Xu, F., Zhao, S., Li, B., Li, H., Ling, Z., Zhang, G., & Liu, M. (2024). Current Status of Zero Liquid Discharge Technology for Desulphurization Wastewater. *Water*, 16(6), 900.
- Xu, W., Yang, H., Mao, Q., Luo, L., & Deng, Y. (2022). Removal of heavy metals from acid mine drainage by red mud-based geopolymer pervious concrete: batch and long-term column studies. *Polymers*, 14(24), 5355.
- Younger, P. L., Banwart, S. A., & Hedin, R. S. (2002). *Mine Water: Hydrology, Pollution, Remediation*. Kluwer Academic Publishers.